Investigation of Soil Stabilize and Strengthening by Using Biopolymer

by

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Contents

Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. I declare that no portion of this thesis has been submitted for a degree at any other University. Parts of the work in this thesis have been published or under reviewed by the author in peer-reviewed or conference papers as listed.

Zhanbo Cheng

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List of Published Work

Relevant Peer-Reviewed Journal Papers:

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Abstract

Civil engineering infrastructures are commonly constructed on weak soil (e.g., poor drainage and low bearing capacity) and there need various reinforcement methods to efficiently increase soil strength. Biopolymer, as an eco-friendly material, extracted from plants, metastatic products of microorganisms, or cell walls of algae easily, is abundant in nature. Moreover, it was successfully used in the fields of packaging, medical, food, and oil recovery processes before. In recent years, biopolymer has been attempted to enhance and improve soil strength in geotechnical engineering.

The aims of this thesis are to comprehensive reveal the physical and mechanical properties of biopolymer treated various soil types (e.g., clay, sand/sand-clay mixture, and natural soil) with considering various factors (e.g., biopolymer cross-linking, initial water content, long-term curing, mixing method). The objections of the current research can be concluded: 1) To investigate the soil consistency of various biopolymer treated clay (Chapter 3); 2) To illustrate the strengthening and durability of biopolymer treated soil (Chapter 4, 5, 6); 3) To reveal the influence of various factors on the strength of biopolymer treated soil (Chapters 4, 5, 6); 4) To propose the application fields and limitations of biopolymer treated soil (Chapters 3, 4, 7).

The first part of this research is to summarize and review the current literature on the compaction properties, Atterberg limits, shear strength behaviours, and unconfined compressive strength of biopolymer treated soil (Chapter 2). Throughout the literature view, the previous researches mainly consider the influence of soil type, biopolymer type and compaction energy on the compaction properties of biopolymer treated soil. However, it mainly focuses on the compaction properties of biopolymer treated sand. In section 3.2, taking the typical biopolymer, xanthan gum as an example, the maximum dry density and optimum moisture content of xanthan gum treated kaolinite are obtained at different xanthan gum concentrations from 0.2% to 5%. In addition, the soil consistency and undrained shear strength of of biopolymer treated soil mainly focuses on the xanthan gum treated different soil types under various pore fluids. For meeting this gap, in section 3.3-3.4, the soil consistency, undrained shear strength and shear

viscosity of biopolymer treated clay are explored and predicted with considering eight biopolymer types under a wide range of biopolymer concentrations from 0.1% to 5% (Chapter 3).

In terms of the mechanical behaviours of biopolymer treated soil, although the thesis summaries the previous research on the unconfined compressive strength of biopolymer treated soil with considering biopolymer type, biopolymer concentration, soil type, curing time, curing temperature, rewetting-drying, freeze-thaw, most of research mainly focuses on single biopolymer treated one type of soil in the same paper. Moreover, there is limited research on illustrating the influence of initial water content and mixing method on the strength of biopolymer treated soil. In addition, there is no research to investigate the unconfined compressive strength of biopolymer treated soil with considering biopolymer cross-linking. Thus, the unconfined compressive of biopolymer treated clay are comprehensively explored by considering biopolymer type (e.g., xanthan gum (XG), sodium alginate (SA), locust bean gum (LBG), guar gum (GG), carrageenan kappa gum (KG), gellan gum (GE) and agar gum (AG), chitosan (CH)), biopolymer concentration (e.g., 0.5%-5%), initial mositrue content (e.g., 30%-60%), curing time (e.g., 0-70 days), durability (e.g., curing 378 days and rewetting-drying), biopolymer cross-linking (xanthan gum-agar gum, xanthan gum-carrageenan kappa gum and xanthan gum-locust bean gum) and mixing method (e.g., room temperature water-dry (RDM), room temperature water-wet (RWM), hot water-dry (HDM) and hot water-wet (HWM)) (Chapter 4). Subsequently, the unconfined compressive strength of biopolymer treated sand/sand-clay mixture is illustrated by considering biopolymer type (e.g., XG, SA, LBG, KG, GE and AG), biopolymer concentration (e.g., 1%, 2% and 3%), soil type (e.g., two comerical sand, kaolinite, each commercial sand-kaolinite with the ratio of 4-1, 1-1, 1-4) and curing time (e.g., 14-70 days) (Chapter 5). For revealing the performance of biopolymer treated natural soil, the unconfined compressive strength of biopolymer treated three types of natural soil is demonstrated by considering biopolymer type (e.g., XG, SA, LBG, KG, GE and AG), biopolymer concentration ((e.g., 1%, 2% and 3%)) and curing time (e.g., 0-365 days) (Chapter 6).

Although the shear behaviours of biopolymer-treated soil have been verified in previous direct shear tests, there has limited attempt to examine shear behaviours under different confining stress conditions. Moreover, the previous research mainly focuses on biopolymer treated sand. The effectiveness of biopolymer treatments in practical conditions has been limited analysis, especially for biopolymer treated clay. Therefore, in section 4.3, varying confining pressures (e.g., 30 kPa, 100 kPa, 200 kPa, 300 kPa and 400 kPa) representing construction depths are applied to investiage the shear behaviors of biopolymer treated kaolinite using a laboratory triaxial system by considering biopolymer type (e.g., carrageenan kappa gum, xanthan gum, agar gum, locust bean gum, sodium alginate, gellan gum, guar gum, chitosan, casein, sucralose, wine tannin, glycerine), biopolymer concentration (e.g., 1%, 2% and 5%) and water condition (e.g., hydrated and dehydrated conditions) (Chapter 4). In addition, the possible implementation and filed application, further research and limitation of biopolymer treated clay are comprehensive illustrated (Chapters 3, 4 and 7).

The main innovation and contribution of this research are highlighted as follows.

(1) The previous research mainly focused on the soil consistency of XG treated various soil types under different pore fluids without considering the influence of various biopolymer types and concentrations. Therefore, in this study, it can be found that the plastic limit of biopolymer treated clay increases with the increase of biopolymer concentration regardless of biopolymer type, and the trend of the plasticity index is consistent with the liquid limit. In addition, the liquid limit of biopolymer treated clay can be divided into three conditions depending on biopolymer types. The liquid limit of KG, SA and GE treated clay decreases firstly at low concentration (e.g., 0.2%), and then continuously increasesing with the increase of biopolymer concentration. Moreover, the liquid limit of XG, LBG and GG treated clay has a peak point of 0.5%, 1% and 1%, respectively, and the liquid limit tends to keep constant after 3% concentration. Meanwhile, the liquid limit of AG and CH treated clay tends to remain constant. Moreover, *m* value of 0.323 can be used to estimate the liquid limit of biopolymer treated clay by one fall cone test with cone penetration falling between 15 and 25 mm. Meanwhile, two empirical equations are proposed to predict the undrained shear strength and shear viscosity of biopolymer treated clay.

(2) The previous researches mainly illustrated the uncondined compressive strength of single biopolymer treated one soil type with limited biopolymer concentrations (e.g., < 2%) and curing time (e.g., less 28 days), and there are limited references on researching the influence of rewetting-drying, initial water content, mixing method and biopolymer cross-linking on the mechanical behaviours of biopolymer treated soil, espcically for clay and clay-sand mixture. Therefore, in this study, it can be illustrated that the biopolymer can significantly increase the mechanical properties of soil. Especially for after even curing 378 days, the unconfined compressive strength of biopolymer treated soil can be still more 7 times than that of untreated soil. In addition, the unconfined compressive strength of biopolymer treated clay after rewetting-drying cycles is also more 2 times than that of the highest unconfined compressive strength of untreated clay, while the untreated clay samples are broken after one rewetting-drying cycle due to the weak connection of soil particles. Through performing single control variable method on each factor, it can be obtained that there is the optimum biopolymer type (e.g., XG, SA and LBG), optimum biopolymer concentration (e.g., 1%-2%), optimum curing time (e.g., 14-35 days), optimum biopolymer cross-link (e.g., XG-KG) to obtain the better reinforcement effect. The optimum soil type, optimum initial water content and optimum mixing method depends on curing time, biopolymer type and concentration. For example, the optimum initial water of 0.5%, 1%, 2% and 3% XG treated clay is 40%, 45%, 50% and 60%, respectively, while the optimum intial water of SA treated clay is 50% or 55% depending on SA concentration. The maximum unconfined compressive strength of XG, SA and KG treated clay is obtained in the hot water-dry mixing method, while the optimum mixing method of AG, GE and LBG (thermal gelation biopolymers) treated clay is the hot water-wet mixing method. At 1% XG concentration, the highest UCS is obtained in the S_1C_{1-1} regardless of curing time, and the highest UCS is observed in pure sand for less than 42 days at 2% XG concentration, while the UCS of 3% XG treated pure clay can be observed as the highest value at curing 70 days. Overall, the clay content plays a vital role in the strength of biopolymer treated sand-clay mixture, especially for high biopolymer concentration.

(3) The shear beviours of biopolymer treated soil in previous work are illustrated through direct shear tests, and there are limited refereces concerning the mechanical proeperties of biopolymer treated clay by considering different confining stress conditions, especially for clay. Therefore, in this study, it can be revealed that biopolymer significantly increases the peak deviatoric stress for strengthening and stabilising clay at hydraulic conditions. SA, AG, GE and guar gum (GG) are the most effective biopolymer to increase soil cohesion among twelve biopolymers treated clay. Subsequently, KG, Glycerine (GL) and casine (CA) have a similar effect on enhancing soil cohesion. With the increase of biopolymer concentration, the increment of cohesion decreases and there exists the optimum biopolymer concentration (e.g., 1-2%) to obtain the better shear behavious of biopolymer treated soil. On the other hand, the internal friction angle of biopolymer treated clay varies with the increase of biopolymer concentration depending on biopolymer type. At hydrated condition, there is an optimum curing time to obtain the maximum shear strength of biopolymer treated clay (e.g., 42 days for XG treated clay). With the continuous increase of curing time, the shear strength decreases, while the shear strength of biopolymer treated clay is still significantly larger than that of untreated clay, and the strength decrement ratio of biopolymer treated clay is smaller than untreated clay.

List of Figures

List of Tables

List of Symbols and Abbreviations

Symbols:

w	water content
$m_\mathrm{b}/m_\mathrm{c}$	the Mass Ratio of Biopolymer to Clay
d	cone penetration
c	the water content at a penetration depth of 1 mm
m	the slope of the linear relationship between the logarithmic water content and the logarithmic cone penetration
S_u	Undrained Shear Strength
W	weight of the cone
K	no-dimensional fall cone factor
μ	shear viscosity of soil
h_eq	dynamic penetration depth
$m_\mathrm{XG}/m_\mathrm{B}$	xanthan gum to biopolymer ratio in mass
C_XG	XG concentration
IR_UCS	UCS increment ratio
C_SA	SA concentration
$m_\mathrm{c}/m_\mathrm{s}$	clay-to-soil ratio in mass
BC_ts	the ratio of biopolymer weight to total soil weight
BC_c	the ratio of biopolymer weight to clay content weight

Abbreviations:

KG	Carrageenan Kappa Gum
LBG	Locust Bean Gum
XG	Xanthan Gum
AG	Agar Gum
GG	Guar Gum
SA	Sodium Alginate
GE	Gellan Gum
CH	Chitosan
CA	Casein
SU	Sucralose
WT	Wine Tannin
GL	Glycerine
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
USCS	Unified Soil Classification System
SM	Silty Sand
ML	Silt
CL	Clay of Low Plasticity
SEM	Scanning Electron Microscope
UCS	Unconfined Compressive Strength
PL	Plastic Limit
LL	Liquid Limit
CH	Clay of High Plasticity
C_u	Uniformity Coefficient
C_c	Curvature Coefficient
PI	Plasticity Index
D_{60}	the Ratio of the Weight of Less a Specific Soil Particle Size to Total Soil Weight is 60%
D_{30}	the Ratio of the Weight of Less a Specific Soil Particle Size to Total Soil Weight is 30%

D_{10}	the Ratio of the Weight of Less a Specific Soil Particle Size to Total Soil Weight is 10%
RDM	Room-temperature Dry Mixing
RWM	Room-temperature Wet Mixing
HDM	Hot-dry Mixing
HWM	Hot-wet Mixing
RT	Room Temperature
HT	100°C
MT	Melt Temperature
LL_{one}	Liquid Limit Determined by One-point Method
LL_{four}	Liquid Limit Determined by Four-point Method
DC	Dry Curing
RS	Re-submerge
S1	Paving Joint Sand
S2	Sharp Sand
SP	Poorly Graded Sand
S_1C_{4-1}	the paving joint sand-clay mixture with the ratio of 4:1
S_1C_{1-1}	the paving joint sand-clay mixture with the ratio of 1:1
S_1C_{1-4}	the paving joint sand-clay mixture with the ratio of 1:4
S_2C_{4-1}	the sharp sand-clay mixture with the ratio of 4:1
S_2C_{1-1}	the sharp sand-clay mixture with the ratio of 1:1
S_2C_{1-4}	the sharp sand-clay mixture with the ratio of 1:4
HS2	High Speed 2
NS1	Natural Soil 1
NS2	Natural Soil 2
NS3	Natural Soil 3

Chapter 1 Introduction

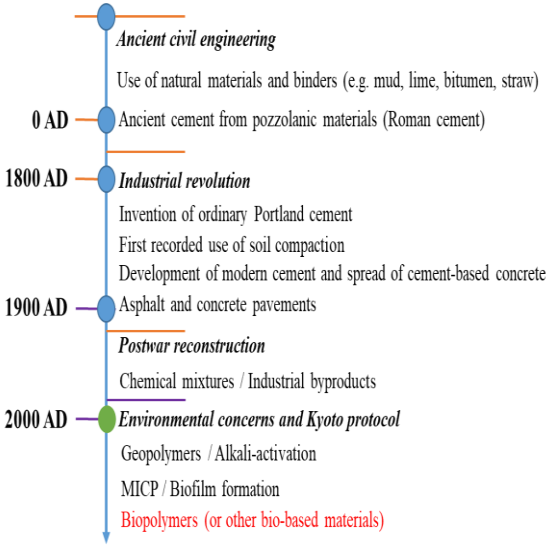
1.1 Background

Civil engineering infrastructures are commonly constructed on weak soil (Zhang et al. 2015, Rondonuwu et al. 2016, Hegde and Sitharam 2017, Khemissa et al. 2018, Shi et al. 2018, Wang et al. 2019a, Yu et al. 2019, Saleh et al. 2019). It normally causes poor drainage, the differential settlement of the foundation, a decrease in bearing capacity and wind erosion, and an increase in liquefaction susceptibility (Cai et al. 2017, Lazorenko et al. 2019, Clarkson and Williams 2021, Li et al. 2021, Patil et al. 2021, Sun et al. 2021, Liu et al. 2022a, Liu et al. 2022b, Sun et al. 2022). Therefore, various ground improvement materials and methods are proposed aiming to solve these geotechnical problems dating to the beginning of human civilization as shown in Table 1.1. In ancient society, natural materials and binders (e.g., mud, lime and bitumen) were used as common construction materials for various forms of bricks to create engineering infrastructures (Delatte 2001, Yang et al. 2009, Yang et al. 2010). After the industrial revolution, ordinary cement (e.g., Portland cement) as one of the most common construction and building materials was used to stabilize and strengthen soil performance (Nikoo et al. 2017, Sadeghi and Nouban 2017). In the late 20th century, mechanical improvement (e.g., compaction, drainage, external loading, consolidation and geosynthetics) and chemical treatment (e.g., fly ash, polyacrylamide and polyethylene oxide) (Lee et al. 1994, Ghosh and Yasuhara 2004, Shen et al. 2005, Lo et al. 2010, Yang and Tang 2012, Kang and Bate 2016, Kang et al. 2019a, Kang et al. 2019b, Kang et al. 2019c, Wang et al. 2019b, Wang et al. 2020) were two primary methods to enhance the engineering characteristics of a particular soil. However, these traditional techniques have caused numerous problems, especially for detrimental impacts on the environment problems (e.g., ecosystem contamination, water pollution and carbon dioxide emission) (Danthurebandara et al. 2012, Koptsik et al. 2015, Ibrahim et al. 2016, Arora et al. 2018). For example, the ratio of the CO_2 emissions from the cement industry to global CO_2 emissions increased from 2% in 2016 to 8% in 2018 (Andrew 2018). Thus, it is urgent to find out eco-friendly alternatives to replace traditional soil treatment and improvement techniques associated with these environmental concerns (Van Paassen et al. 2010).

Since the beginning of the 21st century, several attempts to enhance the mechanical properties of soil for construction and geotechnical engineering applications using biological processes or excretions with a remarkably smaller environmental impact have been extensively reported (Whiffin et al. 2007, Sigel et al. 2008, DeJong et al. 2010, Harkes et al. 2010, Larson et al. 2012, Khatami and O'Kelly, 2013, Chang et al. 2015b, Choi et al. 2017, Nakamatsu et al. 2017, Ham et al. 2018, Sharma et al. 2018, Biju and Arnepalli 2019, Muguda et al. 2019). Especially, microbial induced calcite precipitation (MICP) as the most recognized soil treatment method among biomineralization strategies has been investigated to increase the strength and stiffness of soils (Whiffin et al. 2007, DeJong et al. 2010). However, a problem in the application of bacteria was that they were slow growing organisms with low rate of exopolysaccharide production and their applications required long-term treatment of soil for its clogging. Secondly, microbial clogging in-situ was that the penetration of microbial cells in soil depth was limited by the minimum soil pore size from 0.5 to 2 μm (Ivanov and Chu, 2008). Therefore, the method can only be used for soil with suitable hydraulic conductivity and is unsuitable for soil with low permeability (e.g., clay).

However, biopolymer, as directly extracted from plants and utilized biogenic excrement, is characterized as one type of potential eco-friendly material, which is abundant in nature. It has wide applicability and high reliability to be utilised for ground improvement. Moreover, it has been successfully used in the fields of packaging, medical, food and oil recovery processes before (Van de Velde and Kiekens 2002). Nowadays, biopolymer has been paid more attention on the application of geotechnical engineering, especially for water retention characteristics (Chang et al. 2016c, Tran et al. 2017, Tran et al. 2018, Rahmati et al. 2019), soil erosion resistance (Orts et al. 2000, Kavazanjian et al. 2009, Chang et al. 2016d, Larson et al. 2016, Kwon et al. 2017, Lee et al. 2019a, Lee et al. 2020), soil hydraulic conductivity (Wiszniewski and Cabalar 2014, Ayeldeen et al. 2016, Cabalar et al. 2017, Cabalar et al. 2018, Dehghan et al. 2019, Liu et al. 2019, Sujatha and Saisree 2019, Wen et al. 2019, Bonal et al. 2020, Khosravi et al. 2020, Ng et al. 2020) and soil strength improvement purposes (Cole et al. 2012, Chang et al. 2016b, Kulshreshtha et al. 2017, Ayeldeen et al. 2018, Şengör 2019, Jang 2020, Choi et al. 2020, Smitha and Rangaswamy 2021a, Smitha and Rangaswamy

Table 1.1 Characteristics and Applications of various treatment methods

Treatment method	Advantages	Disadvantages	Applications	Advanced process
Ordinary Portland Cement	High strength, High durability, High workability, High hydraulicity, Low cost	Produced large CO_2 emitted, Raising the PH of soil, Increasing heat islands, Prevention of vegetation growth, Cement demolition waste, Lung diseases, Huge amounts of binders	Ground Improvement, Concrete structures, Pavement, Deep cement mixing, Grouting, Soil nails, Soil stabilization	
Geosynthetics family	High tensile strength, Flexibility, Impervious	Strengthening almost, Completely depend on the material itself and not the soil	Soil separation, Filtering, Reinforcement, Drainage	
Chemically synthesized polymers	Reduce soil erosion, Runoff control, Impervious	Concerning about toxicity, Water pollution problems, Require massive injection of chemical solutions	Agricultural purpose, Construction, Military applications, Soil grouting practices	
Bio-mineralization	Environment-friendly, Increase soil strength, Increase soil stiffness, Self-proliferation, Biodegradation	Not suitable for fine soils, Performance of bacteria not consistent, Highly concentrated ammonium chloride byproduct	Remediation of heavy metals, CO_2 sequestration, The repair of concrete	
Biopolymer	Environment-friendly, Increase soil strength, Resistance to erosion, Reduce permeability, Reduce time for cultivation, Appropriateness with clayey soil, Readily found in nature, Promoting vegetation growth	Market price expensive, Concern about biodegrade with time, Development of suitable equipment	Building materials, Earth pavement, Farmland erosion prevention, Slurry walls, Seepage barriers, Grouting	

2021b, Smitha and Rangaswamy 2021c, Smitha and Rangaswamy 2021d). Biopolymers are polymer materials that consist of bio-based raw materials and/or being biodegradable materials (Imre and Pukánszky 2013). In general, biopolymers can be classified into three major groups: 1) nucleic acids and nucleotides, 2) proteins and amino acids, and 3) carbohydrates (e.g., polysaccharides) (Kalia and Averous 2011). As a result, bio-manufacturing biopolymer induced by organisms in the exo-cultivation facility can provide in large quantities and high quality for civil engineering purposes (Chang et al. 2020). Moreover, direct biopolymer mixing with soil forms uniform biopolymer-treated soil mixtures that show instant strengthening due to the electro-static biopolymer-soil matrix formation (Chang et al. 2015). Therefore, biopolymers can be recognized as a soil improvement and strengthening technique due to their potential cost savings, low environmental impact, non-toxicity and non-secondary pollution.

To date, most studies on these applications of biopolymers were experimental efforts that have produced preliminary findings and analyses. It found that biopolymers such as agar, starch, gellan gum, gellan gum, beta-glucan and xanthan gum can effectively stabilise and strengthen soil characteristics (Chang et al. 2012, Chang et al. 2015c, Chang et al. 2015d, Ayeldeen et al. 2016, Chang et al. 2016a, Latifi et al. 2016a, Kulshreshtha et al. 2017, Latifi et al. 2017b, Chang and Cho 2019). In addition, biopolymer showed the high performance to improve the soil strength even under a low biopolymer-to-soil ratio. For example, the unconfined compression strength of 0.25% beta-1,3/1,6-glucan treated soil (2.17MPa) with lower density was similar to that obtained with 10% cement mixing (2.65 MPa), while the strength of 0.5% beta-1,3/1,6-glucan treated soil yielded to 4310 kPa (Chang et al. 2012). However, throughout literature review, the previous research mainly explored the unconfined compressive strength of sigle biopoplymer treated one soil type with less curing time (e.g., less 28 days) in the same study. Therefore, it is lack of comprehensive comparing the reinforcement effect of various biopolymer types treated different soil types under keeping the same conditions, and the durability of biopolymer treated soil, especially for clay, should be further emphasized with curing long-term and undertaking rewetting-drying cycles. Moreover, most researches mainly considered the influence of curing stage (e.g., curing temperature) on the mechanical properties of biopolymer treated soil, while the roles of preparing conditions (e.g., initial water content and mixing method) are neglected. For example, in the preparation stage of previous research, the initial moisture content was usually set as a fixed value (e.g., optimum moisture content and liquid limit) to mix soil and biopolymer (Chang and Cho 2012; Cabalar et al. 2018; Fatehi et al. 2018; Hataf et al. 2018; Latifi et al. 2016). It normally cannot enough reach the maximum strengthening efficiencies of biopolymer treated soil because the workability of biopolymer-soil matrix may be badly impacted due to the limited amount of water causing incomplete diffusion of biopolymer, while high water content can obviously decrease the dry density of soil to have adversely effect on mechanical strength (Kulshreshtha et al. 2017). Therefore, it is expected to exist an ideal initial moisture content contributing to the highest strength. Meanwhile, the mixing method can also impact on the formation of soil-biopolymer matrix through changing the procedure of soil-biopolymer-water mixture and water temperature. In addition, the shear behaviours of biopolymer treated soil were mostly investigated through direct shear tests, while the effectiveness of biopolymer treatments in practical conditions is limited analysed by considering different confining stress, especially for clay. In terms of the basic physical and mechanical properties, the previous research had comprehensive illustration on the soil consistency of xanthan gum treated different soil types with various pore fluids, and the emperica eqution predicting the undrained shear strength of xanthan gum and guar gum treated mine tailings was obtained (Chen et al. 2013). However, there is limited research on investigating the influence of biopolymer type with a wide rane of biopolymer concentration on soil consistency. There also needs to develop the empirical equation to predict the undrained shear strength and shear viscosity of biopolymer treated soil based on the results of fall cone tests. Most researches mainly concerned on the compaction properties of biopolymer treated sand. At the same time, the mechanical behaviours of biopolymer treated soil is sensitive to water content and there is lack of illustrating the water evaporation ratio of biopolymer treated soil at curing conditions in the previous works.

For meeting these gaps, this study comprehensively recognizes the physical and mechanical properties of biopolymer treated soil through various experimental tests (e.g. compaction test, thread rolling test, fall cone test, water evaporation test, unconfined compressive test and static triaxial test). To be specific, taking the typical biopolymer (XG) as example, the compaction properties (e.g., maximum dry density and optimum moisture content) and water evaporation ratio of biopolymer treated clay are revealed under different XG concentration. Meanwhile, the Atterberg limits of biopolymer treated soil are illustrated by considering eight typical biopolymers (e.g., XG, SA, GG, GE, KG, LBG, AG and CH) and a wide range of biopolymer concentration from 0.1% to 5%. Based on the results of fall cone tests, the undrained shear strength and shear viscosity of biopolymer are predicted, and the relevant empirical equations are obtained. Moreover, the unconfined compressive strength of biopolymer treated soil is explored by considering biopolymer type (e.g., XG, SA, KG, LBG, AG and GE), biopolymer concentration (e.g., 0.5%-5%), biopolymer cross-linking (e.g., XG-AG, XG-KG and XG-LBG), curing time (e.g., 5-378 days), hydrated condition (e.g., initial status), initial water content (e.g., 30%-60%), mixing method (e.g., RDM, RWM, HDM and HWM), durability (e.g., curing 378 days and undertaking rewetting-drying cycles) and soil type (e.g., clay, clay-sand mixture, sand and natural soil). In addition, the shear behaviours (e.g., internal friction angle and cohesion) of biopolymer treated clay are illustrated through triaxial shear tests under different confining stress conditions by considering typical twelve biopolymers and various biopolymer concentration at hydrated condition. Taking the typical biopolymer (XG) as example, the shear strength of biopolymer treated clay at dehydrated condition and different confining stress conditions are revealed by considering different curing time. At last, the promising application fields, limitations and future work are also listed and illustrated.

1.2 Objectives and contents of present study

Selecting different biopolymers types (e.g., carrageenan kappa gum, KG; locust bean gum, LBG; xanthan gum, XG; agar gum, AG; guar gum, GG; sodium alginate, SA; gellan gum, GE; chitosan, CH) as example, this thesis is aimed to illustrate the strengthening and stabilization of biopolymer treated different soil types (e.g. clay, sand, clay-sand mixture, natural soil) by considering different biopolymer concentrations (e.g. 0.5%, 1%, 2%, 3%, 4%, 5%), curing time (e.g. 0, 7, 14, 21, 28, 35, 42, 49, 70, 378 days), mixing method (e.g. dry and wet mixture), mixed water temperature (e.g. room temperature water and hot water), biopolymer cross-linking (e.g. XG-KG, XG-LBG, XG-AG), initial water content (e.g. 30%, 35%, 40%, 45%, 50%, 55%, 60%) and rewetting-drying (e.g. 1, 2, 3 cycles). The main objectives of this thesis can be illustrated as follows.

1) To investigate the soil consistency of various biopolymers treated clay under a wide range of biopolymer concentrations and propose the empirical equations to predict the undrained shear strength and shear viscosity of biopolymer treated soil.

2) To illustrate the reinforcement effect and durability of biopolymer treated soil, and reveal the optimum value of each influence factor on the strength of biopolymer treated soil.

3) To explore the shear behaviours of biopolymer treated soil under different confining stress at hydrated and dehydrated conditions by considering biopolymer type, biopolymer concentration and curing time.

4) To propose the application fields, limitations and futher work of biopolymer treated soil.

1.3 Organisation of Dissertation

There are seven chapters in the dissertation. Following the Introduction in Chapter 1, Chapter 2 presents a review of geotechnical engineering properties of biopolymer treated soil from five aspects with compaction properties, Atterberg limits and undrained shear strength, unconfined compressive strength, shear behaviours and microstructures. It is illustrated that the influence of soil type, biopolymer type and concentration, compaction energy and mixing of other stabilization materials on the experimental results of the compaction test. Moreover, soil type, biopolymer type and concentration, and pore fluid condition contribute to the Atterberg limits and undrained shear strength of biopolymer treated soil. Similarly, the mechanical properties of biopolymer treated soil depend on soil type, biopolymer type and concentration, water condition, curing method, soil mixing method and mixed other reinforced methods (e.g. fibre and fly ash), which can be further explained by the formed microstructure with physical absorption (e.g. van der Waals forces), strong polar attraction (e.g. hydrogen bonding) and chemisorption (e.g. ionic/electrostatic or covalent bonds) between biopolymer and soil.

Chapter 3 illustrates the basic physical and mechanical properties of biopolymer treated clay. Firstly, the compaction test of the most widely used biopolymer (xanthan gum) treated clay is performed to obtain the change of maximum dry density and optimum water content with the increase of XG concentration. Moreover, the plastic limit and liquid limit of eight biopolymers (carrageenan kappa gum, KG; locust bean gum, LBG; xanthan gum, XG; agar gum, AG; guar gum, GG; sodium alginate, SA; gellan gum, GE; chitosan, CH) treated clay are illustrated through conducting thread rolling test and fall cone test. And then the plasticity index and soil classification of various biopolymer treated clay can also be illustrated. Furthermore, based on the results of the fall cone test, the undrained shear strength and shear viscosity of biopolymer treated clay can be evaluated, and the corresponding empirical equations are given. At the same time, the water evaporation percentage of biopolymer treated soil is recorded with the increase of curing time.

Chapter 4 shows the mechanical behaviours of biopolymer treated clay. Firstly, the unconfined compressive strength of biopolymer treated clay is illustrated by considering various factors, such as biopolymer concentration (e.g., 0.5%-5%), biopolymer type (e.g., XG, SA, LBG, KG, GE and AG), initial moisture content (e.g., 30%-60%), curing time (e.g., 0-70 days), durability (e.g., curing 378 days and rewetting-drying), biopolymer cross-linking (XG-AG, XG-KG and XG-LBG) and mixing method (e.g., room temperature water-dry, room temperature water-wet, hot water-dry and hot water-wet). Moreover, the shear behaviours of biopolymer treated clay are revealed at the hydraulic condition considering biopolymer type (e.g. KG, XG, AG, LBG, SA, GE, guar gum, chitosan, casein, sucralose, Wine Tannin, Glycerine) and biopolymer concentration (e.g., 1%, 2% and 5%). Meanwhile, selecting XG as an example, the shear strength of biopolymer treated clay under dehydrated conditions is also illustrated. Lastly, the feasibility analysis of biopolymer treated soil in the aspects of reinforcement mechanism and economic indexes is conducted to reveal the competitiveness of biopolymer comparison with traditional materials for strengthening and stabilising soil in engineering practices.

Chapter 5 describes the mechanical behaviours of biopolymer treated sand/sand-clay mixture. In this part, selecting kaolinite and two commercial sand (e.g., paving joint sand (S1) and sharp sand (S2)) as soil materials, the strengthening and stabilization efficiency of biopolymer treated soil are investigated by considering biopolymer type (e.g., XG, SA, LBG, KG, GE and AG), biopolymer concentration (e.g., 1%, 2% and 3%), soil type (e.g., the ratio of sand-clay mixture with 0:1, 1:4, 1:1, 4:1 and 1:0) and curing time (e.g., 14-70 days).

Chapter 6 provides the case study about biopolymer treated natural soils. Selecting three in-site soils as example, the particle grade test is carried out to obtain the relevant gradation coefficient. Moreover, the unconfined compression test is performed to obtain the strength of biopolymer treated soil by considering biopolymer type (e.g., XG, SA, LBG, KG, AG and GE), biopolymer concentration (e.g., 1%, 2% and 3%), curing time and initial water content.

Chapter 7 summarizes the current research conclusions and highlights, and provides potentile field applications, discusses and recommends for future research work. Lists of references follow Chapter 7.

Chapter 2 Literature Review

2.1 Compaction properties

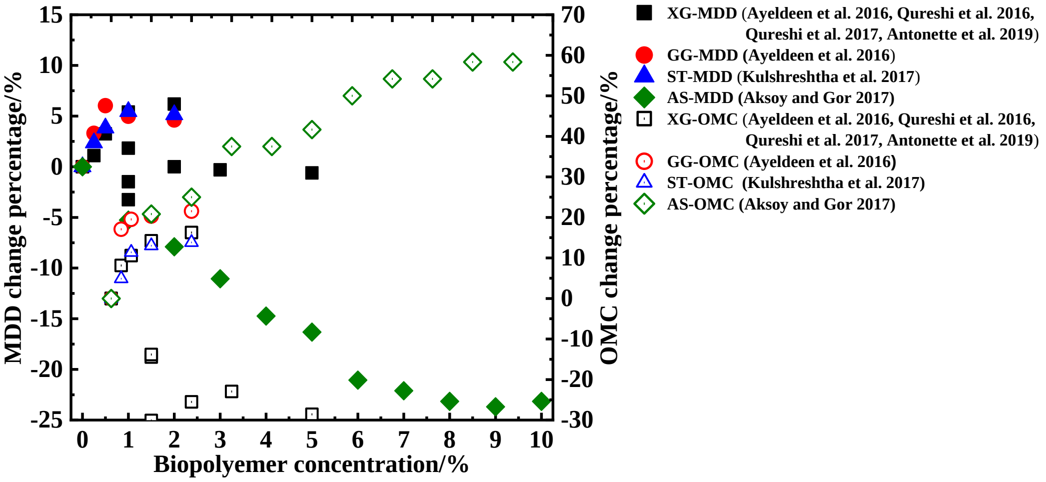
Soil density and void ratio representing particle arrangement, are essential parameters controlling many mechanical properties of soil (e.g. shear strength, settlement rate, bearing capacity and permeability) (Chang and Cho 2014a, Cabalar et al. 2018, Abd El-Hafez et al. 2019, Dehghan et al. 2019). Thus, it is necessary to examine the variations of biopolymer treated soil density induced by soil type, biopolymer properties and compaction energy.

2.1.1 Influence of soil type on compaction properties

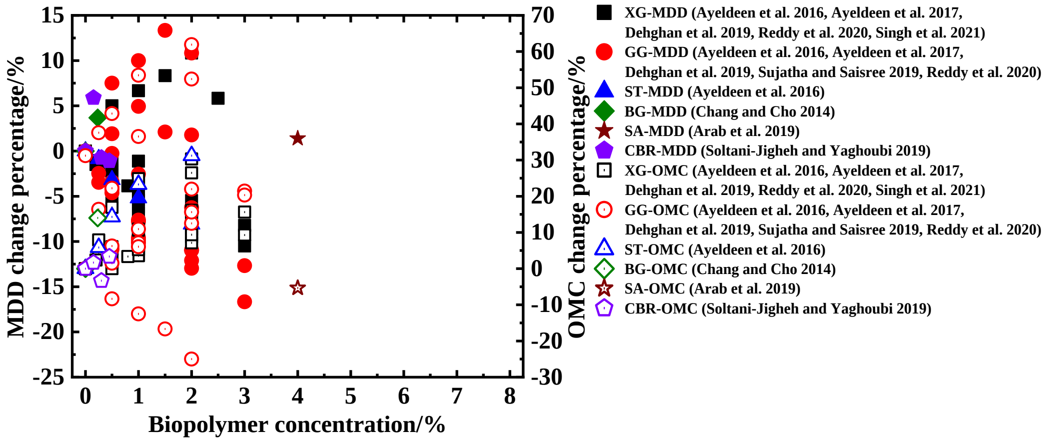
As shown in Figure 2.1 (a), the maximum dry density (MDD) of biopolymer treated sand reached the peak value at a lower concentration (e.g. <1%), which was about 1.05 times of MDD of untreated soil. And then, it decreased with the continued increase of biopolymer concentration. It can be interpreted that the lubricant effect of gels and the slight increment of solution viscosity in inter-granular pores at lower biopolymer concentrations can reduce the friction between cohesionless sand particles to enhance particle compressibility (Nugent et al. 2010, Bate et al. 2014, Chang and Cho 2014a, Ayeldeen et al. 2016, Qureshi et al. 2017, Ahmed et al. 2018, Kang et al. 2019a). Beyond the optimal dosage, the higher solution viscosity disturbed the compaction mechanism causing the particles to shift away from each other and increasing the global volume of void spaces (Chang and Cho 2014a, Ayeldeen et al. 2016, Qureshi et al. 2017, Dehghan et al. 2019, Sujatha and Saisree 2019). As a result, the MDD of biopolymer treated sand decreased after reaching optimum biopolymer concentration.

In most cases, the MDD of biopolymer treated fine-grain soil (e.g. well grade sandy with silt (Aksoy and Gor 2017), silty (Ayeldeen et al. 2016), silty-clay (Dehghan et al. 2019), clay (Cabalar et al. 2018, Joga and Varaprasad 2019)) decreased with the increase of biopolymer concentration as shown in Figures 2.1 (b) and (c). The electrostatic repulsion forces among the biopolymer strands can inhibit the development of a hydrogen-bonding network to increase the interparticle void space (Zhang et al. 2013, Kang et al. 2019a). In addition, compared to the sandy soil, fine soil grain became effortlessly moved away by the effect of the solution viscosity regardless of the concentration (Ayeldeen et al. 2016, Ayeldeen et al. 2017). However, it was also expected to increase the MDD of biopolymer treated fine-grain soil at very low biopolymer concentration. For example, Chang and Cho (2014) illustrated that the MDD of 0.23% β-1,3/1,6-glucan gum treated Korean residual soil had a little bit increase from 13.6 to 14.1 kN/m^3. Kang et al. (2019a) found that the MDD of 0.1% XG treated kaolinite slightly increased from 14.7 to 15.08 kN/m^3.

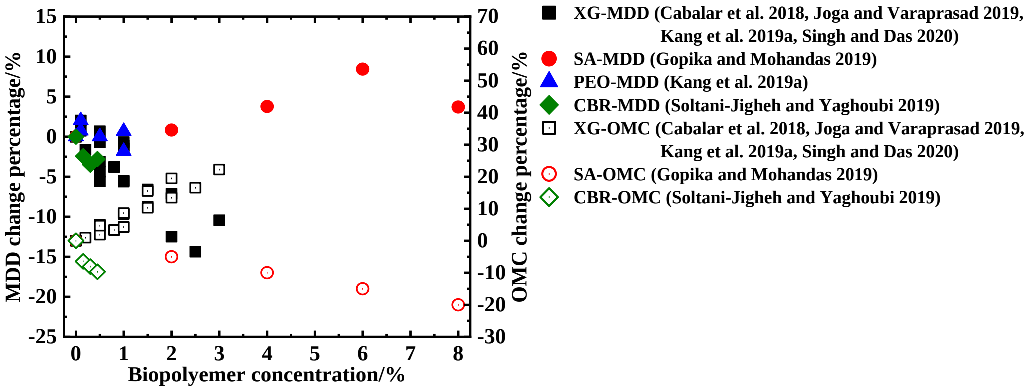
On the other hand, the optimum moisture content (OMC) of biopolymer treated soil was observed to be increased with the increase of biopolymer concentration for most specimens regardless of soil type. It can be attributed that the increased biopolymer can cause the increased absorbed water consumed for hydration (Qureshi et al. 2016, Kulshreshtha et al. 2017, Antonette et al. 2019, Arab et al. 2019, Reddy et al. 2020, Singh and Das 2020, Singh et al. 2021). And the nature of the biopolymer usually indicated that the hydrogel formation continued to take place until strong polymer bonds developed into a complete viscous gel (Ayeldeen et al. 2016, Dehghan et al. 2019).



(a) Biopolymer treated sand



(b) Biopolymer treated silty soil



(c) Biopolymer treated clay

Figure 2.1 Compaction test results of biopolymers treated soil

Note: GG-guar gum, ST-starch, AS-astragalus, BG- β-1,3/1,6-glucan gum, CBR-chocolate brown viscous fluid, PEO-polyethylene oxide

2.1.2 Influence of biopolymer type on compaction properties

Ayeldeen et al. (2016, 2017) and Reddy et al. (2020) illustrated that the MDD of guar gum treated soil was lower and the OMC of guar gum treated soil was higher than that of modified starch or xanthan gum treated soil at 2% concentration because the solution viscosity of guar gum was higher than that of modified starch or xanthan gum. Moreover, the divergence in MDD and OMC between guar gum and xanthan gum widened with the increase of biopolymer concentration (Ayeldeen et al. 2017, Reddy et al. 2020).

2.1.3 Influence of other factors on compaction properties

a) Compaction energy

The compaction properties of biopolymer treated soil also depended on the amount of compaction energy applied (Kulshreshtha et al. 2017, Singh and Das 2020).

Singh and Das (2020) found that the MDD of xanthan gum treated high plastic silt under low compaction energy was higher than that of high compaction energy, while the OMC of biopolymer treated soil with light compaction was lesser than that of heavy compaction. It was probably due to the stiffening of biopolymer treated soil under the higher impact (non-Newtonian behaviour) that may allow the inclusion of more air. Moreover, under light compaction, the MDD of biopolymer treated soil decreased and the OMC of biopolymer treated soil increased with the increase of xanthan gum concentration, respectively, while it can be observed the converse trend in heavy compaction (Singh and Das 2020). It can be explained that the lubricating effect of biopolymer made the soil particles more easily slide over one another and compacted to a more oriented denser matrix under heavy compaction than that of light compaction (Singh and Das 2020).

b) Mixing with other stabilizer materials

Some research investigated the compaction properties of biopolymer mixed other stabilizer materials (e.g. bentonite, fly-ash) treated soil (Antonette et al. 2019, Kang et al. 2019a). Kang et al. (2019a) illustrated that the MDD of biopolymer treated 30% fly-ash and kaolinite mixture was larger than that of xanthan gum treated kaolinite. It was due to the replacement of kaolinite by fly ash causing the finer particles of kaolinite can fill in the voids between fly ash particles during compaction processing. In addition, the corresponding OMC decreased, which was related to the fly ash hydration along with a higher degree of flocculation and a reduction of the electrical diffuse double layer thickness.

2.2 Atterberg limits and undrained shear strength

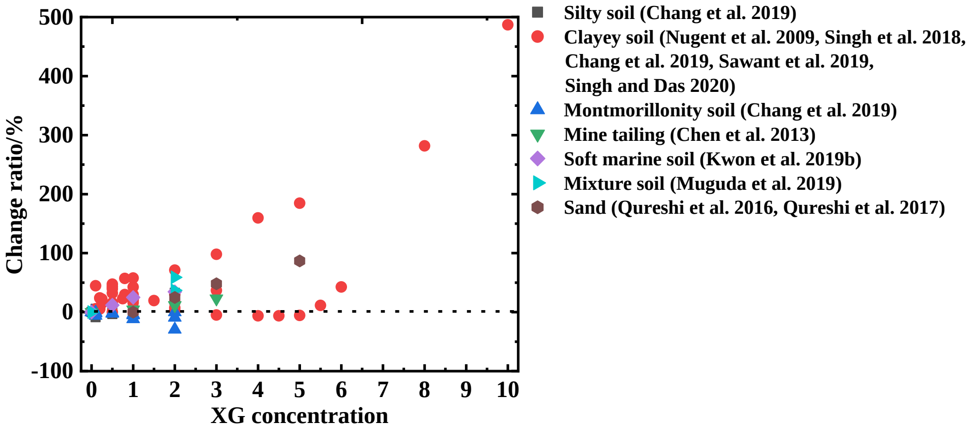
Atterberg limits and undrained shear strength can reflect the particle-level interactions and soil microstructure to classify soil type, calculate the natural consistency of soil and predict soil erosion resistance (Zhang et al. 2004, Nugent et al. 2009, Cabalar et al. 2018, Zhao et al. 2020). Moreover, it had been recognized that soil type, biopolymer type and concentration, and pore-fluid conditions directly contributed to the Atterberg limits and undrained shear strength of biopolymer treated soil (Chen et al. 2013, Chang and Cho 2014a, Chang et al. 2019).

2.2.1 Influence of soil type on Atterberg limits and undrained shear strength

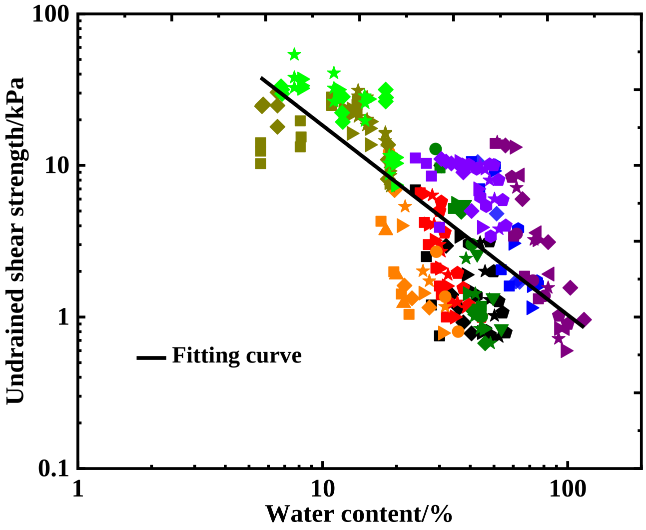
As the most common biopolymer, xanthan gum was adopted to explore the consistency limits of biopolymer treated soil. The Vander Waals attractive force became predominant over particle-to-particle repulsive force. Thus, soil particles came closer to each other and made a flocculated structure. This flocculated structure entrapped water between the void spaces, increasing the plastic limit of the treated soil mass regardless of soil type (Qureshi et al. 2017, Singh and Das 2020).

Figure 2.2 illustrates the liquid limit, undrained shear strength and soil classification of xanthan gum treated various soil types. For clayey silt-sand or pure sand soils, XG mainly interacted with deionized water in the form of hydrophilic hydrogel and the swelling rheology of XG was owing to nominal surface charges of silt and sand. Therefore, the liquid limit of clayey silt-sand soils increased with the occurrence of XG (Mitchell and Soga 2005, Qureshi et al. 2017, Chang et al. 2019, Sawant et al. 2019). With the increase of XG concentration, the water retention capacity of soil increased simultaneously to increase the liquid limit, which altered the USCS classification of clayey silt-sand or pure sand from SM or ML to CL (Chang et al. 2019). Moreover, XG treatment soil increased the undrained shear strength as well (Kwon et al. 2019a). Therefore, XG treatment was expected to significantly enhance the shear strength and the erosion resistance of cohesionless desert sands or silt-sand (Sharma and Bora 2003, Chang et al. 2015, Smitha and Sachan, 2016, Qureshi et al. 2017).

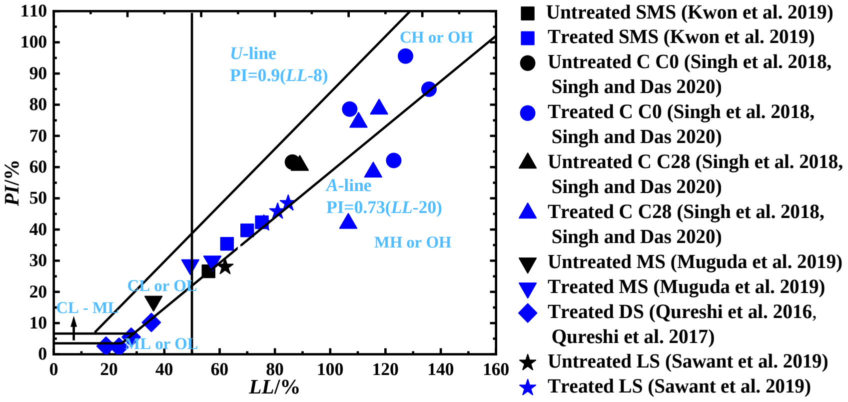
For clay-based soils, Chang et al. (2019) illustrated that the mass ratio of xanthan gum to clay (m_b/m_c) mainly governed biopolymer-clay matrix formation (Chang and Cho 2019, Kwon et al. 2019a). At low biopolymer concentration, xanthan gum instantly formed hydrogels with high viscosity. It enhanced the inter-particle attraction force increasing the specific surface area of xanthan gum-clay media and the number of water molecules that can be adsorbed on xanthan gum-soil surfaces. Therefore, the liquid limit and undrained shear strength of XG treated clay-based soil reached the peak value at $m_b/m_c = 0.5\%$ (Chang et al. 2019, Kwon et al. 2019b, Cheng et al. 2020, Cheng and Geng 2021). With the increase of xanthan gum concentration to 1%, it initiated kaolinite aggregation via ionic or hydrogen bonding, which accompanied a decrease in liquid limit and undrained shear strength (Chang et al. 2019, Kwon et al. 2019a). Meanwhile, the liquid limit and undrained shear strength of XG treated clay-based soil kept constant for $m_b/m_c >$ 1%, which was attributed to the equilibrium between XG hydrogel formation and the simultaneous kaolinite aggregation induced by XG (Chang et al. 2019, Kwon et al. 2019b). In addition, XG treated kaolinite-based soil was classified as clay or silt soil (Chang et al. 2019).



(a) LL



(b) Undrained shear strength (data from Chen et al. 2013, Cabalar et al. 2018, Chang and Cho 2019, Kwon et al. 2019a Kwon et al. 2019b, Qureshi et al. 2019)



(c) Plasticity chart

Figure 2.2 XG treated various soils

However, xanthan gum hydrogel had a limited effect on the variation in pore-fluid viscosity of montmorillonite-based soil due to its high specific surface area and cation exchange capacity. Therefore, xanthan gum induced montmorillonite aggregation resulting in the reduction of the double layer thickness, which accompanied liquid limit and undrained shear strength decrement with the increase of xanthan gum concentration. And xanthan gum treated montmorillonite-based soil can be classified as clay with high plasticity (Chang et al. 2019).

2.2.2 Influence of pore fluid conditions on Atterberg limits

Because cross-links make biopolymer systems more rigid, the addition of chemical solution to biopolymer resulted in a noticeable increase in viscosity, which contributed to the rise of liquid limit. However, some chemical cations can also disrupt the interfacial water layer around kaolinite particles. It enhanced the ability of biopolymer to approach and bond the kaolinite causing more aggregation, which led to the decrease of liquid limit (Kang et al. 2013). Therefore, the overall performance of adding chemical solution depends on whether the increment degree of liquid limit due to the increase of viscosity overcame the decrement degree of liquid limit due to the effects of increased adsorption and aggregation (Dontsova and Bigham 2005, Nugent et al. 2009, Cho and Chang 2018).

Figure 2.3 illustrates the liquid limit of biopolymer treated soil with different pore fluid conditions. Under brine pore-fluid conditions, the liquid limit increases with xanthan gum treatment, regardless of the soil type (e.g. clayey silt-sand soil, kaolinite-sand soil, montmorillonite-sand soil), which can be attributed to the increase in viscosity of pore fluids and interacting with concentrated Na^+ ions in the double-layer reduction. On the other hand, the insignificant variation in liquid limit with kerosene implied the importance of water for the hydrogel formation of xanthan gum (Chang et al. 2019).

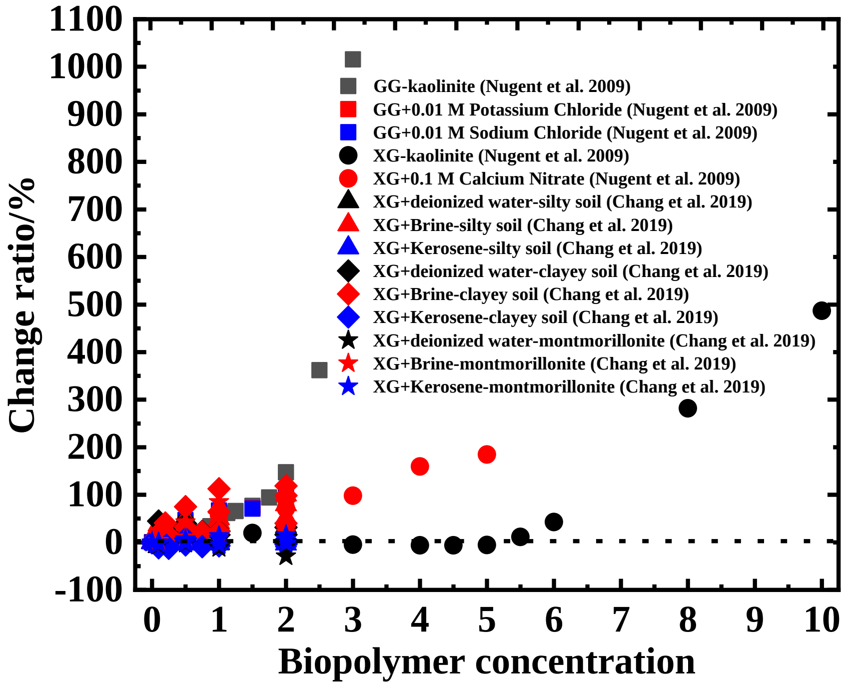


Figure 2.3 Biopolymer treated soil with different pore fluids

2.3 Shear Strength Behaviours

Adequate shear strength is more vital for assessing the likelihood of ultimate limit state failure of various geotechnical engineering structures (e.g. shallow foundations, retained structures, earth dams, pavements, natural slopes) (Im et al. 2016a, Im et al. 2017a, Latifi et al. 2017b, Fatehi et al. 2018, Joga and Varaprasad 2019, Międkoś et al. 2019). Increasing the shear strength will directly improve the soil bearing capacity, lateral earth pressure, and settlement (Latifi et al. 2017b, Latifi et al. 2018). The results show that the strength of soils modified with biopolymer generally depends on several factors, such as biopolymer type and concentration, water conditions (initial, drying, re-submerge), soil type (e.g. sand, silty sand, clay, collapsible soil), dry density (Chang et al. 2015, Chang et al. 2017, Lee et al. 2017, Chang and Cho 2019, Dehghan et al. 2019, Lee et al. 2019c, Lee et al. 2019d).

2.3.1 Influence of biopolymer properties on shear strength behaviours

Ayeldeen et al. (2016) illustrated that the occurrence of biopolymer membrane and interaction forces between soil particles caused them to resist the movement of particles. Moreover, the adhesion depended on the membrane strength and the condition of the membrane enwrapping soil particles (Liu et al. 2018a, Liu et al. 2019a). Chang and Cho (2012) examined the tensile strength of pure biopolymer typically ranging from 20 to 80 MPa. Furthermore, it significantly reduced the tensile strength if biopolymer interacted with other materials. Meanwhile, soil changed its ductile behaviour to a more brittle and dilative behaviour due to the firm biopolymer films existing (Khatami and O'Kelly 2013, Chang and Cho 2014b, Chen et al. 2016, Lee et al. 2017, Chang and Cho 2019, Lee et al. 2019c, Kang et al. 2020). Therefore, the reinforcement mechanism of biopolymer treated soil strongly depends on biopolymer properties.

a) Biopolymer type

Different biopolymers can be observed a significant difference in performance on treated with the same species of soil. Biopolymers possessed various chemical functional groups such as hydroxyl, ester, or amines depending on the biopolymer-soil matrix. Moreover, their long-chain structure also provided frequent sites for the characteristic chemical reaction of a given functional group to occur. Therefore, the improvement in the shear strength of the mixtures was caused by the interaction between biopolymer and soil particles through ionic/electrostatic or covalent bonds (chemisorption), hydrogen bonding (strong polar attraction), and van der Waals forces (physical absorption) (Ayeldeen et al. 2016). Among them, short-range ionic/electrostatic and covalent bonds had higher bonding energy and therefore gave the strongest bond. However, Van der Waals forces, which were the interaction between dipoles within the bulk material, developed the weakest bonds over a long-range (Khatami and O'Kelly 2013, Zhao et al. 2020). On the other hand, as the biopolymer molecular weight increased, the solution viscosity and the chance of sustained crystallization of its macromolecule chain can be usually enhanced leading directly to an increase in the degree of cross-linking inside the soil matrix (Khatami and O'Kelly 2013). It has been illustrated that guar gum treated silt and sand had a higher shearing resistance than modified starch, xanthan gum, chitosan, alginate treated soil due to guar gum had the highest viscosity solution (Chen et al. 2013, Ayeldeen et al. 2016, Ayeldeen et al. 2017, Soldo et al. 2020). However, xanthan gum had a more significant impact on improving clay shear strength than guar gum (Dehghan et al. 2019, Bonal et al. 2020). It can be explained that guar gum was a neutral biopolymer due to the absence of carboxylic acid groups, whereas XG had an electrical charge to cause the formation of ionic bonding with clay particles. Moreover, Fatehi et al. (2018) found that the casein treated soil demonstrated superior performance in increasing friction angle amount compared to sodium caseinate treated soil samples, while it was different in the aspect of cohesion depending on biopolymer content.

b) Biopolymer concentrations

Lower biopolymer concentration had weak effectiveness in strengthening compared with the same material without biopolymer at the measured strain level because the insufficient biopolymer cannot form continuous biopolymer-soil matrices (Cabalar and Canakci 2011, Lee et al. 2017, Qureshi et al. 2017, Antonette et al. 2019, Zhao et al. 2020). On the other hand, higher biopolymer concentrations would create a wider spread of higher viscosity gel to enhance the interparticle contacts and fill the voids better with stronger inter-particle bonds (Ayeldeen et al. 2016, Caballero et al. 2016, Chang et al. 2016a, Acharya et al. 2017, Latifi et al. 2017b, Swain et al. 2017, Wiszniewski et al. 2017, Hataf et al. 2018, Soldo and Miletić 2019). Meanwhile, the specimens prepared at higher biopolymer concentrations tended to have a more stable three-dimensional bridge (Cabalar and Canakci 2011, Liu et al. 2018b, Chen et al. 2019b, Soldo and Miletić 2019, Soltani-Jigheh and Yaghoubi 2019). Therefore, the shear stress increased with the increase in the biopolymer content (Ayeldeen et al. 2016, Smitha and Sachan 2016, Qureshi et al. 2017, Wiszniewski et al. 2017, Liu et al. 2018a, Zhao et al. 2020), while specimens with higher biopolymer concentration required more curing to gain full strength than those with lower concentrations (Ayeldeen et al. 2016). Furthermore, the relation between mechanical properties and biopolymer concentration was not linear because an excessive amount of biopolymer reduced the connections between soil particles (Latifi et al. 2016c, Soltani-Jigheh and Yaghoubi 2019, Soldo et al. 2020). It was expected that there existed the optimum concentration of biopolymers varying with biopolymer type, soil type and water content, which should be considered when utilizing biopolymers for soil stabilization (Ayeldeen et al. 2016, Chang et al. 2016a, Acharya et al. 2017, Qureshi et al. 2017, Wiszniewski et al. 2017, Liu et al. 2018b, Dehghan et al. 2019, Soltani-Jigheh and Yaghoubi 2019, Soldo et al. 2020). Specifically, the cohesion of biopolymer treated increased dramatically with the biopolymer concentration varying from 1 to 5%, while the rate of increase varied with biopolymer type (Ayeldeen et al. 2016, Wiszniewski et al. 2017, Zhao et al. 2020). However, the change of peak internal friction angle with the increase of biopolymer concentration depended on soil type. Chang and Cho (2014), Acharya et al. (2017) and Lee et al. (2017) illustrated that the internal friction angle almost kept constant for pure sand with the increase of biopolymer concentration. In terms of biopolymer treated clay, the internal friction angle has a smaller increased (Cabalar and Canakci 2011, Chang and Cho 2014a, Chen et al. 2016, Latifi et al. 2017b, Wiszniewski et al. 2017, Liu et al. 2019a, Khosravi et al. 2020, Zhao et al. 2020) or gradual decreased (Khatami and O'Kelly 2013, Ayeldeen et al. 2016, Acharya et al. 2017, Aksoy and Gor 2017, Ayeldeen et al. 2017, Cabalar et al. 2018) with the increase of biopolymer concentration. Then it tended to converge after a particular biopolymer concentration (e.g. 2%) (Lee et al. 2017).

Moreover, the residual friction angle increased with the increase of biopolymer concentration regardless of soil moisture conditions, which was still higher than that of untreated soil (Gong et al. 1999, Tominaga et al. 2008, Chang et al. 2016a). Especially for the dried condition, condensed biopolymer gels were broken into fragments under large strains, which were expected to behave as frictional materials for improving interlocking between soil particles (Chang et al. 2016a, Lee et al. 2017, Lee et al. 2019c). And residual cohesion increased or almost kept constant with the increase of biopolymer concentration (Chang et al. 2016a, Lee et al. 2017).

2.3.2 Influence of water conditions on shear strength behaviours

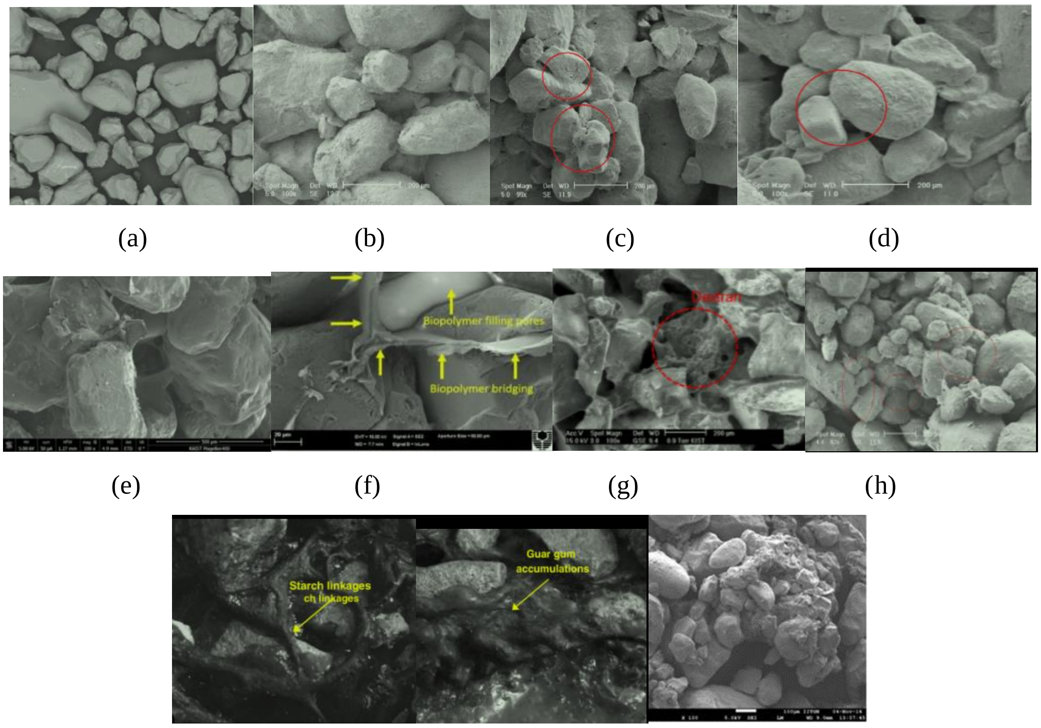
At initial water condition, the strong hydrophilic property of membranes as three-dimensional bridges or electrical interactions was formed to interact with soil particles for changing void fills and reducing the surface roughness (Moore 1991, Mitchell and Soga 2005, Wilson and Wilson 2014, Ayeldeen et al. 2016, Chang and Cho 2016, Chen et al. 2016, Wiszniewski et al. 2017, Hataf et al. 2018, Liu et al. 2019a). The lubrication action can reduce the asperity interlocking of soil grains, which led to the frictional interaction forces between soil particles remaining almost constant or having a slight decrease (Lambe and Whitman 1991, Khatami and O'Kelly 2013, Chang and Cho 2016, Cabalar et al. 2017, Hataf et al. 2018, Liu et al. 2018a, Chen et al. 2019a, Lee et al. 2019c, Smitha et al. 2021). On the other hand, the cohesion of treated soil increased immediately due to highly viscous hydrogels (Khatami and O'Kelly 2013, Chang and Cho 2016, Cabalar et al. 2017, Lee et al. 2019c). Therefore, the peak shear strength of biopolymer treated soil increased at initial water content (Lee et al. 2017), and the strain-hardening behaviours can be observed. It indicated that the hydrogels in soil induced the strengthening effect persisted at high strain levels (Lee et al. 2004, Chang et al. 2016a, Lee et al. 2017). As the curing time increased, the more elasticity and softer membrane structure can be observed in the biopolymer-soil mixture to provide more substantial inter-particle stress (Chang et al. 2015a, Ayeldeen et al. 2016, Chang and Cho 2016, Qureshi et al. 2017, Rashid et al. 2017, Swain et al. 2017, Latifi et al. 2018, Chang and Cho 2019, Dehghan et al. 2019, Joga and Varaprasad 2019, Rashid et al. 2019, Bonal et al. 2020, Soldo et al. 2020). As expected, the cohesion shown an increasing trend with the increase of curing time (Fattet et al. 2011, Qureshi et al. 2014, Qureshi et al. 2017, Liu et al. 2018a, Chen et al. 2019a, Dehghan et al. 2019, Lee et al. 2019c, Joga and Varaprasad 2019, Smitha et al. 2021). Mainly, the most significant cohesion enhancement occurred in the first few days of curing (Smitha and Sachan 2016, Latifi et al. 2017b, Antonette et al. 2019, Arab et al. 2019, Joga and Varaprasad 2019, Smitha et al. 2021). On the other hand, Cabalar et al. (2018) illustrated that a clear relation between internal friction angle and curing time was not observed. It seemed that the internal friction angle of biopolymer treated sand varied gently (Caballero et al. 2016, Lee et al. 2017, Liu et al. 2018a) or had a minor decrease with the increase of curing time (Ayeldeen et al. 2016, Antonette et al. 2019, Arab et al. 2019, Dehghan et al. 2019, Smitha et al. 2021). In contrast, the internal friction angle of biopolymer treated clay increased with the increase of curing time (Qureshi et al. 2017, Chang and Cho 2019, Dehghan et al. 2019, Joga and Varaprasad 2019, Lee et al. 2019c, Rashid et al. 2019). According to the gel property, the gel can finally form a thin film with the water continual evaporation, and the mobility of biopolymer gradually decreased to zero (Grillet et al. 2012). Once the thin film attached to the soil particle cannot shrink in each direction, the film was fixed and unable to present fluidity (Brinker et al. 1992). Thus, some surface connections between the soil particles and biopolymer became brittle. In general, there was still a considerable increase in soil strength, but this increase was unpredictable and inconsistent (Chen et al. 2019b).

Moreover, re-wetting the gel might cause it to swell back to hydrogels resulting in viscosity and stiffness reduction. During this process, biopolymer elements gradually detached from the outside rim of the main biofilm body (Lee et al. 2017, Soldo et al. 2020). Due to the gradual breakdown of biopolymer structure bonding soil grains upon wetting, the shear behaviours (e.g. cohesion) of specimens reduced with an increase in the immersion time and cycles (Chang and Cho 2016, Chang et al. 2017, Lee et al. 2017, Chen et al. 2019a). And it seemed to keep stable at a value for more rewetting-drying cycles because the membrane softens reached a saturation state (Chang et al. 2015c, Chang and Cho 2016, Liu et al. 2018a). However, higher biopolymer content might show a higher peak shear strength in re-submerged condition than the initial state as a result of the gradual and incomplete swelling of gels showing remaining biofilm layers near soil particles with dispersed hydrogel layers (Lee et al. 2017), while peak internal friction angle significantly decreased (Chang et al. 2015a, Ghadir and Ranjbar 2018, Liu et al. 2019a). It indicates that the re-wetting and swelling of the primarily dried biopolymer hydrogels were not reversible (Chang and Cho 2016).

2.3.3 Influence of soil type on shear strength behaviours

a) Biopolymer treated sand

Application of biopolymer for soil treatment required consideration of soil type, which affects the biopolymer-soil matrix formation (Yakimets et al. 2007, Chang et al. 2015, Lentz 2015, Tiwari et al. 2016, Chang et al. 2017, Chang and Cho 2019, Lee and Chang 2019, Szewczuk-Karpisz and Wiśniewska 2019). To observe the influences of biopolymer on sand particles, the scanning electron microscope (SEM) images of various biopolymer treated/untreated sand have been presented in Figure 2.4. It can be seen that clean cohesionless sand particles separated from particulates through existing pores and dispersed freely into the air, which made them be able to move freely without any obstacles no bond to stick soil particles together as shown in Figure 2.4 (a) (Tang et al. 2003, Fatehi et al. 2018, Fatehi et al. 2019, Chen et al. 2019b, Soldo and Miletić 2020). After compacting and adding the biopolymer into the soil (Figure 2.7 (b-n)), microscopic observations revealed that biopolymer gels were condensed and accumulated inside the soil gaps with the continuous biopolymer matrix formation inside inter-granular pores (Qureshi et al. 2015, Im et al. 2017b). Various biopolymers treated sand showed a similar inter-particle stable structure with continuous thin biofilms encompassing sand particles to create linkages connecting the soil particle or forming bridges between the sand grains. It can enlarge interparticle contact areas and cause small particles aggregated to form a larger one (Chang et al. 2015a, Ayeldeen et al. 2016, Chang et al. 2016a, Im et al. 2017b, Cabalar et al. 2018, Chen et al. 2019b, Fatehi et al. 2019). Therefore, it can significantly increase the bonding and interlocking forces between sand particles (Liu et al. 2018b). However, the enhancement in strength of treated sand would be mainly observed in the increment of cohesion due to the formation of biopolymer hydrogel, and it might not significantly affect the internal friction angle (Smitha and Sachan 2016, Soldo and Miletić 2019).



(a) (b) (c) (d)

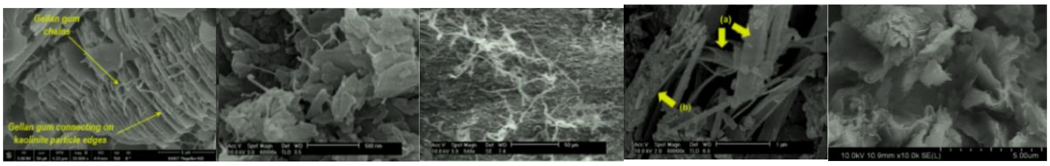
(e) (f) (g) (h)

(i) (j) (k)

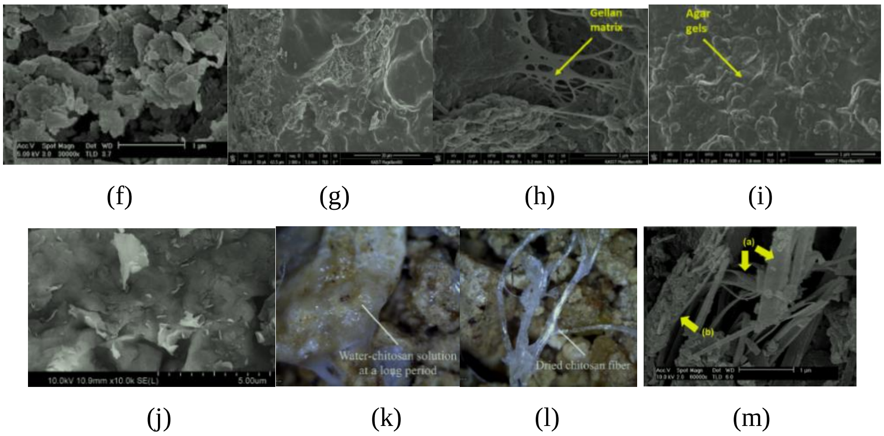
Figure 2.4 SEM of various biopolymers treated sand (a) clean sand (Chen et al. 2019b) (b) Compacted untreated sand (Fatehi et al. 2018) (c) casein treated sand (Fatehi et al. 2018) (d) sodium caseinate treated sand (Fatehi et al. 2018) (e) Gellan gum treated sand (Chang et al. 2015a) (f) XG treated sand (Ramachandran et al. 2019) (g) dextran treated silica sand (Ham et al. 2018) (h) sodium alginate treated sand (Fatehi et al. 2019) (i) modified starch treated sand (Ayeldeen et al. 2016) (j) guar gum treated sand (Ayeldeen et al. 2016) (m) agar treated Sabarmati sand (Smitha and Sachan 2016)

b) Biopolymer treated clay

Figure 2.5 shows the scanning electron micrograph (SEM) images of the biopolymer treated/untreated clayey grains. The virgin soil possessed flaky soil particles and large void spaces. In contrast, with the occurrence of biopolymer, it can be seen that biopolymer strands or bundles interacted directly with clay particles to form partially conglomerated aggregates, creating a firm web-like matrix and well-bonded biopolymer-clay matrix (Chandrasekaran and Radha 1995, Morris et al. 2012, Chang et al. 2015a, Chang et al. 2015c, Aksoy and Gor 2017, Latifi et al. 2017b, Singh and Das 2020). Moreover, the electrical surface properties of fine particles can cause the creation of strong interactions (hydrogen or electrostatic bonding, cation bridging or others) with biopolymer. For example, some anionic biopolymer monomers were expected to enhance the ionic bonding by attaching to the diffuse double layer of clay minerals (i.e. Na^+, Mg^{2+}, and Ca^{2+} from the soil) (Mitchell and Soga 2005, Morris et al. 2012). On the other hand, the clay particles with negatively charged surface minerals can more easily attach to positively charged biopolymer to enhance plate particle stacking (Chang and Cho 2012, Hataf et al. 2018). The firm biopolymer-soil matrix can significantly reduce void spaces to increase interlocking forces between soil particles (Chang and Cho 2012, Lee et al. 2015, Jung and Hu 2017, Rashid et al. 2017, Chang and Cho 2019). Therefore, the biopolymer can significantly enhance the internal friction angle of clayey soil, and it might not significantly change the cohesion compared to biopolymer treated sand (Chang and Cho 2019).



(a) (b) (c) (d) (e)



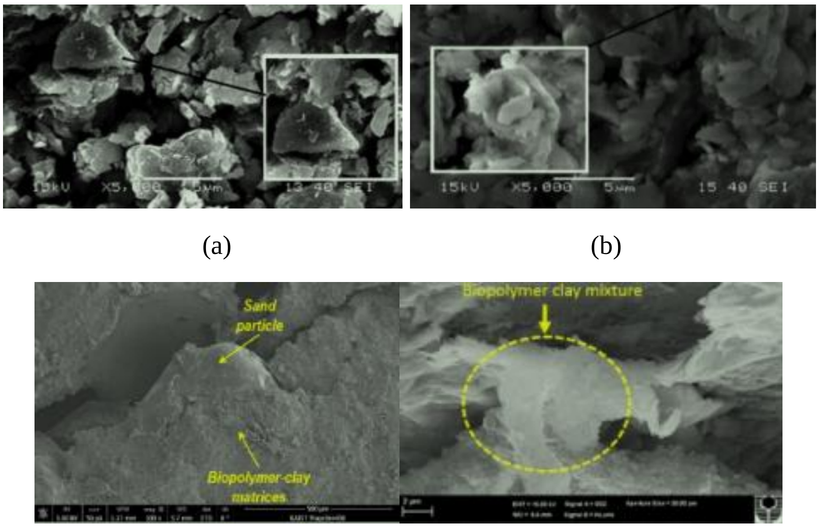
(f) (g) (h) (i)

(j) (k) (l) (m)

Figure 2.5 SEM of various biopolymers treated clay (a) low-plastic clay (Cabalar et al. 2018) (b) GE treated kaolinite (Chang and Cho 2019) (c) XG treated red yellow soil (Chang et al. 2015a) (d) XG treated kaonite (Chang et al. 2015a) (e) beta-1, 3/1, 6-glucan treated Korean residual soil (Chang and Cho 2014a) (f) Natural hwangtoh (Chang and Cho 2012) (g) CA treated residual soil (Chang et al. 2018) (h) GE treated residual soil (Chang et al. 2015c) (i) AG treated residual soil (Chang et al. 2015c) (j) XG treated bentonite (Latifi et al. 2017b) (k) CH treated clay (Hataf et al. 2018) (l) CH incorporated soil at DC condition (Hataf et al. 2018) (m) Beta 1,3/1,6 glucan treated residual soil (Chang and Cho 2014a)

c) Biopolymer treated mixture soil

Figure 2.6 illustrates the SEM images of biopolymer-treated/untreated mixture soil. The enhancement mechanism of biopolymer treated mixture soil can be explained as a combined effect of biopolymer stable matrix formation with sand as well as the hydrogen bonding and/or ionic bonding between biopolymer and clay particles (Ramachandran et al. 2019). Soldo and Mileti ́c (2019) illustrated that the maximum deviatoric stress was achieved for the silty-sand mixed with XG, followed biopolymer-clay mixture. The highest increment in strength was achieved in biopolymer treated sand compared to untreated soil, which was not surprising when considering that the plain sand had a virtually negligible strength. Similarly, Chang and Cho (2019) found that gellan gum treatment of single-grained soils (pure sand and pure clay) appeared to be more appropriate for increasing cohesion, while gellan gum treatment of multi-grained soils showed significant increases in internal friction angle, and it dominated the shear behaviour of biopolymer treated sand-clay mixtures.



(a) (b)

(c) (d)

Figure 2.6 Biopolymer treated mixture soil (a) mixture soil (Singh and Das 2020) (b) XG treated soil (Singh and Das 2020) (c) GE treated clay/sand=1:1 (Chang and Cho 2019) (d) XG treated sand clay mixture (Ramachandran et al. 2019)

2.3.4 Influence of other factors on shear strength behaviours

a) Dry density

With a decrease in the dry density, the membranes easily enwrapped the soil particles. However, it usually built a relatively weakened connection between the long macromolecular chains and the soil particles because of the loose structure of the specimens (Ajalloeian et al. 2013, Liu et al. 2018a, Liu et al. 2018b). Therefore, the shear strength increased linearly with an increase in the dry density (Dehghan et al. 2019, Liu et al. 2018a). However, for the specimen with a denser structure, the soil particles were incompletely wrapped by the biopolymer membranes because of a slight adhesion surface contact and the mostly fill up voids. Therefore, there was an optimum dry density that can be easy to fill the soil voids and enwrap the soil particles to have strong bonding and interlocking forces (Liu et al. 2018a, Liu et al. 2018b).

b) Curing method

For biopolymer treated sample drying at room temperature, the outer part of the sample was exposed to the air-dry condition, and biopolymer would quickly show its crystallization and cementation effect. However, it was still moist weak-link gel inside the sample due to slowing down the cementation process in the inner part of the samples. During the shearing, the location of the shear plane was the internal part of the sample, which was weak and uncross-linked and finally showed the limited effect of biopolymer in the soil. Therefore, the strengthening effect was still neglectable even at lower water content levels (Chen et al. 2019b). However, cured in oven condition, the cementation process in the external and inner was simultaneous. Moreover, within a certain temperature range, the increasing temperature would activate biopolymer molecules and increase their particles' kinetic energy (Wu et al. 2018). It can accelerate the molecular mobility and increase the interaction between biopolymer and soil particles (Chen et al. 2019b).

c) Confining pressure

Lee et al. (2019) illustrated that the deviatoric stress in biopolymer treated soil at the higher confining pressure was slightly decreased compared to that of the untreated soil in a hydrogel state. In the dry state, the peak strength of biopolymer treated soil increased under high confining pressure (Chen et al. 2016, Lee et al. 2019c). Similarly, Chen et al. (2016) found that the elastic modulus of biopolymer treated mine tailings increased with the increase of confining pressure due to the reduction in void ratio causing a denser structure. Moreover, Dehghan et al. (2019) illustrated that there was threshold confining pressure, beyond which there was a decrease in deviator stress. Therefore, the biopolymer treatment was more effective at shallow depths (Lee et al. 2019c, Smitha et al. 2021). Meanwhile, under high confining pressure, since biopolymer gel by itself behaved plastically, increasing its concentration introduced some degree of ductility to the treated soil, while the addition of biopolymer increased the brittleness of treated soil under low confining pressure (Khatami and O’Kelly et al. 2013, Cabalar et al. 2017, Wiszniewski et al. 2017).

2.4 Unconfined Compressive Test

The untreated soil exhibited a dispersed and discontinuous structure, where the voids and porosity were generally visible because of the absence of hydration products (Latifi et al. 2017a). It appeared to have a continuous and flaky shaped structure with the occurrence of biopolymer. Moreover, new crystalline cementing products were formed (Latifi et al. 2016b, Soldo et al. 2020). Therefore, there was a remarkable improvement in unconfined compressive strength for all the mix percentages of biopolymer in comparison to untreated sand (Chang et al. 2016e, Qureshi et al. 2017, Joga and Varaprasad 2019, Wen et al. 2019, Reddy et al. 2020, Singh et al. 2021). And it mainly depended on various factors, such as biopolymer properties, soil type, curing condition, durability and preparation condition.

2.4.1 Influence of biopolymer properties on unconfined compressive test

a) Biopolymer type

Reddy et al. (2020) illustrated that XG treated red mud waste yielded higher compressive strength than that of guar gum stabilised samples. It can be explained that xanthan gum with highly negative charges can develop ionic bonds with red mud waste having higher energy than hydrogen bonds formed by guar gum with non-ionic material. Similarly, Soldo et al. (2020) also illustrated that xanthan had the highest impact on increasing the compressive strength of well-graded sand with silt from 240 kPa to 1061 kPa at curing 30 days and concentration 4%, following guar gum, alginate and chitosan at the same conditions. Tran et al. (2019) found that xanthan gum demonstrated the best performance in strength improvement for sand due to its high viscosity that strongly bonded the sand particles compared to modified starch. Chang et al. (2018) revealed that 5% casein content in the mass of soil significantly increased the unconfined compressive strength at a dried condition (i.e., 4.34 MPa), similar to the results for 1% xanthan gum and gellan gum (4.94 MPa and 4.59 MPa, respectively), and the strength is approximately double that of 10% cement-treated soils (i.e., 2.65 MPa). Moreover, the UCS of 1% agar and 0.5% b-glucan gum treated soil also significantly enhanced to 3.24 MPa and 1.68 MPa, respectively, compared to untreated soil (i.e. 1.01 MPa). After 24 h of saturation, the casein treated soils were capable of retaining a more considerable degree of dry strength than the previous biopolymer-treated soils (e.g. xanthan gum, gellan gum, agar and b-glucan gum) due to the lower water absorbance of proteins, which resulted in denser particle composition. Similarly, Chang et al. (2015b) also revealed that gellan gum could result in higher unconfined compressive strength than agar gum treatment of clayey soil given the same biopolymer concentration, while neutral sandy soil showed similar strength values for agar and gellan gum. It can be explained that gellan gums had a shorter molecular structure with electrically charged that consequently direct interactions with fine soil particles were achievable to create web-like matrices. However, agar gums had a more extended molecular structure making direct interactions more difficult. Furthermore, this structure caused agar gum to coat and coagulate soil particles to form massive soil-biopolymer aggregates via gelation. Moreover, Fatehi et al. (2018) illustrated that the mixture of sand with sodium caseinate represented a better performance than casein treated sand because the pasty shape of sodium caseinate compared to the cheesy state of casein biopolymer provided better conditions to produce a homogeneous mixture. On the other hand, more curing time was needed for sodium caseinate treated soil to obtain maximum compressive strength compared with casein treated soil because sodium was replaced with hydrogen causing the production of sodium caseinate and water. Therefore, the moisture content was more than the casein, and the curing time was expected to take longer.

b) Biopolymer concentration

In general, biopolymers with high specific surfaces can induce the formation of cementations materials, aggregated and flocculated microstructure in the biopolymer-soil framework with strong resistance to an external load and the increase of strength. Therefore, even a small amount of biopolymer (e.g. 0.25%) can also produce a significant increase in compressive strength under a lower dry density (Chang et al. 2016a). Obviously, the strengthening mechanisms of biopolymer became significantly more efficient at higher concentrations regardless of dry or wet conditions (Larson et al. 2010, Keita et al. 2014, Chen et al. 2016, Latifi et al. 2016a, Arasan et al. 2017, Chen et al. 2017, Rashid et al. 2017, Fatehi et al. 2019, Liu et al. 2020a, Soldo et al. 2020). At lower content, biopolymer monomers randomly attach to the soil surfaces forming a clumpy accumulated biopolymer layer (Chang et al. 2018). Higher biopolymer was expected to lead to a larger and thicker biopolymer matrix in coarse soils and more soil-biopolymer interactions in fine soils (Chang et al. 2015a). However, the electrostatic repulsion force among biopolymer and soil particles reduced the effective stress on the soil skeleton beyond the optimal biopolymer dosage. Moreover, the higher viscosity resulted in a lack of bonding between soil-gum-water mixtures. In addition, the coefficient of friction between biopolymers was smaller than that of coefficient friction between soil particles. Under high concentration, failure might occur between organic coatings (biopolymer to biopolymer contacts) rather than the soil-to-soil contact during testing. Therefore, the UCS of biopolymer treated soil would level off (Bate et al. 2014, Chang et al. 2015a, Ayeldeen et al. 2016, Im et al. 2016b, Latifi et al. 2016a, Cabalar et al. 2018, Gopika and Mohandas 2019, Liu et al. 2020b) or even had a slight decrease (Qureshi et al. 2017, Latifi et al. 2018, Joga and Varaprasad 2019) under high biopolymer concentration. The optimum biopolymer concentration mainly depended on the biopolymer type (Liu et al. 2019a, Soldo et al. 2020). For example, it showed that only margined change was observed in the UCS test with the XG concentration of more than 3% (Wiszniewski et al. 2017, Cabalar et al. 2018), while 12% casein concentration was the dividing line between a solution with low viscosity and Newtonian behaviour (which occurs below 12%), and a pseudoplastic solution (above 12%) to impact on the strength of soil (Puri et al. 1972).

2.4.2 Influence of soil type on unconfined compressive test

Biopolymer added a cohesive property in cohesionless sand and enhanced the inter-particle bonding of fine soil, showing six-fold compressive strength improvement (Chang et al. 2015a, Chang et al. 2015c). Most importantly, the biopolymer can be more effectively used to enhance the UCS of well-graded soils than poorly graded soils. And then, biopolymer rendered a higher compressive strength for clayey soils than sandy soil (Chang et al. 2015a).

As mentioned in section 2.3.3, there were direct linkage bridges between biopolymer and electrically charged fine grain particles via cation interactions and hydrogen bonding to form the firm biopolymer-fine soil matrices enhancing particle alignment and improving strength (Bouazza et al. 2009, Chang et al. 2015a, Chang et al. 2015d, Lee et al. 2019b). On the other hand, the sand particles were enwrapped closely by a thin and toughened layer of biopolymer membranes which provided the bonds between sand particles. With the development of the inter-particle voids filling, the cementation was further enhanced through a series of mutual crisscross and interconnected membranes. These membranes served as bridges that join the adjacent sand particles together as a whole system to increase the grain contact characteristics in soil. Such bridging effect of membranes contributed to the final formation of the three-dimensional cross-linked network structure to a large extent (Cabalar et al. 2018, Liu et al. 2019a). Because the biopolymer membranes coated and bound sand particles, the strength of the treated sand was very dependent on the strength of the biopolymer matrix itself (Akbulut and Cabalar 2014, Liu et al. 2019a). The strengthening mechanism of biopolymer treated sand-clay mixture could be explained as a combined effect of biopolymer matrix formation as well as the hydrogen bonding and ionic bonding between biopolymer monomers and clay particles (Ramachandran et al. 2019).

2.4.3 Influence of curing condition on unconfined compressive test

a) Curing time

The significant reduction in strength under the wet condition appeared at the initial stage due to looser inter-particle structures. Moreover, the strength of treated soil in this stage should be mainly governed by the strength of biopolymer gels and the biopolymer solution viscosity inside the soil, especially for saturated cohesionless soil (Chang et al. 2015c). Furthermore, the wet strength became less sensitive to biopolymer concentration variation (Chang et al. 2018). Without the curing process, the formation of hydrogels was not complete, and they tended to accumulate in the pore spaces by coating soil particles (Sujatha and Saisree 2019). Chang et al. (2018) illustrated that most biopolymers treated soil retained below 1.8% of their dry strength for wet conditions.

Many kinds of research had revealed that the UCS of biopolymer treated soil increased with the increase of curing time (Park and Kim 2016, Latifi et al. 2017a, Hataf et al. 2018, Kwon et al. 2019b, Lee et al. 2019b, Nikolovska et al. 2019, Khosravi et al. 2020). Normally, after 3 days of curing, it was evident that there was a new formation of cementing products in the form of crystals to fill the pores in the samples (Latifi et al. 2017a, Qureshi et al. 2017). A fine tubular shape identified cementitious products (e.g. thick and high-tensile dehydrated gel) and well-knit structures (needle-like form) bridging the aggregates during earlier formation (Rashid et al. 2019). The compressive strength of biopolymer treated specimens had been significantly growing until 7 days because it revealed new products filling the porosity in the soil structure, and more pores were filled with more cementing products like a ductile material (Latifi et al. 2018, Rashid et al. 2019). In addition, the strength reached almost maximum values within the first 28 days at room temperature curing (Chang and Cho 2012, Chang et al. 2015c, Latifi et al. 2017a, Latifi et al. 2017b, Muguda et al. 2017, Cabalar et al. 2018, Sujatha and Saisree 2019, Reddy et al. 2020, Soldo et al. 2020). It was converged to a particular value (Latifi et al. 2017b, Latifi et al. 2018, Soldo et al. 2020) or even decreased (Liu et al. 2018c, Razali et al. 2018) after long-term curing days (e.g. 56 days at room temperature) (Wiszniewski et al. 2017, Cabalar et al. 2018, Nair and Kannan 2019). Moreover, there was a limited change in water content and dry density of biopolymer treated soil under the dry condition. Thus, it illustrated that the strength variation of cured specimens was mainly induced by the biopolymer type and concentration (Chang and Cho 2012, Hataf et al. 2018). Meanwhile, the curing time reaching converge UCS value decreased with the increase of curing temperature (Liu et al. 2019b).

b) Curing temperature

The curing temperature had a distinct effect on the strength improvement of biopolymer treated soil, especially for thermo-gelation biopolymers and higher biopolymer concentration (Givoni and Katz 1985). Fatehi et al. (2018) illustrated that the UCS of sodium caseinate and casein treated soil improved until the curing temperature rose to 60℃. Moreover, the same result was observed in beta-1,3-glucan polymer treated soil (Chang and Cho 2012, Chang et al. 2012). Fatehi et al (2019) also found the optimum curing temperature to obtain the maximum UCS of sodium alginate treated sand can be observed at curing 45℃, and then sodium alginate treated sand had a gradual decrease of compressive strength up to 80° C. Similarly, Wen et al. (2019) found that the highest UCS of Ca-alginate hydrogel treated sand was around 430 kPa at 50 ℃ oven-dried curing condition, and the lowest one was 160 kPa at 100 ℃ oven-dried curing condition. It can be explained that high temperature or excessive thermal curing can decrease and disturb the strength evolution of biopolymer to interrupt its strengthening function. Furthermore, it was also easy to be decomposed to amino acids causing a loose structure and separated fibrils (Chang and Cho 2012, Fatehi et al. 2018). Moreover, Kulshreshtha et al. (2017) illustrated that the unconfined compressive strength of corn starch treated sand formed by heating in a microwave was significantly higher than corn starch treated sand heated in a convection oven. It can be explained that the temperature of the treated sample increased such that the gelatinisation temperature was achieved in a short time due to the rapid heating and closed boundary condition. In contrast, the low heating rate and open boundary at the top of an oven might have caused the water to evaporate before gelatinisation temperature was reached. Thus, it resulted in a lower degree of gelatinisation as compared to microwave heated specimen (Kulshreshtha et al. 2017).

2.4.4 Influence of durability on unconfined compressive test

a) Rewetting-drying

Once the dried biopolymer-treated sand was re-submerged, the dried gels were expected to absorb water due to their hydrophilicity. Gradual swelling of the biopolymer gels from the outside rim resulted in weaker viscosity (or stiffness) of the re-hydrated biopolymer gel relative to the initial, uniform hydrocolloid state (Chang et al. 2016a). Therefore, clayey soil showed less reduction than sandy soil compared to their initial condition due to their different structures (Chang et al. 2015c, Chang et al. 2017). The severe reduction in strength of sandy soil indicated that sandy soils were more sensitive to the structural disruption of the biopolymer–soil matrix caused by re-wetting due to the absence of direct hydrogen bonding between the biopolymers and coarse soil particles (Chang et al. 2015c). Moreover, at low biopolymer concentration, the formation of hydrogels was not complete in the soil matrix, and this might also cause the treated matrix to degrade faster due to the breaking of the bonds that showed lower resistance to wetting and drying (Sujatha and Saisree 2019). Regardless of soil type, the UCS of the same biopolymer treated submerged specimens showed similar strength values because the compressive strength of pure biopolymer gels became a critical parameter in the strengthening behaviour of saturated biopolymer-soil mixtures (Chang et al. 2015c).

Although the reattached biopolymer fibres may not be as firmly bound as the initial fibres and would fail to recover the primary strength of the material, the surface interactions of the biopolymer molecules allowed a certain amount of strength retention (Chang et al. 2017). Therefore, during the re-drying process, the USC of the submerged still increased, which did not match the trend of unconfined compressive strength of biopolymer treated soil in the previous drying process. Moreover, re-dried specimens showed a significantly lower reduction in strength with each cycle than wet specimens. Meanwhile, the UCS of biopolymer treated soil was still remarkably higher than those of non-treated natural soils in the process of rewetting-drying (Chang et al. 2015c). With increases in the wetting and drying cycles, the dry strength of the biopolymer treated soil was reduced, while the maximum elastic strains increased (Chang et al. 2017). The maximum unconfined compressive strength and stiffness of the dried samples deteriorated nearly linearly and a higher biopolymer induced greater strength deterioration. In addition, biopolymer treated sands showed a gradual reduction of strength under cyclic wetting and drying instead of a sudden collapse at the early step of cyclic wetting and drying. Moreover, the artificial cohesion provided by biopolymers to cohesionless sands remained influential up to the 35 th cycle of wetting and drying (Chang et al. 2017).

b) Freeze-thaw

Wen et al. (2019) found no significant difference in UCS for sodium alginate solution with $CaCl_2$ agents treated sand subjected to 3 freeze-thaw cycles. After 3 cycles, the UCS of Ca-alginate hydrogel-impregnated sand started to decrease with the increase of freeze-thaw cycles. Moreover, 60% of the original UCS of the hydrogel-impregnated sand still remained after 12 freeze-thaw cycles. Compared with other reinforced methods, Kampala et al. (2014) used fly-ash to reinforce clay soil, and the UCS was reduced by over 50% after 6 wet-dry cycles. Eskişar et al. (2015) found that cement-treated clay reduced 50% in strength after 5 freeze-thaw cycles. With these studies, it was indicated that the biopolymer hydrogel has a superior durability performance (Sujatha and Saisree 2019).

2.4.5 Influence of preparation condition on unconfined compressive test

a) Thermal-gelation

Heating should be an essential concern in using thermo-gelation biopolymers (e.g. agar and gellan gum) for soil treatment in construction and building engineering purposes (Chang et al. 2015c). The unconfined compressive strength of 1% gellan gum treated clayey soil mixed at room temperature was double that of natural soil, while the strengthening effect of the gellan gum biopolymer with thermal treatment in preparing condition was promoted twofold above that of the soil without thermal treatment (Chang et al. 2015c).

b) Initial water content

Kulshreshtha et al. (2017) illustrated that the strength of hardened core starch treated sand was observed to be sensitive to the amount of water in the fresh core starch-sand mixture. With an increase in water content, the UCS of core starch treated sand increased, and then it decreased when the initial water content was above a specific value. Subsequently, Ni et al. (2020) found that there existed an ideal initial moisture content leading to the maximum strengthening efficiency. In terms of xanthan gum treated Shanghai clay, this ideal value was between 1.1 and 1.2 times the treated optimum moisture content.

c) Mixing method

Change et al. (2015a) illustrated that dry mixing of 1% xanthan gum treated Red Yellow soil was more effective than wet mixing with curing 28 days. It can be explained by the solubility and viscosity of xanthan gum in water. If the biopolymer concentration was well above the solubility point, thorough mixing of biopolymer into the water might not have been possible for these mixing conditions. Moreover, an even distribution of xanthan gum in the soil was unlikely, while dry mixing provided a well-distributed xanthan matrix in the soil. It implied that dry mixing would be more appropriate for practical applications in the field, where thermal treatment was inconvenient.

2.5 Summary

In this part, a comprehensive literature review is performed to illustrate the current research on the physical and mechanical properties of biopolymer treated soil. Specifically, the influence of soil type, biopolymer type, compaction energy and mixed other stabilizer materials on compaction properties (e.g., maximum dry density and optimum moisture content) is described. In addition, XG treated sand, silty, clay, mixed soil and biopolymer treated soil with the mixture of brine, kerosene and deionized water are selected to explore the influence of soil types and pore fluid on the Atterberg limits and undrained shear strength of biopolymer treated soil. Moreover, combined with the SEM of biopolymer treated soil, the influence of biopolymer type and concentration, water condition, soil type, curing method, confining pressure and soil dry density on the shear strength behaviours (e.g., internal friction angle and cohesion) of biopolymer treated soil is explored. Finally, the UCS of biopolymer treated soil is comprehensive literature reviewed considering biopolymer type, biopolymer concentration, soil type, curing time, curing temperature, rewetting-drying cycle, freeze-thaw cycle, thermal-gelation, initial water content and mixing method. The following conclusions can be drawn.

(1) The maximum dry density of biopolymer treated soil typically increases at low concentration (e.g., less than 1% for sand, less than 0.1% for clay) and then decreases with the increase of biopolymer concentration. And the optimum moisture content of biopolymer treated soil increases with the increase of biopolymer concentration.

(2) The Atterberg limits and undrained shear strength behaviours of XG treated soil in the deionized water depend on soil type, while the pore-fluid chemistry conditions contribute to the soil consistency and interparticle characteristics of XG treated soil in the conditions brine and kerosene.

(3) Biopolymer types and soil types have the significant roles in the strength of biopolymer treated soil with the interaction between biopolymer and soil particles through ionic/electrostatic or covalent bonds (chemisorption), hydrogen bonding (strong polar attraction), and van der Waals forces (physical absorption). Typically, the strength of biopolymer treated soil increases with the increase of biopolymer concentration, while the strength increment ratio tends to decrease. And it is expected that there exists the optimum biopolymer concentration to achieve the best performance on the soil reinforcement effect.

(4) In addition, there is the optimum initial water content, mixing method, curing time and curing temperature to obtain the maximum strength of biopolymer treated soil. However, the strength of biopolymer treated soil tends to decrease under the rewetting-drying, while the strength can keep stable under certain cycles of rewetting-drying.

In terms of the basic physical properties of biopolymer soil, throughout the literature view, most researches mainly concerned on the compaction properties of biopolymer treated sand. Meanwhile, the previous research mainly focused on the soil consistency of XG treated various soil types under different pore fluids without considering the influence of various biopolymer types and concentrations. There also needs to develop the empirical equation to predict the undrained shear strength and shear viscosity of biopolymer treated soil based on the results of fall cone tests. Moreover, the mechanical behaviours of biopolymer treated soil is sensitive to water content and there is lack of illustrating the water evaporation ratio of biopolymer treated soil at curing conditions in the previous works.

Through summarying the investigation on the mechanical behaviours of biopolymer treated soil in literature review, the previous researches mainly illustrated the uncondined compressive strength of single biopolymer treated one soil type with limited biopolymer concentrations (e.g., < 2%) and curing time (e.g., less 28 days) in the same study, while it is lack of comprehensive comparing the reinforcement effect of various biopolymer types treated different soil types under keeping the same conditions. In addition, there are limited references on researching the influence of rewetting-drying, initial water content, mixing method and biopolymer cross-linking on the mechanical behaviours of biopolymer treated soil, espcically for clay and clay-sand mixture. On the other hand, the shear beviours of biopolymer treated soil in previous work are illustrated through direct shear tests, and there are limited refereces concerning the mechanical proeperties of biopolymer treated clay by considering different confining stress conditions, especially for clay.

For meeting these gaps, in the following parts, taking the typical biopolymer (XG) as example, the compaction properties (e.g., maximum dry density and optimum moisture content) (Section 3.2) and water evaporation ratio of biopolymer treated clay (Section 3.5) are revealed under different XG concentration. Moreover, the Atterberg limits of biopolymer treated soil are illustrated by considering eight typical biopolymers (e.g., XG, SA, GG, GE, KG, LBG, AG and CH) and a wide range of biopolymer concentration from 0.1% to 5% (Section 3.3). Based on the results of fall cone tests, the undrained shear strength and shear viscosity of biopolymer are predicted, and the relevant empirical equations are obtained (Section 3.4).

The unconfined compressive strength of biopolymer treated soil is explored by considering biopolymer type (e.g., XG, SA, KG, LBG, AG and GE), biopolymer concentration (e.g., 0.5%-5%), biopolymer cross-linking (e.g., XG-AG, XG-KG and XG-LBG), curing time (e.g., 5-378 days), hydrated condition (e.g., initial status), initial water content (e.g., 30%-60%), mixing method (e.g., RDM, RWM, HDM and HWM), durability (e.g., curing 378 days and undertaking rewetting-drying cycles) and soil type (e.g., clay, clay-sand mixture, sand and natural soil) (Section 4.2, Section 5.3, Section 6.3). In addition, the shear behaviours (e.g., internal friction angle and cohesion) of biopolymer treated clay are illustrated through triaxial shear tests under different confining stress conditions by considering typical twelve biopolymers and various biopolymer concentration at hydrated condition. Taking the typical biopolymer (XG) as example, the shear strength of biopolymer treated clay at dehydrated condition and different confining stress conditions are revealed by considering different curing time (Section 4.3).

Chapter 3 Basic Physical Properties of Biopolymer Treated Clay

3.1 Materials and Method

3.1.1 Clay

The kaolinite used in this experimental study was quarried from the South West of England. Its plastic limit (PL) and liquid limit (LL) values were 30.7% and 69.9%, respectively. The specific gravity of the clay grains was found to be 2.6. The clay has been classified as clay of high plasticity (CH) based on the Unified Soil Classification System (USCS). Moreover, clay's uniformity coefficient (C_u) and curvature coefficient (C_c) were 3.95 and 0.66, respectively, which belonged to poor gradation. The clay grains were mainly SiO_2 47% and Al_2O_3 38%, respectively. Table 3.1 summarises the specific physical parameters of the Kaolinite, and Figure 3.1 illustrates the grading curve of clay.

Table 3.1 Basic physical parameters of kaolinite

Soil type	Kaolinite
D_{60}/μm	0.976
D_{30}/μm	0.4
D_{10}/μm	0.247
Specific surface area (m^2/g)	14
C_u	3.95
C_c	0.66
PL/%	30.7
LL/%	69.9
PI/%	39.2
USCS	*CH*
Specific gravity	2.6

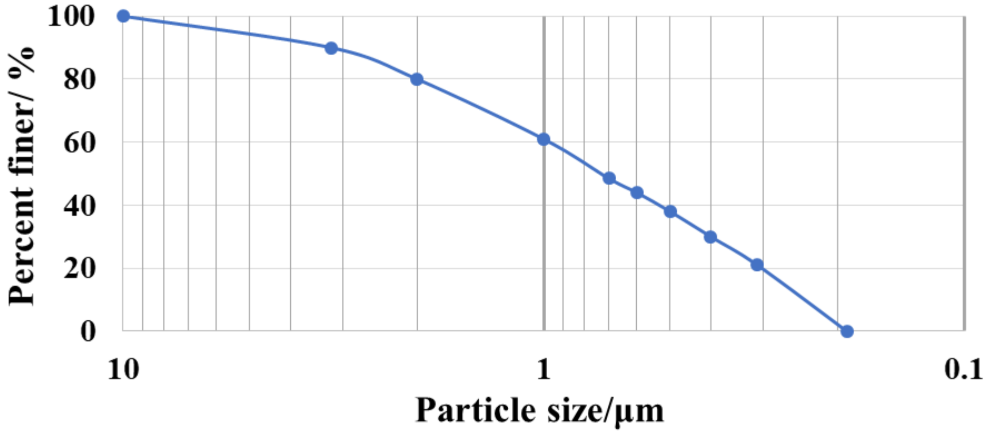


Figure 3.1 Grading curve of clay

3.1.2 Biopolymer

Eight biopolymers, e.g. carrageenan kappa gum (KG, CAS No: 90000-07-1), locust bean gum (LBG, CAS No: 9000-40-2), xanthan gum (XG, CAS No: 11138-66-2), agar gum (AG, CAS No: 9002-18-0), guar gum (GG, CAS No: 9000-30-0), sodium alginate (SA, CAS No: 9005-38-3) gellan gum (GE, CAS No: 71010-52-1) and chitosan (CH, CAS No: 9012-76-4) were used in the present study as shown in Figure 3.2. And the description of each biopolymer can be illustrated as following.

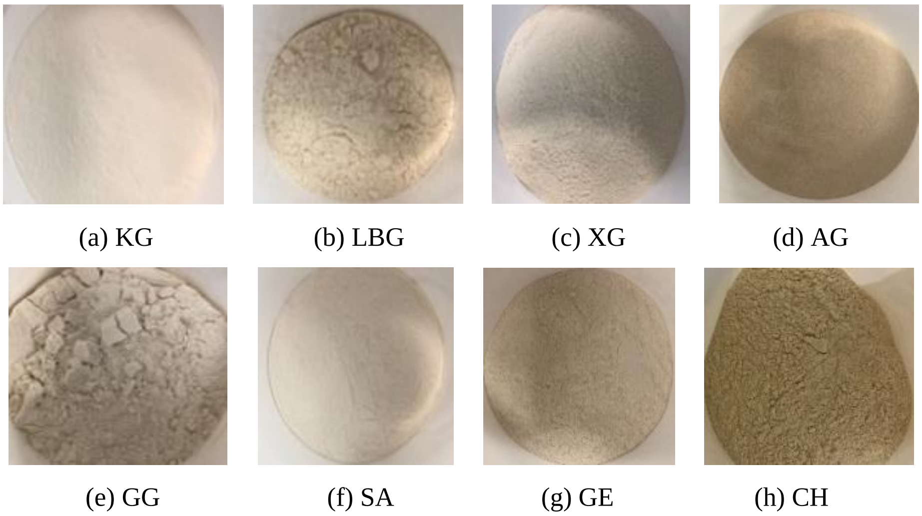

(a) KG (b) LBG (c) XG (d) AG
(e) GG (f) SA (g) GE (h) CH

Figure 3.2 Biopolymer productions

KG is extracted from red algae called kappaphycus alvarezii wherein. It belongs to the carrageenan algae family and is also a commercial source, which has been identified to produce gelling, thickening, stabilizing and viscous properties. It is ideal for room temperature gels with soluble in hot and cold water (van de Velde 2008).

LBG is a galactomannan vegetable gum extracted from the carob tree seeds (Barak and Mudgil 2014). LBG is soluble in cold but dissolves easier using hot liquids. It can increase the viscosity, thickness, and texture of liquids or produce stable heat gels depending on the dosage.

XG is an anionic and high molecular weight polysaccharide fermented from Xanthomonas campestris bacterium (García-Ochoa et al. 2000), and it has been widely used as a thickener due to its viscous hydrogel formation with the presence of water (García-Ochoa et al. 2000).

AG obtains from the cell walls of some species of red algae of the Gelidiella Gelidium and Gracilaria or red seaweeds (Rhein-Knudsen et al. 2015). It is a hydrocolloid, forming a hard, brittle, transparent and neutral gel to provide rigid textures as a stabilizer.

GG is a galactomannan polysaccharide extracted from guar beans that has thickening and stabilizing properties useful in food and industrial applications. GG is a powerful short texture thickener and can be used even in cold water or liquids (Smitha and Sachan 2016, Cao et al. 2018).

SA is the sodium salt form of alginic acid and gum mainly extracted from marine brown algae (Karmakar et al. 2009). It can be soluble in cold and hot water with vigorous agitation. The most significant advantage of alginates is their liquid-gel behaviour in aqueous solutions.

GE is a water-soluble anionic polysaccharide produced by the bacterium Sphingomonas elodea. It can be used as a thickener, binder, and stabilizer in different food applications. The low acyl gellan gum producing firm, non-elastic, brittle gels was used in this study.

CH is a naturally biodegradable and biocompatible polysaccharide made by treating the chitin shells of shrimp and other crustaceans with an alkaline substance, such as sodium hydroxide. It has excellent moisture absorption, moisture retention, opsonization and bacteria inhibition.

3.1.3 Sample Preparation

There are four categories to prepare soil samples called dry mixing (DM), wet mixing (WM), hot-dry mixing (HDM) and hot-wet mixing (HWM), respectively. For the first step of sample preparation, the soil is completely dried in an oven at 105 ℃ for 24 hours and then is cooled at room temperature. In terms of dry mixing, varying quantities of biopolymer are poured into the soil with a thorough mix. And then, the soil-binder mixture is blended with a particular value of distilled water at room temperature. For wet mixing, the biopolymer is dissolved in distilled water. And then, the biopolymer solution is thoroughly mixed with soil. Moreover, the process of hot-dry mixing is identical to that of dry mixing except for using the distilled water with 100°C. Similarly, the biopolymer is dissolved in heated distilled water with 100°C to form a biopolymer solution in hot-wet mixing. For a reference group with untreated specimens, only distilled water at room temperature (RT) and 100°C (HT) is added to the soil with the same other conditions. The homogeneity distribution of the ultimate mixtures is guaranteed by hand mixing with palette knives.

To evaluate the engineering properties of the soil-biopolymer mixture, various laboratory tests (e.g. water evaporation test, compaction test, Atterberg limits test, undrained shear strength test and unconfined compressive test) are performed on biopolymer treated soil. Table 3.2 lists the program details for each experimental test of untreated/biopolymer treated soil.

Table 3.2 Experimental program summary

(a) Compaction test

Soil	Biopolymer	Concentration	Standard method	Mixing method
Clay	XG	0, 0.2, 0.5, 1, 2, 3, 4, 5	BS 1377-4	DM

(b) Atterberg limits test and undrained shear strength

Soil	Biopolymer	Concentration	Standard method	Mixing method
Clay	KG	0, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0	Plastic limit: ASTM D4318 Liquid limit: BS 1377	DM
	BG	0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0		
	XG	0.1, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0		

	SA	0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0		
	GG	0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0		
	AG	0.1, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0		
	GE	0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0		
	CH	0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0		

(c) Water evaporation test

Soil	Biopolymer	Concentration	Initial water content	Mixing method	Curing temperature
Clay	XG	0, 0.5, 1, 2, 5	30, 35, 40, 45, 50	DM	RT

3.1.4 Experimental programme

The materials testing methods (e.g. compaction test, Atterberg limits test, undrained shear strength based on the results of fall cone test and water evaporation test) are described as follow.

1) To determine the optimum water content and maximum dry density, compaction tests were performed with various percentages of XG (e.g. 0.2, 0.5, 1, 2, 3, 4, 5%) treated clay under dry mixing following the standardized procedure BS 1377-4 (1990). After compaction, each specimen was oven dried to obtain dry density under various moisture contents. Three compaction tests were performed for each case.

2) The plastic limit of various biopolymers (e.g. KG, LBG, XG, SA, GG, AG, GE, CH) treated soil samples with different biopolymer concentrations (e.g. 0.1, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0) was determined following the procedures recommended in ASTM D4318 (2017) by rolling out a thread of the soil until its plastic state. And then the soil samples were oven dried to obtain the moisture content. Moreover, fall cone test was conducted to determine the liquid limit of biopolymer (e.g. KG, LBG, XG, SA, GG, AG, GE, CH) treated clay with different biopolymer concentrations (e.g. 0.1, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0) by using a cone with 80g weight and 30 ° tip angle, and a sample cup with 55 mm diameter and 40 mm height (BS 1377-2 1990). The liquid limit values reflect the water content when the cone penetration depth is 20mm. And test was repeated five times in each water contents to determine the Atterberg limits. In terms of undrained

shear strength, it can be determined from the measure cone penetration (Hansbo 1957).

3) The specimen moisture retention was evaluated by measuring the weight loss of cylinder samples from initial hydrated biopolymer treated soil condition and pure biopolymer solution (e.g. XG, GE, SA) under room temperature. The data was continuously recorded with total 45 days.

3.2 Compaction test results

Soil density representing particle arrangement is highly related to the strength and bearing capacity of the soil. Thus, it is necessary to identify the variations in soil density induced by XG. Variation of the maximum dry density (MDD) and Optimum water moisture (OWM) with various XG concentrations is shown in Figure 3.3. It can be observed that OWM increases from 30.3% to 33.5% with the increase of XG concentration from 0% to 5%, which is attributed to the increase of absorbed water consumed with the occurrence of plenty of hydrophilic groups in XG molecules and high water absorption capacity of XG helix.

On the other hand, MDD slightly increases from 13.96 kN/m^3 to 14 kN/m^3 at 0.2% concentration. It can be interpreted that the lubricant effect of gum gels and the slight increment of biopolymer solution viscosity in inter-granular pores reduce the friction of soil particles to enhance its compressibility with highly aggregated microfabric at low concentration. However, with the increase of XG concentration, the additional monomers absorb water and form the suspension with high viscosity caused flocculated structure and high shear resistance, which restrains the soil particles to shift away from each other (Ayeldeen et al. 2016, Dehghan et al. 2019). Meanwhile, the spaces between soil particles become loose because the development of hydrogen bonding network is interrupted by the electrostatic repulsion forces among the XG strands, which causes an increasing global volume of void spaces and thereby a declining dry density (Kang et al. 2019, Zhang et al. 2013). As a result, MDD almost linear decreases to 12.7 kN/m^3 at 5% concentration.

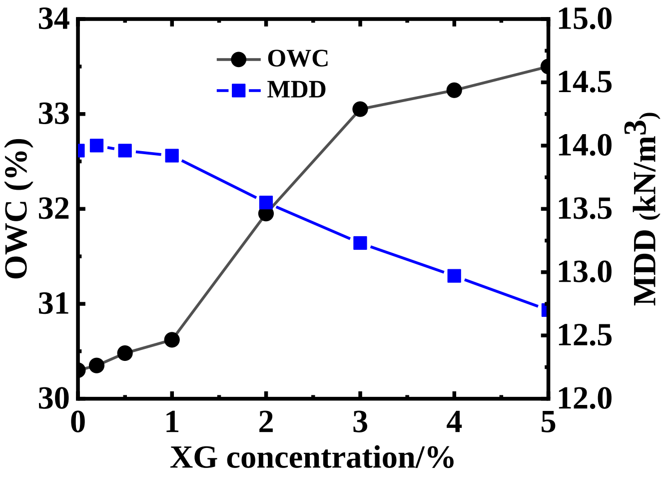


Figure 3.3 Variation of OWM and MDD versus XG concentration

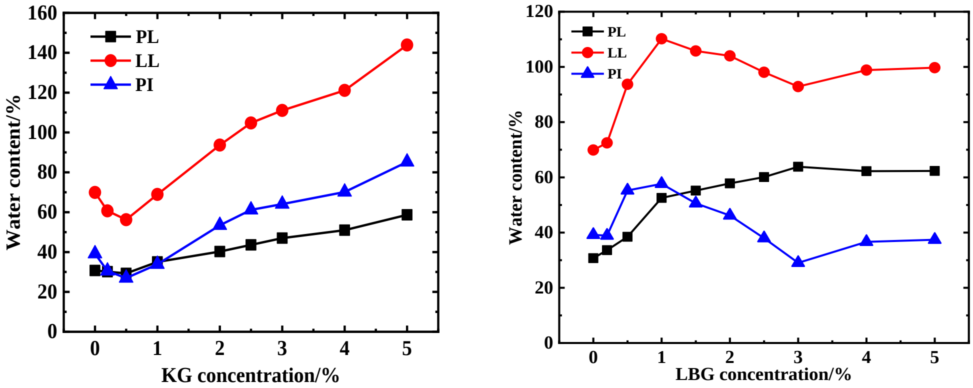
3.3 Soil consistency results

3.3.1 Atterberg limits results

The relationship between the logarithmic water content (w) and the logarithmic cone penetration (d) was found to be linear for any soil types (Feng 2000, 2001) as given by Eq. (3.1).

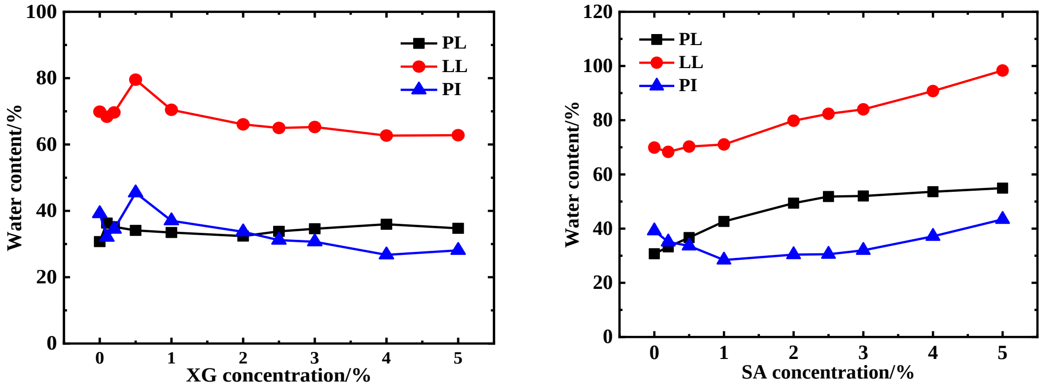
$$\lg w = \lg c + m \lg d \tag{3.1}$$

where c is the water content at a penetration depth of 1 mm and m is the slope of the linear relationship. The variation of liquid limit, plastic limit and plasticity index (*PI=LL-PL*) with biopolymer contents for soils treated with eight biopolymers are shown in Figure 3.4.

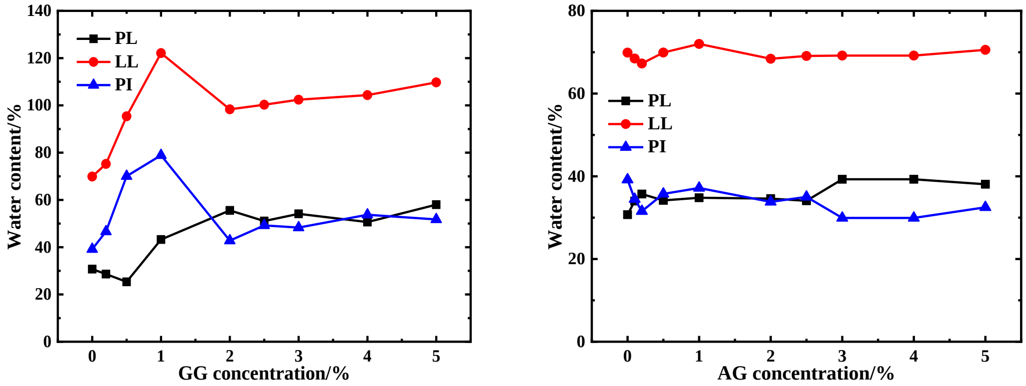


(a) KG-treated kaolinite

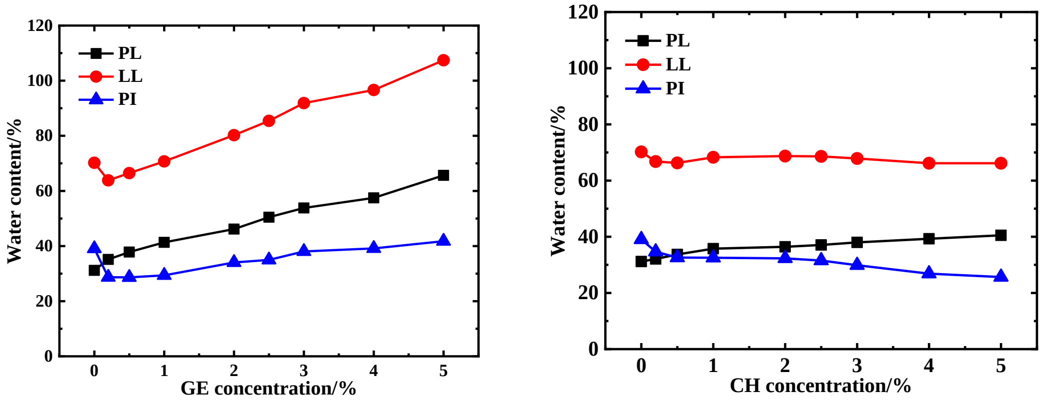
(b) LBG-treated kaolinite



(c) XG-treated kaolinite (d) SA-treated kaolinite



(e) GG-treated kaolinite (f) AG-treated kaolinite



(g) GE-treated kaolinite (h) CH-treated kaolinite

Figure 3.4 Consistency limits versus biopolymer concentration

where c is the water content at a penetration depth of 1 mm and m is the slope of the linear relationship. The variation of liquid limit, plastic limit and plasticity index (PI=LL-PL) with biopolymer contents for soils treated with eight biopolymers are shown in Figure 3.4.

As shown in Figure 3.4 (a), the soil consisting of KG treated clay can be divided into two stages with increased of concentration. Firstly, the *PL*, *LL* and *PI* of KG treated clay has slight decrease from 30.7% to 29.3%, from 69.9% to 56.2%, and from 39.2% to 26.9%, respectively, at a valley point ($m_b/m_s = 0.5\%$). And then, an approximately linear increase can be observed until 5% KG with the *PL*, *LL* and *PI* increasing to 58.7%, 143.9% and 85.2%, respectively. The *LL* in this condition is more than 2 times of the *LL* of untreated soil. Interestingly, the increment rate of *LL* is larger than that of *PL* after $m_b/m_s > 0.5\%$. Variation of soil consistency with mb/ms implies the hydrogel viscosity increase and particle aggregation effects induced by KG. At lower concentrations, the lubricant effect of gels and the very slight increment of biopolymer solution viscosity in inter-granular pores reduce the soil consistency. With the increase of concentration, the solution viscosity of biopolymer solution has a significant increment to increase *LL*. On the other hand, KG is anionic polysaccharides consisting of Ester sulphate, Glycosidic linkage, 3,6-anhydro-D-galactose and D-galactose-4-sulphate as shown in Figure 3.5 (a) (Kaushik et al. 2016, Zafar et al. 2016), initiating kaolinite aggregation via ionic or hydrogen bonding, which accompanies a decrease in surface area by particle aggregation reducing the amount of free pore water. After KG concentration is more than 0.5%, the increase in soil consistency seems to be attributed to the positive effect of KG hydrogel formation always greater than the simultaneous kaolinite aggregation induced by KG. On the other hand, the plastic limit shows a slight increase, which can be explained by the threads of the monomeric molecules making the soil stiffer (Ayeldeen et al. 2016).

In terms of LBG treated clay, as shown in Figure 3.4 (b), the *PL* initially slightly increases to 63.8% until 3% of biopolymer concentration and then almost keeps constant until 5%. On the other hand, the *LL* and *PI* increase from 69.9% to 111% with more than 1.5 times increment, and from 39.1% to 57.6%, respectively, at 1%. And then both of them reduce to 92.9% and 29%, respectively, followed by almost keeping constant until 5% LBG concentration. It can be explained that LBG is a neutral polysaccharide consisting of a polymeric mannose chain branched with galactose units, and the main chain consists of (1-4) linked beta-D mannose residues, and the side chain of (1-6) linked alpha-D galactose as shown in Figure 3.5 (b) (Simões et al. 2011, Prajapati et al. 2013, Wang et al. 2014). LBG has numerous hydroxyl groups, which can form hydrogen bonds between LBG and soil particles inducing particle aggregation to reduce *LL*. On the other hand, the increase in LBG concentration transforms pore fluids into a viscous hydrogel which causes an increase in the viscosity of pore fluids. Therefore, the significant increase in viscosity and the slight particle aggregation at lower concentrations cause a significant increase in *LL*. With the increase of LBG concentration, plenty of molecular chains lead to hydrogen bonds and significant particle aggregation. Moreover, reducing in surface area by particle aggregation reduces the amount of free pore water. Thus, *LL* can be observed some degree of decrease until 3% concentration. And then, the behaviour of *LL* for m_b/m_s >3% seems to be attributed to the equilibrium between LBG hydrogel formation and the simultaneous kaolinite aggregation induced by LBG because more LBG molecular tends to interact with each other rather than forming hydrogen bonds with kaolinite. However, it should be noted that the *LL* of LBG treated clay is always larger than untreated clay, which indicates the positive factors throughout in the dominant position.

The soil consistency of XG treated kaolinite can be illustrated in Figure 3.4 (c). *LL* and *PI* initially have a slight decrease to 68.4% and 32.1%, respectively, with shallow biopolymer content (e.g. 0.1%), followed by increasing to a peak point with 79.5% and 45.4%, respectively, at 0.5% concentration, and then decreases to an inflexion point with 66% and 33.7%, respectively, at 2.0% concentration. The results are under the previous finding from Chang et al. (2019) and Nugent et al. (2009). Conversely, the maximum *PL* with 36.3% can be observed at 0.1% concentration, decreasing to 32.4% at 2.0% concentration. After that, the soil consistency keeps constant with the increase of XG concentration reaching 5%. XG is a long-chain polysaccharide having d-glucose, d-mannose, and d-glucuronic acid having hydroxy and carboxy groups with highly negative charges, as shown in Figure 3.5 (c). At shallow XG content (e.g. 0.1%), the change of fluid viscosity can be almost neglected, while the lubrication effect of XG leads to a slight decrease in *LL*. With the increase of XG content, it forms hydrogels with high fluid viscosity in soil pore space, which results in the increase of *LL* with the increment of 14% at 0.5% concentration (Chang et al. 2019, Singh and Das 2019). However, more XG strands provide the mechanism for aggregation, binding multiple clay particles together via ionic or hydrogen bonding (Laird 1997, Sastry et al. 1995), which accompanies a decrease in *LL*. Moreover, the soil consistency almost keeps constant after a concentration larger than 2.0% due to the equilibrium between XG hydrogel formation and the simultaneous kaolinite aggregation induced by XG (Nugent et al. 2009).

In Figure 3.4 (d), only a small valley is found around 0.2% SA achieving *LL* with 68%, while *PI* can be observed at the lowest point with 28.4% at 1% SA. Consequently, *LL* and *PI* almost linear increase with an increase of SA content from 1% to 5% with 98.3% and 48.4%, respectively. On the other hand, *PL* continuously increases to 51.8% at 2.5% concentration and remains constant until 5% concentration. The growth rate of *PL* decreases gradually since SA has strong hydrophilicity, which means that the soil can adsorb more film water. Moreover, SA is a linear polysaccharide derivative of alginic acid comprised of 1,4-β-d-mannuronic (M) and α-l-guluronic (G) acids having hydroxy and carboxyl groups with negative charges, as shown in Figure 3.5 (d). At the low concentration, only slight pore viscosity of SA treated clay can be achieved, while the chemical groups and strong ionic characteristics of SA can be interacted with clay with apparent aggregation to reduce surface area and soil pore volume. Thus, it is observed that a slight decrease in *LL* at 0.2% concentration. Moreover, the hydrogel viscosity of SA exponentially increases with the increase of SA concentration contributing to the increase of *LL* after 0.2% concentration.

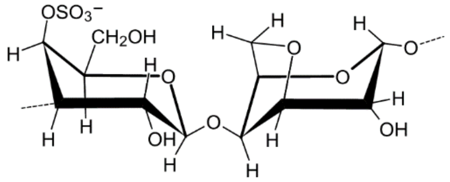
In terms of GG treated kaolinite (Figure 3.4 (e)), *LL* and *PI* initially increase to a peak point with 122.1% and 78.9%, respectively at 1% concentration, and then decrease to an inflexion point with 100.3% and 49.2%, respectively at 2.0% concentration, followed by a slight increase to 109.7% and 51.8%, respectively, at 5% concentration. Conversely, *PL* decreases to 25.3% firstly at 0.5% concentration, followed by increasing to 55.5% at 2% concentration before approximately keeping constant until 5% concentration. GG is a neutrally charged polysaccharide (Chudzikowski 1971), and its backbone is a linear chain of β 1,4-linked mannose residues to which galactose residues are 1,6-linked at every second mannose with numerous hydroxy groups, as shown in Figure 3.5 (e). Therefore, it can produce strong hydrogel viscosity by adding a small amount of GG, and only slight particle aggregation can be observed, which contributes to the appearance of the peak point of *LL* with 1.7 times more than that of untreated clay. However, with the increase of GG, plenty of hydroxy groups can be interacted with clay to form large particle aggregation to reduce the free water in the pore. Moreover, a slight decrease of *LL* can be observed until 2% concentration, which agrees with Nugent et al. (2009). On the other hand, the hydrogel viscosity has a significant exponential increase after 2% concentration, causing a slight increase of *LL* again. Overall, the *LL* of GG treated clay is always larger than that of untreated clay regardless of GG concentration, indicating the increase of *LL* caused by increasing pore fluid viscosity outpaces the decrease of *LL* caused by aggregation of clay particles.

Figure 3.4 (f), shows that *LL* and *PI* of AG-treated kaolinite slightly decrease to 67.2% and 31.6%, respectively, at 0.2% concentration, while *PL* increases to 35.7%. And then *LL* and *PL* come back to 72% and 37.2%, respectively, at 1% concentration. Conversely, *PL* decreases to 34.8%. With the increase of AG concentration, *LL* keeps constants around 70%. On the other hand, *PL* and *PI* slightly increase and decrease to 39.3% and 29.9%, respectively, at 3% concentration, followed by almost remaining constant. AG is a linear polymer made up of the repeating unit of agarobiose, a disaccharide made up of D-galactose and 3,6-anhydro-L-galactopyranose with numerous hydroxy groups, as shown in Figure 3.5 (f). An agar-agar solution is slightly negatively charged. Its stability depends upon two factors: hydration and the electric charge. However, AG is insoluble in cold water, and AG solution in hot water forms a characteristic gel after setting, with a melting point between 85 to 95 ℃. Therefore, AG can be slight soluble in room-temperature water, causing a slight change in pore fluid viscosity and particle aggregation. Overall, there is no significant change of AG treated clay consistency compared to untreated clay.

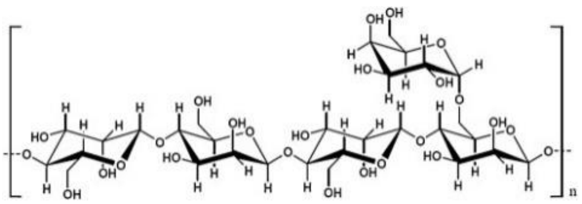
Figure 3.4 (g) illustrates the soil consistency of GE treated clay. *LL* and *PI* slightly decrease to 63.9 and 28.7%, respectively, at 0.2% concentration, followed by increasing to 107.4% and 41.8%, respectively, at 5% concentration. Meanwhile, *PL* almost shows a linear increase to 65.7% at 5% concentration. GE is a negatively charged, linear, exopolysaccharide, composed of the tetrasaccharide repeat unit of glucose, glucuronic acid, and rhamnose with lots of hydroxyl groups, as shown in Figure 3.5 (g). At low concentration (e.g. <0.5%), there is no significant increase for fluid viscosity. Thus, the particle aggregation caused by ionic or hydron bonds lead to *LL* decrease. With the increase of GE concentration, the solution viscosity significant increases overcoming the negative effective of particle aggregation. As a result, the *LL* of 5% GE treated clay is 1.5 times more than that of untreated soil.

For CH treated clay, as shown in Figure 3.4 (h), *LL* decreases to 66.3% at 0.5% concentration and then almost remains constant until 5% concentration. On the other hand, *PL* continuously increases to 40.5% at 5% concentration, while *PI* decreases to 25.6% at the same concentration. CH is a cationic polysaccharide produced by N-deacetylation of its origin with lots of hydroxyl groups and amino on its surface, as shown in Figure 3.5 (h). And CH has low solubility and viscosity in water. Therefore, there is only limited CH causing particle aggregation via cation bonding or chemical interaction along with the slight decrease of *LL* at low concentrations. Moreover, *PL* shows a slight increase because the threads of the monomeric molecules make the soil stiffer.

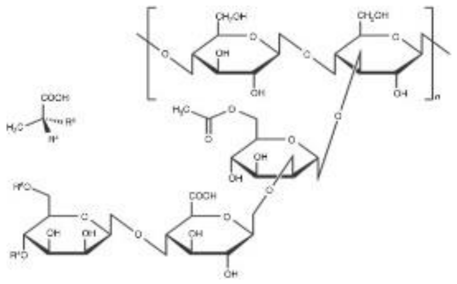
In total, it can be observed that the *LL* of KG, GE, SA and XG treated clay decreases in the low biopolymer concentration and then increases with the continued increase of biopolymer concentration. Moreover, the *LL* of LBG and GG treated clay increases to the peak point with the increase of biopolymer concentration to 1% and then decreases with the continued increase of biopolymer concentration, followed by an equilibrium state. Moreover, there is the limited effect of AG and CH on the *LL* of treated clay.



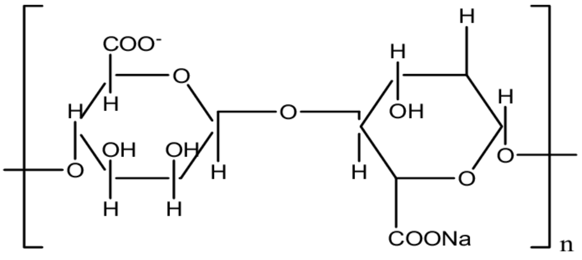
(a) KG



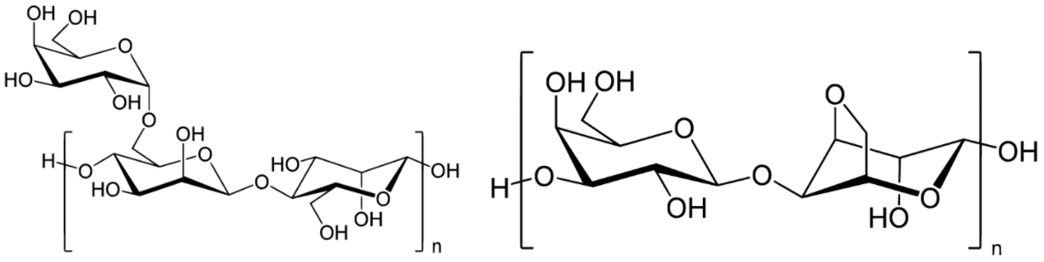
(b) LBG



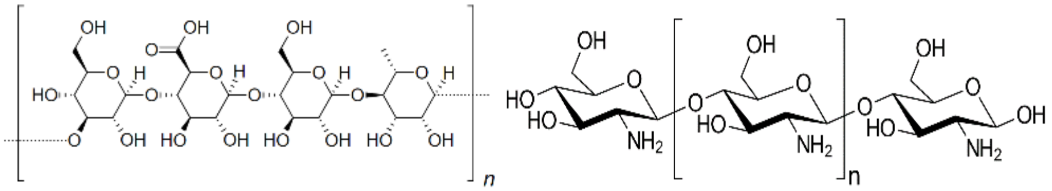
(c) XG



(d) SA



(e) GG (f) AG



(g) CH (h) GE

Figure 3.5 Chemical structure of various biopolymer type (Lahaye and Rochas 1991, Barak and Mudgil 2014, Petri 2015, Bacelar et al. 2016, Hecht and Srebnik 2016, Thombare et al. 2016, Dave and Gor 2018, Kang et al. 2019, Piotrowska-Kirschling and Brzeska 2020)

3.3.2 Mechanism

Biopolymer mainly interacts with distilled water forming hydrophilic hydrogel with the kaolinite surface, and the water absorbing capacity of biopolymer-treated soil can decrease by altering the particle packing of clays (Sridharan et al. 1988, Sridharan et al. 1999). It is influenced by particle mineralogy, fluid viscosity, and biopolymer type and content electrochemical properties. The chemical and physical properties of various biopolymers can be summarized in Table 3.3.

Table 3.3 Chemical and physical properties of various biopolymers

BP	Chemical group	Charge	Soluble in water	MT/°C	Composed
KG	Hydroxyl, hydroxymethyl	negative	Yes	70	repeating galactose units and 3,6 anhydrogalactose
GE	Hydroxyl	negative	Yes	70	tetrasaccharide repeat unit of glucose, glucuronic acid, and rhamnose
SA	Hydroxyl, carboxy	negative	Yes	99	1,4-β-d-mannuronic (M) and α-l-guluronic (G) acids
XG	Hydroxyl, hydroxymethyl, carboxy	negative	Yes	65	d-glucose, d-mannose, and d-glucuronic acid

LBG	Hydroxyl	neutral	Yes	> 90	(1-4) linked beta-D mannose residues and the side chain of (1-6) linked alpha-D galactose
GG	Hydroxyl	neutral	Yes	80	β 1,4-linked mannose residues to which galactose residues are 1,6-linked at every second mannose
AG	Hydroxyl	negative	Yes (insoluble in cold water)	85-95	D-galactose and 3,6-anhydro-L-galactopyranose
CH	Hydroxyl	positive	No	102.5	β-(1→4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit)

To increase LL, the limit increase of solution viscosity can be observed at low biopolymer concentration. On the other hand, a strong short-range ionic bond can be immediately formed between the negatively charged biopolymer and the positive component of clay. Moreover, biopolymers are polysaccharides consisting of various chemical groups (e.g. Hydroxyl, hydroxymethyl, carboxy) to form hydrogen bonding with clay (Nugent et al. 2009, Chang et al. 2019, Kang et al. 2019c). Both ionic and hydrogen bonding cause particle aggregation to decrease surface area. Meanwhile, there is a lubrication effect with low biopolymer concentration. All of these factors reduce the amount of free pore water (Kwon et al. 2019). Therefore, it can be illustrated that the *LL* of KG, GE, SA and XG treated clay decreases at an initial stage.

However, with the increase of biopolymer concentration, the viscosity has a significant increase overcoming the negative effect of particle aggregation caused by ionic and hydrogen bonding, which leads to the increase of *LL*. In particles, the maximum *LL* of KG, GE, SA and XG treated clay is about 2.1, 1.5, 1.6 and 1.14 times that of untreated soil. The less chemical function group sites, short chains and high viscosity of hydrogel of KG contribute to the maximum *LL* achieved compared to other biopolymers. However, due to the lower solution viscosity, higher electricity, various types and plenty of chemical functional groups of XG compared to other biopolymer types, the maximum *LL* of XG treated clay can be observed at 0.5% concentration, followed by a slight decrease and then having an equilibrium state between XG hydrogel formation and the simultaneous kaolinite aggregation induced by XG, which by the previous findings (Nugent et al. 2009, Chang et al. 2019).

For the neutral polysaccharide, there is no formation of strong short-range ionic bonding induced particle aggregation. Therefore, GG and LBG forms high viscosity of hydrogel, leading to the increase of *LL*, which is 1.78 and 1.6 times more than that of untreated clay, respectively. GG has less chemical functional groups and molecule weight than LBG as well as GG is more soluble than LBG due to its extra galactose branch points. Thus, the *LL* of GG treated clay is more significant than that of LBG at the same concentration.

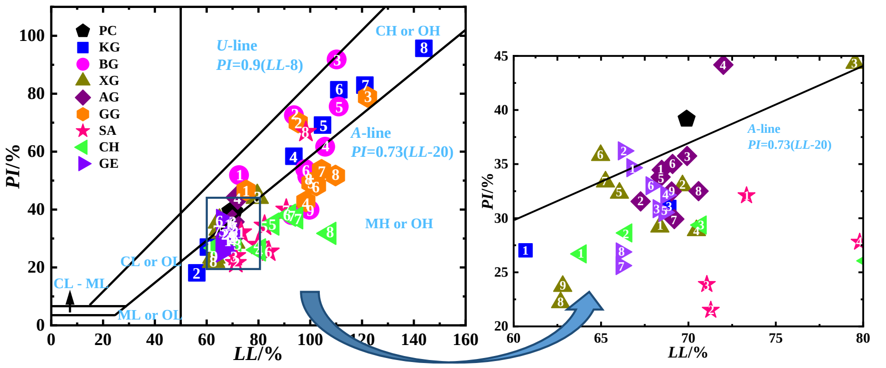
With the increase of GG and LBG concentration, the particle aggregation caused by the hydrogen bonds can be observed, which offsets the positive effect of the viscosity of GG and LBG, leading to the decrease of *LL* after 1% concentration. However, there is a limited GG and LBG soluble in room-temperature water with the continuous increase of biopolymer concentration. Thus, the *LL* of GG and LBG treated clay remains constant at higher concentrations because there is an equilibrium state between biopolymer hydrogel formation and the simultaneous kaolinite aggregation caused by chemical functional groups. It is illustrated that the optimum concentration of GG and LBG is 1% to achieve the maximum *LL*. Interestingly, the *LL* of GG and LBG treated clay is consistently higher than that of untreated clay regardless of biopolymer concentration because the increase of solution viscosity has a dominant effect on the results of *LL*.

However, AG and CH are limited insoluble or even insoluble in room-temperature water, which contributes to the limit change of *LL* with the increase of AG and CH concentration. The effectiveness of eight biopolymer types in increasing the *LL* of kaolinite is attributed to the variety in viscosities of biopolymer hydrogel and aggregation levels of kaolinite particles caused by ionic or hydrogen bonding.

In total, biopolymer has contrary effects on the soil consistency. On the one hand, biopolymer interaction with pore-fluid forms hydrogel with a high viscosity increases the liquid limit. On the other hand, biopolymer-induced aggregation of clay particles via cation bridging and hydrogen bonds tends to decrease the liquid limit. Specificlly, the effectiveness of biopolymers in decreasing the liquid limit of biopolymer-kaolinite mixtures depends on the aggregation of kaolinite particles attributable to the added biopolymer concentration and the type of bonding between the biopolymer and kaolinite particles.

3.3.3 Soil classification

Plasticity index and liquid limit are frequently adopted to classify and estimate the behaviour of natural soils in geotechnical engineering. The *LL-PI* plane is plotted in Figure 3.6. Most of both the *LL* and *PI* of biopolymer-based soils are larger than that of pure kaolinite. It illustrates that most of the samples can be considered as silt falling below *A* line. Others are classified as clay falling between *U* line and *A* line. The soil plasticity tends to increase owing to the biopolymer-induced formation of viscous hydrogel, while decreasing due to elevated clay particle aggregation. Therefore, both biopolymer types and contents have an effect on soil classification.



	0	0.1	0.2	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
PC	⬟										
KG			1	2	3		4	5	6	7	8
BG			1	2	3	4	5	6	7	8	9
XG		1	2	3	4		5	6	7	8	9
AG		1	2	3	4		5	6	7	8	9
GG			1	2	3		4	5	6	7	8
SA			1	2	3		4	5	6	7	8
CH			1	2	3		4	5	6	7	8
GE			1	2	3		4	5	6	7	8

Figure 3.6 Chart for the classification of soils used in this study based on USCS

3.3.4 One-point method

Determination of liquid limit of soils using only one value of cone penetration and its water content was proposed by many researchers (Feng 2001, Spagnoli 2012, Shimobe and Spagnoli 2020). This method is beneficial for evaluating the liquid limit when the soil sample and time availability for the testing are limited. Eq. (3.1) can be rewritten to form a one-point fall cone method to determine the liquid limit as follows.

$$w = c(d)^m \tag{3.2}$$

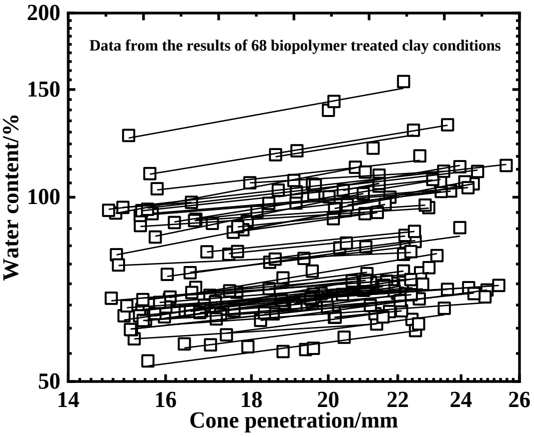
Since *LL* is the water content corresponding to 20 mm,

$$LL = c(20)^m \tag{3.3}$$

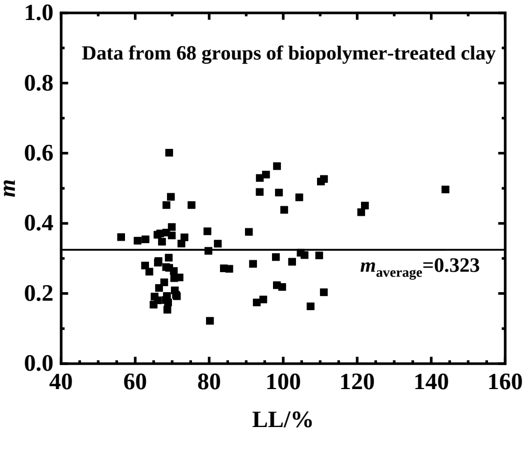
Dividing Eq. (3.2) by Eq. (3.3), one obtains

$$\frac{LL}{w} = (\frac{20}{d})^m \tag{3.4}$$

With a set of data (*d*, *m*) from a fall cone test, the liquid limit can be computed using Eq. (3.1) with a given value of *m*. The test results of water content versus the cone penetration ranging from 15 mm to 25 mm more than 200 points are shown in Figure 3.7 (a). The slope *m* has a maximum value of 0.6, a minimum value of 0.12, and an average value of 0.323 from 68 biopolymer treated clay conditions as shown in Figure 3.7 (b).



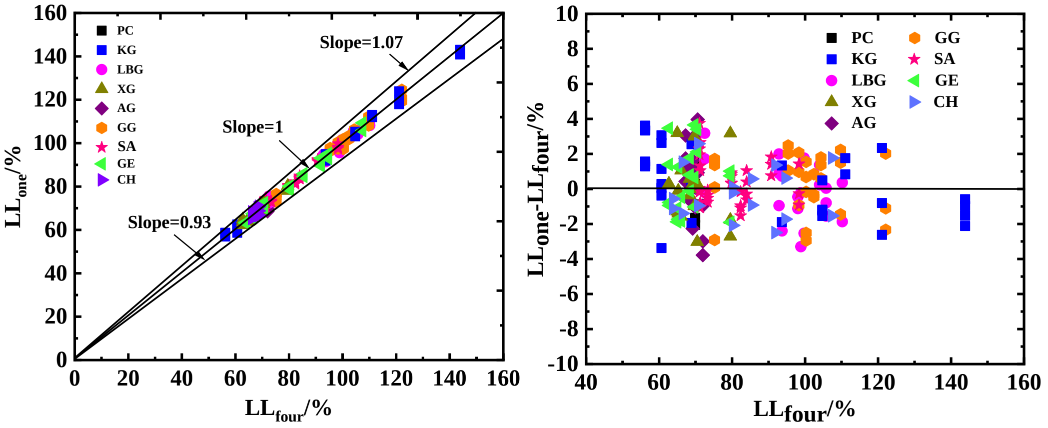
(a) Measured flow curves



(b) Empirical data for LL versus *m*

Figure 3.7 Determination of slope *m*

Moreover, the ratios of *LL* (one-point method) to *LL* (four-point method) ranges from 0.93 to 1.07 for all biopolymer-treated soils as shown in Figure 3.8 (a). On the other hand, the difference between the *LL* (one-point method) and *LL* (four-point method) versus *LL* (four-point method) shows that the maximum difference is below 4% and the average difference is only around 0.24% as shown in Figure 3.8 (b). Therefore, it is clear that Eq. (3.4), with an *m* value of 0.323, can be used to estimate the liquid limit of biopolymer-treated kaolinite by one fall cone test with cone penetration falling between 15 and 25 mm.



(a) Comparison of two methods

(b) Difference of two methods

Figure 3.8 Verify of one-point method

3.4 Predicted of undrained shear strength and shear viscosity

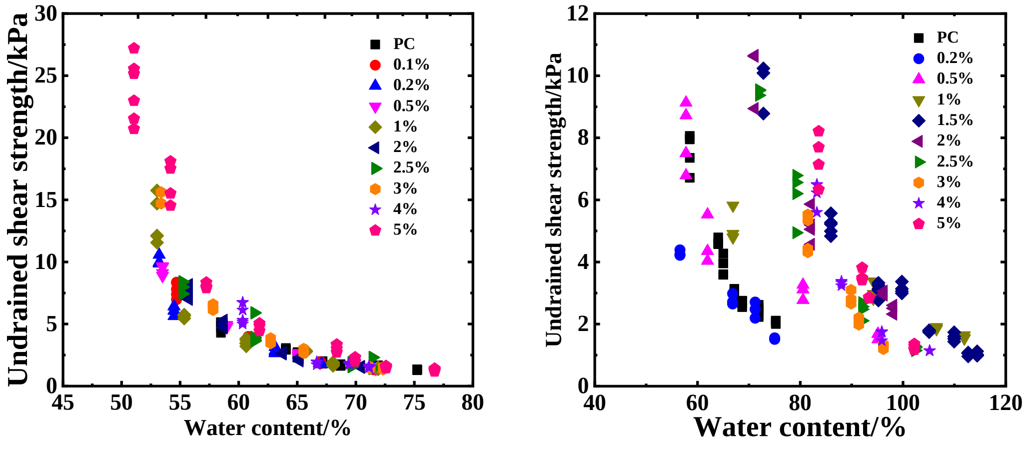
3.4.1 Undrained shear strength based on fall cone tests

The fall cone undrained shear strength of various biopolymer types treated kaolinite with a wide range of biopolymer concentrations is evaluated through the results of fall cone penetration tests. It has been conducted to assess the effect of biopolymer types and concentrations on the shear strength at various water contents. Hansbo (1957) proposed that the undrained shear strength (S_u) could be determined by the cone penetration (d) as shown in Eq. (3.5).

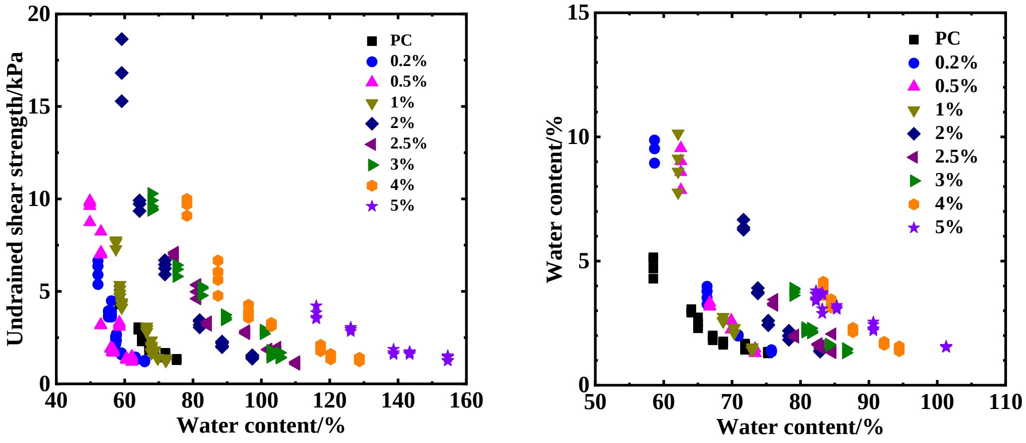
$$S_u = K\frac{W}{d^2} \tag{3.5}$$

where W is weight of the cone, 80g; K is no-dimensional fall cone factor, 0.85 (Wood, 1985).

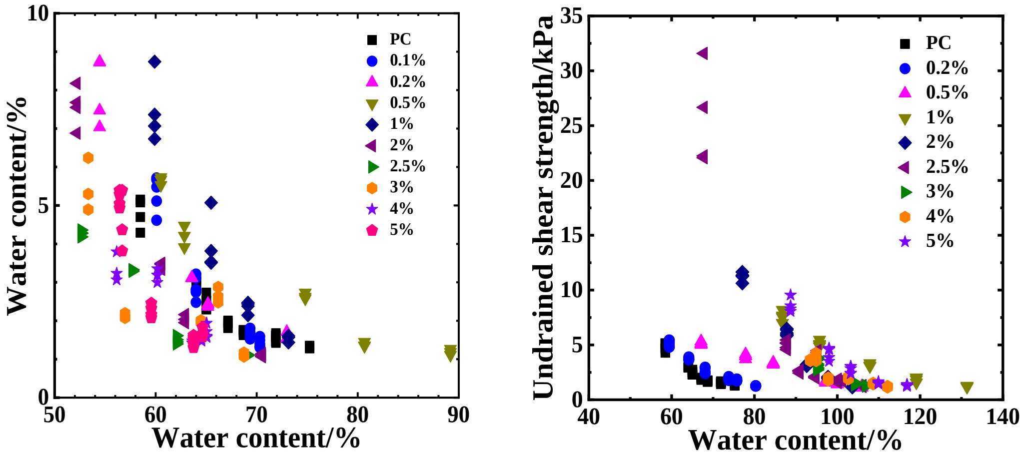
The undrained shear strength of biopolymer-treated kaolinite is illustrated in Figure 3.9, which is mainly dependent on the net attractive force and the mode of particle arrangement as determined by the inter-particle forces. With the decrease of water content, the undrained shear strength increases, regardless of biopolymer types and concentrations. In terms of LBG and GG treated kaolinite, its undrained shear strength is larger than pure clay, regardless of biopolymer concentrations due to these three biopolymers absorbing pore water and forming a viscous hydrogel in pore space to increase the shearing resistance. However, a large number of intermolecular bonds (e.g. electrostatic bonds, van der Waals, ionic-dipole, hydrogen bonds or hydrophobic interactions) between biopolymer and electrically charged kaolinite particles to enlarge aggregate size that leads to the reduction of undrained shear strength. Therefore, the undrained shear strength of charge biopolymer (e.g. KG, SA, GE and XG) treated kaolinite has a slight decrease at lower concentration. On the other hand, with the increase of biopolymer concentration, the high viscous hydrogel can be formed to increase undrained shear strength. Therefore, the highest undrained shear strength of XG treated kaolinite can be observed at 0.5% and the undrained shear strength of other biopolymers (e.g. KG, SA and GE) treated clay increases after 0.5% concentration. In addition, there has limit effect on the undrained shear strength of AG and CH treated clay with the increase of biopolymer concentration, which is agreement with the results of soil consistency.



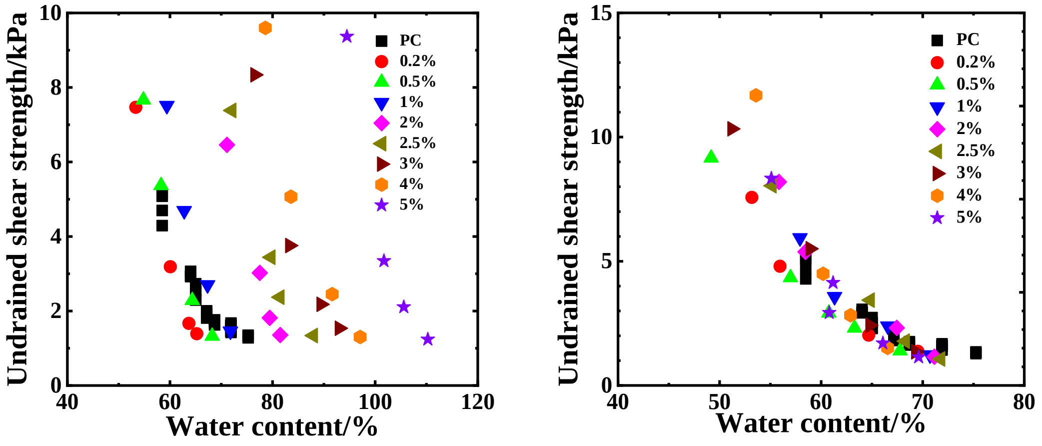
(a) AG-treated clay (b) LBG-treated clay



(c) KG-treated clay (d) SA-treated clay



(e) XG-treated clay (f) GG-treated clay



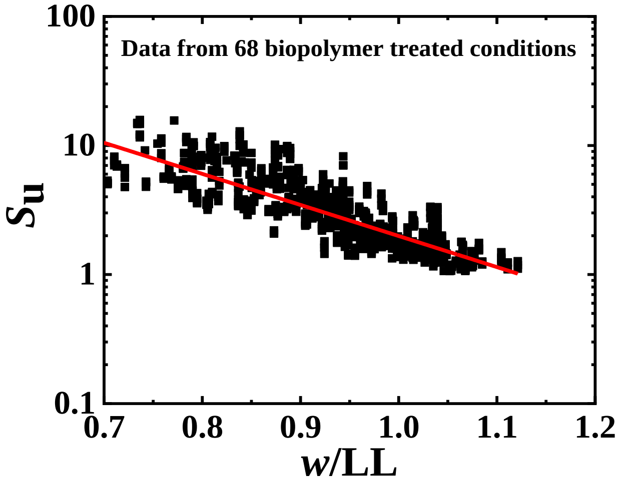
(g) GE-treated clay (h) CH-treated clay

Figure 3.9 Undrained shear strength of biopolymer treated clay

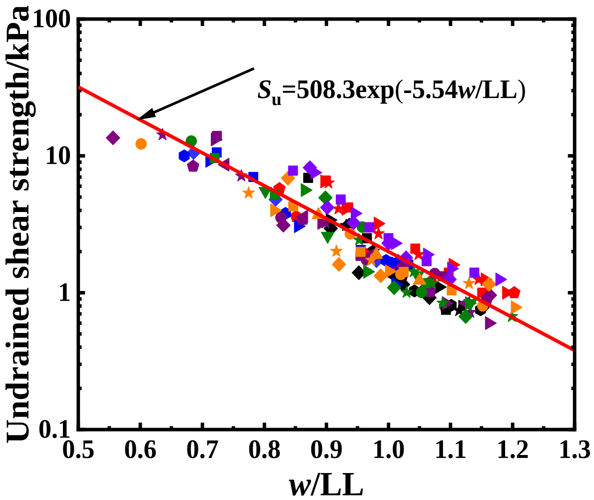
Researchers have proposed many empirical equations by assuming a logarithmic dependence of undrained strength on liquidity index for biopolymer-treated kaolinite (Chen et al. 2013). Based on the best fitting of the test data of S_u versus normalization water content (w/LL) in Semi logarithm scale as shown in Figure

3.10 (a). The following equation can be derived for estimating the S_u of biopolymer-treated kaolinite based on the current results of fall cone test (more than 1200 data) with the coefficient of determination R^2 0.8. Importantly, it also can be found that Eq. (3.6) is better match with experimental results of other researchers as shown in Figure 3.9 (b).

$$S_u = 508.3\exp(-5.54w/\mathrm{LL}) \tag{3.6}$$



(a) Current research



(b) Data collected from references (Chen et al. 2013, Cabalar et al. 2018, Chang and Cho 2019, Kwon et al. 2019a Kwon et al. 2019b)

Figure 3. 10 Undrained shear strength versus normalization water content

3.4.2 Shear viscosity

The viscosity of biopolymer solution is a measure of its resistance to deformation at a given rate. For a simple isotropic biopolymer solution, the shear viscosity is defined in terms of the pressure tensor and the shear rate. The shear viscosity (μ)

of the soil at dynamic equilibrium can be expressed as follows (Mahajan and Budhu, 2009).

$$\mu = 2.94 K W \sqrt{d}\left(\frac{0.67}{h_{\mathrm{eq}}} - \frac{1}{d}\right) \tag{3.7}$$

And the dynamic penetration depth (h_{eq}) can be expressed by cone penetration as follows (Mahajan and Budhu, 2009).

$$h_{\mathrm{eq}} = 0.528d + 0.137 \tag{3.8}$$

In terms of shear viscosity of biopolymer treated clay, the relationship between μ and normalization water content (w/LL) is depicted in Figure 3.11 based on Eqs. (3.7) and (3.8). The data can be fitted quite well (R^2=0.85) by an exponential function expressed as follow.

$$\mu = 375.8\exp(-1.2w/LL) \tag{3.9}$$

However, one of the contributing factors to the accuracy of the calculated μ is linearly related to the value of K. For example, K=1.33 will give a μ about 1.56 times the values of shear viscosity obtained in this study for an adopted K of 0.85 (Koumoto and Houlsby 2001).

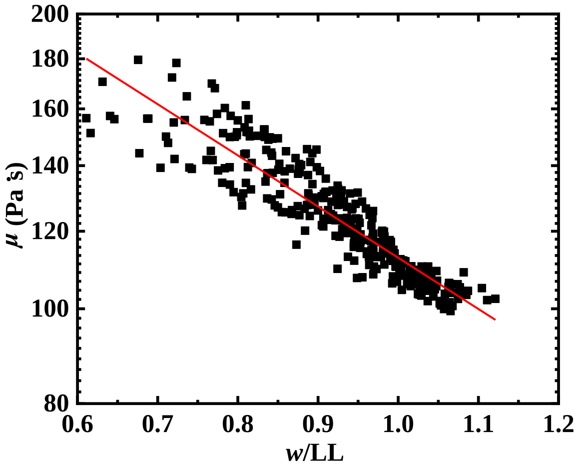
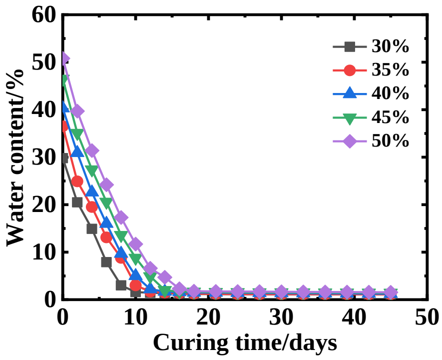


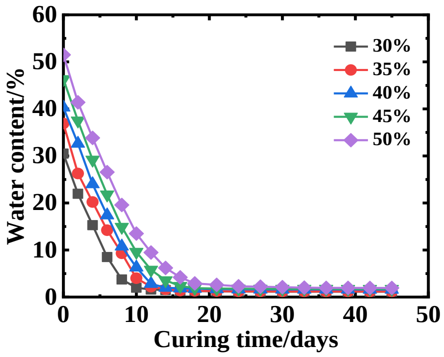
Figure 3.11 Shear viscosity versus normalization water content

3.5 Water evaporation results

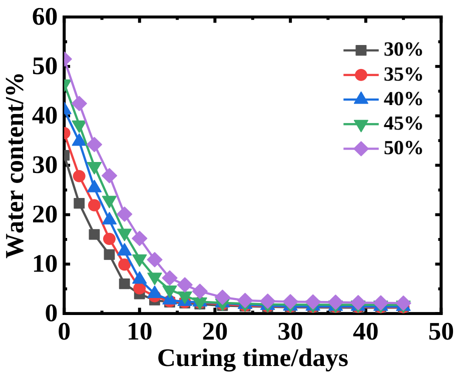
Figure 3.12 shows the rate of moisture loss of various xanthan gum treated specimens at room temperature. Unlike the rate keeping constantly in the oven drying condition (Chen et al. 2019b), the water evaporating rate of sample drying at room temperature gradually decreases because the external part of the sample is exposed on the air-dry condition causing crystallization and cementation effect of biopolymer quickly at initial stage. The ultimate water content has limited differences with about 3% regardless of XG concentration and initial water content in this study. However, the biopolymer content and initial water content have nuance effect on the process of water evaporation. A previous study showed that the microstructure of organic matter and hydrophilic hydrogels in soil includes extremely high specific surfaces with electrical charges which provide stronger bonding with water molecules (Chang et al. 2015d). To be specific, the finally converged curing time increases from 14 to 21 days with the increase of XG concentration from 0 to 5% under initial water content 30%. It tends to have high water retention capacity for higher XG concentrations due to the strong hydration characteristics of the biopolymer. Meanwhile, there are about the increment of 7 curing days for initial water content increasing from 30% to 50% at the same XG concentration. This is associated with the clogging characteristics of the viscous xanthan gum solution which blocks the open porous network of the soil specimens.



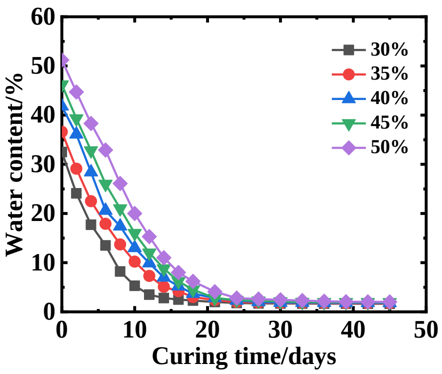
(a) Untreated clay



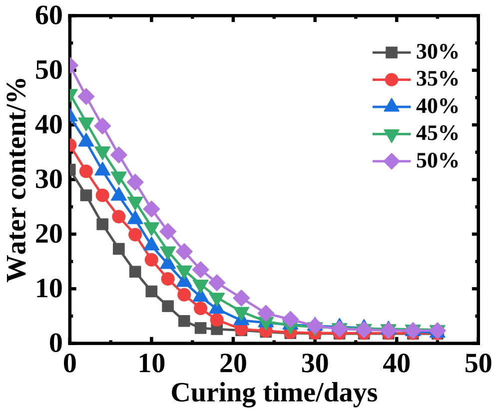
(b) 0.5% XG treated clay



(c) 1% XG treated clay



(d) 2% XG treated clay



(e) 5% XG treated clay

Figure 3.12 Water evaporation percentage of biopolymer treated kaolinite

3.6 Possible implementations and further research

This study assessed the soil consistency and inter-particle characteristics of various biopolymer treated clay. The experimental results indicate that XG, KG, SA and GE can form strong bonds with clay particle aggregation and decreased surface area. Therefore, they have excellent potential for strengthening purposes (e.g. dry conditions) on shallow depth stabilization (e.g. soil pavement and slope surface) and controlling hydraulic properties. GG and LBG with high viscosity at a low concentration significantly increase in undrained shear strength, especially with high water content, which is recommended for stabilizing the soft marine soil and controlling surface erosion. CH has the potential to coagulate clay as bio flocculant due to insoluble water. Therefore, it can be applied to wastewater treatment, tailings management, land reclamation and soil washing.

For better performance and a wide range of geotechnical applications of biopolymer, some further research is recommended. Obviously, the lower the temperature, the lower the rate at which viscosity increases and the lower the final viscosity. Therefore, it is vital to investigate the thermal properties of biopolymer treated soil because biopolymer is only partially soluble in cold water and normally has typically high dissolving temperatures for complete hydration. Moreover, it is expected to increase soil behaviours with the increase of solution temperature.

Furthermore, many free chemical functional groups (e.g. hydroxyl and carboxyl groups) are distributed along the biopolymer backbone. These are highly reactive and amenable to chemical modifications. Thus, the properties like solubility, hydrophobicity and biological characteristics may be altered to have a lot of potential applications for its derivatives. The modifications are accomplished by various chemical processes, including oxidation, sulfation, esterification, amidation, and graft copolymerization (Yang et al. 2011). For example, the firm KG gel texture is perfect for encasing liquid centres in the presence of calcium, making it perfect for use in dairy proteins (Youssef et al. 2017). Moreover, in the presence of calcium, sodium alginate can form a gel without heat. On the other hand, strong acids cause hydrolysis and loss of viscosity and alkalies in substantial concentrations also tend to reduce the viscosity (e.g. GG) (Venugopal and Abhilash 2010).

In addition, one type of biopolymer can combine with other biopolymers to form cross-link interaction. For example, the addition of XG to gelling hydrocolloids, such as KG, AG or LBG, shows improved gelling properties to increase the gel strength and makes the typical brittle gels more elastic (van de Velde 2008). However, several tests need to be performed to illustrate the thermal properties of biopolymers, different pore fluid conditions with chemical modifications, and the cross-linking of various biopolymers.

3.7 Summary

This chapter illustrates the basic physical properties of biopolymer treated clay for meeting the current gaps on the compaction properties of biopolymer treated clay, the soil consistency without considering different biopolymer types and concentration. Taking the typical biopolymer, XG, as example, the compaction test is carried out to obtain the maximum dry density and maximum dry density of biopolymer treated kaolinite with different XG concentrations. In addition, the PL, LL and PI of biopolymer treated kaolinite are comprehensive illustrated with considering eight biopolymer types (KG, SA, XG, GE, LBG, GG, AG and CH) under a wide range of biopolymer concentrations through thread rolling test and fall cone test. One-point fall cone method is also developed to determine the LL of biopolymer treated kaolinite. Most importantly, based on the results of all cone tests, the undrained shear strength and shear viscosity of biopolymer treated kaolinite are estimated. Meanwhile, the relevant empirical equations are develped to predict the undrained shear strength and shear viscosity of biopolymer treated soil under other conditions, which are not found in the previous study. Moreover, due to the mechanical behaviours of biopolymer treated soil is sensitive to water content, the water evaporation ratio of biopolymer treated kaolinite at curing room-temperature condition is also illustrated for meeting the current gaps.

The conclusions are summaried as follows.

(1) The maximum dry density of XG treated clay slightly increases from 13.96 kN/m^3 to 14 kN/m^3 at a shallow concentration (e.g., 0.2%) and then decreases to 12.7 kN/m^3 with the XG concentration increasing to 5%, while the optimum water content continuously increases to 33.5% at 5% XG concentration (3.2% wet of the untreated sample).

(2) The PL of biopolymer treated clay increases with the increase of biopolymer concentration regardless of biopolymer type, and the trend of the plasticity index is consistent with the liquid limit. Most biopolymer treated clay is classified as high plasticity silt.

(3) The liquid limit of biopolymer treated clay can be divided into three conditions depending on biopolymer types. The liquid limit of KG, SA and GE treated clay decreases firstly at low concentration (e.g., 0.2%), and then continuously increasesing with the increase of biopolymer concentration. Moreover, the liquid limit of XG, LBG and GG treated clay has a peak point of 0.5%, 1% and 1%, respectively, and the liquid limit tends to keep constant after 3% concentration. Meanwhile, the liquid limit of AG and CH treated clay tends to remain constant.

(4) *m* value of 0.323 can be used to estimate the liquid limit of biopolymer treated clay by one fall cone test with cone penetration falling between 15 and 25 mm. Meanwhile, $S_\mathrm{u}=508.3\exp(-5.54w/LL)$ and $\mu=375.8\exp(-1.2w/LL)$ are proposed to predict the undrained shear strength and shear viscosity of biopolymer treated clay.

(5) The evaporating water rate of biopolymer treated kaolinite drying at room temperature condition gradually decreases with the increase of biopolymer concentration and curing time. A higher biopolymer concentration has a high water retention capacity. Moreover, the finally converged curing time also increases with

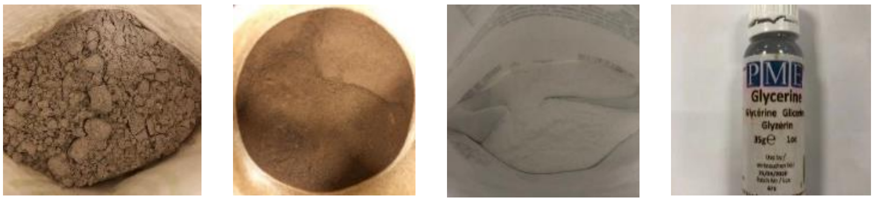
the increase of initial water content and biopolymer concentration. In addition, the ultimate water content of biopolymer treated clay has little difference at below 3% regardless of biopolymer concentration and initial water content.

Chapter 4 Mechanical Properties of Biopolymer Treated Clay

4.1 Materials and Method

4.1.1 Clay and biopolymer

The Kaolinite used in this experimental study was quarried from the South West of England. The details can be found in section 3.1.1. Moreover, in order to investigate the mechanical behaviours of different biopolymer types at initial water content, twelve biopolymers, carrageenan kappa gum (KG, CAS No: 90000-07-1), xanthan gum (XG, CAS No: 11138-66-2), agar gum (AG, CAS No: 9002-18-0), locust bean gum (LBG, CAS No: 9000-40-2), sodium alginate (SA, CAS No: 9005-38-3), gellan gum (GE, CAS No: 71010-52-1), guar gum (GG, CAS No: 9000-30-0) supplied by Special Ingredients Ltd, chitosan (CH, CAS No: 9012-76-4) supplied by Oxford Vitality, casein (CA, CAS No: 9000-71-9), sucralose (SU, CAS No: 56038-13-2) supplied by Bulk Powders, Wine Tannin (WT, CAS No: 1401-55-4) supplied by Young's, Glycerine (GL, EC No: 200-289-5) supplied by The Vanilla Valley, are used in the present study. The former eight biopolymers have been illustrated in section 3.1.2. The other new four biopolymer (i.e., m_{XG}/m_B; XG-to-biopolymer ratio in mass, where m_{XG}/m_B =1.0 indicates pure xanthan gum).



(a) CA (b) WT (c) SU (d) GL

Figure 4.1 Biopolymer types

CA is a protein-based biopolymer, accounting for approximately 80% of all milk proteins. It is inexpensive, non-toxic, and highly stable. It is relatively hydrophobic, making it poorly soluble in water, while solubility enhances in alkaline solutions with high pH.

Tannins can be found abundantly in nature, which is present in wood, bark, leaves and fruit of plants. WT, as one type of tannins, can stem from four primary sources of the grape skins, pips and stems, and the wood barrels used during ageing.

SU is made from sugar in a multistep chemical process in which three hydrogen-oxygen groups are replaced with chlorine atoms. And it is stable at high temperatures.

GL is generally obtained from plant and animal sources where it occurs in triglycerides, esters of glycerol with long-chain carboxylic acids. Owing to the presence of three hydroxyl groups, glycerol is miscible with water and is hygroscopic in nature.

4.1.2 Sample Preparation

Totally, there were four categories to prepare soil samples, called room temperature water-dry mixing (RDM), room temperature water-wet mixing (RWM), hot water-dry mixing (HDM) and hot water-wet mixing (HWM), respectively. The details can be found in section 3.1.3.

To evaluate the engineering properties of the soil-biopolymer mixture, various laboratory tests (e.g. unconfined compressive test and triaxial shear test) are performed on biopolymer treated soil. In terms of performing the unconfined compressive test and triaxial shear test, the uniform biopolymer-soil mixture is compacted into three-part cylinder moulds with diameter and height of 50 mm and 100 mm, respectively. The experimental program is summarised in Table 4.1.

Table 4.1 Experimental program summary

(a) Unconfined compressive test

Soil	Biopolymer	Concentration	Curing time	Initial water content	Water condition	Rewetting-drying cycles	Mixing method
Clay	non	0	7, 14, 21, 28, 35, 42, 49, 70	30, 35, 40, 45, 50	DC	n/a	RDM

			14, 28, 35, 42	45	DC	n/a	RWM, HDM, HWM
			28	45	RS	1	RDM
	XG	0.5, 1, 2, 3, 4, 5	28	30	DC	n/a	RDM
		0.5	14, 28, 42	30, 35, 40, 45	DC	n/a	RDM
		1		35, 40, 45, 50	DC	n/a	RDM
		2		40, 45, 50, 55	DC	n/a	RDM
		3		45, 50, 55, 60	DC	n/a	RDM
		1	7, 14, 21, 28, 35, 42, 49, 70, 378	45	DC	n/a	RDM
		1	14, 28, 35, 42	45	DC	n/a	RDM
		1	28	45	RS	1, 2, 3	RDM
	SA	0.5, 1, 2, 3	14, 21, 28, 49	40, 45, 50, 55	DC	n/a	RDM
		1, 2, 3	7, 14, 21, 28, 35, 42, 49, 70	45	DC	n/a	RDM
		1, 2, 3	7, 28, 42	45	DC	n/a	RWM, HDM, HWM
	GE	1, 2, 3	7, 14, 21, 28, 35, 42, 49, 70	45	DC	n/a	RDM

		1	21, 28, 49	45	DC	n/a	RWM, HDM, HWM
	LBG, AG, KG	1	7, 28, 49	45	DC	n/a	RWM, HDM, HWM
	XG-LBG, XG-AG, XG-KG (4-1, 3-2, 1-1, 2-3, 1-4, 0-1)	1	7, 14, 21, 28, 35, 42, 49, 70	45	DC	n/a	RDM

(b) Triaxial shear test

Biopolymers	PC	KG	CA	CH	WT	SU	XG	BG	GG	GE	AG	SA	GL	XG
Biopolymer concentration (%)	0	1, 2	1, 2, 5	1, 2, 5	1, 2	1, 2	1	1	1	1	1	1	1	0, 1
Confining pressure (kPa)	30, 100, 200, 300, 400						100, 200, 300, 400							30, 100, 200, 300, 400
Water content (%)	30													
Curing time (days)	28													0, 21, 42, 70
Curing temperature	Wrapped with plastic film at room temperature													Room condition

4.1.3 Experimental programme

The materials testing methods (e.g. unconfined compression test and triaxial shear test) are described as follows.

1) Unconfined compressive tests are performed by using Zwick/Roell Testing Machine device. The axial strain rate is controlled at 1.5%/min in accordance with ASTM D2166 (2016) until the strength decreased to 80% of maximum unconfined compressive strength. The maximum unconfined compressive strength can be obtained by tracing the automatically displayed stress-strain behaviours. Three different measurements for each condition are performed to calculate the average of their maximum strengths.

2) A series of triaxial shear tests of biopolymer treated kaolinite are carried out at a strain rate of 0.1mm/min with different confining pressures (30, 100, 200, 300

and 400 kPa) with unconsolidated undrained conditions (UU) (Lee et al. 2019c). Test samples were mounted on the bottom plate within a rubber membrane to isolate them from the pressurized chamber fluid, and porous stones are placed above and below them.

4.2 Unconfined compression test results

4.2.1 Effect of biopolymer concentration on UCS

The initial water content of 30% and curing 28 days are selected as fixed values to investigate the influence of biopolymer concentration on UCS. As shown in Figure 4.2, the USC is 780, 938.1, 1455, 1825, 1867.4, 1936.5 and 2035 kPa for untreated clay, 0.5%, 1%, 2%, 3%, 4% and 5% XG treated clay, respectively, which corresponds the increment of 1.87, 1.25, 1.02, 1.04, 1.05 times, respectively, with the increment of each 1% XG content. The most effective amount of XG content appears to be approximately 1% and the strengthening efficiency tends to keep constant after 2% XG in the current condition. Moreover, although the higher XG concentration tends to retain higher moisture content at the same curing time, the moisture content of all XG treated samples is lower than 3% with curing 28 days.

XG can be directly bonded to clay particles and block the void spaces in the XG-soil matrix via cation bridging and hydrogen bonding to enable firm soil matrices with higher mechanical enhancement. Moreover, higher XG content renders higher compressive strength due to more XG-clay particle interactions along with stronger hydrogen bonding (Sujatha and Saisree 2019). However, the compressive strength would level off with the continuous increase of XG content because extra XG fails to form high stiffer clay-gum-water mixtures with limited water content. The highly viscous suspension fills the spaces between the soil particles, increasing the global volume of void spaces within the treated clay. Moreover, the electrostatic repulsion force among polymers and kaolinite particles reduces the effective stress on the kaolinite skeleton and results in failure might occur between organic coatings (polymer to polymer contacts) rather than the kaolinite-to-kaolinite contact (Latifi et al. 2017a).

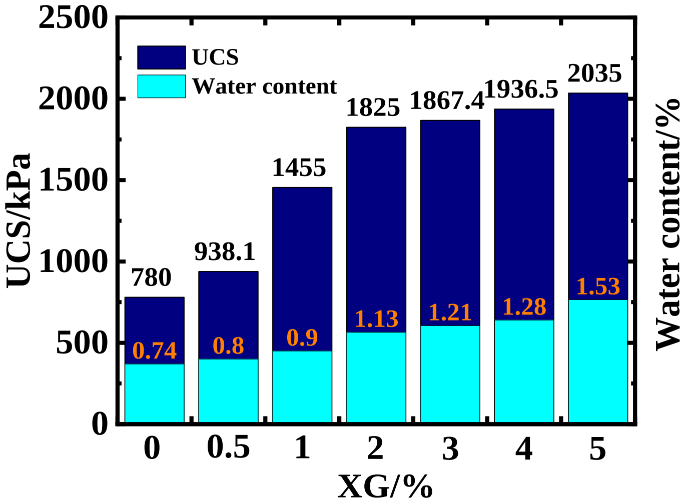


Figure 4.2 UCS of various XG concentrations treated clay

As shown in Figure 4.3, it illustrates the influence of biopolymer concentrations (e.g., 0, 1, 2 and 3%) on the UCS of other three biopolymers (e.g., GE, XG and SA) treated clay with the initial water content of 45% and different curing time. It can be observed that the final water content of biopolymer treated clay increases with the increase of biopolymer concentration, which is consistent with the previous findings that higher biopolymer concentrations tend to have higher water retention capacity. However, there is a little difference in final water content with the increase of biopolymer concentration, especially for curing long time under room-temperature conditions.

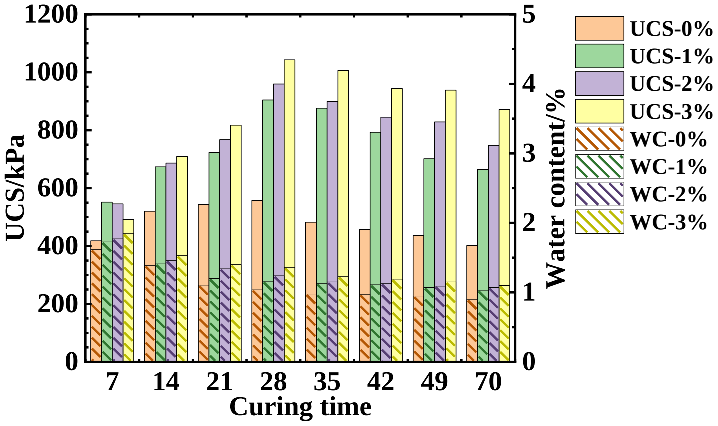
On the other hand, the UCS of biopolymer treated clay increases with the increase of biopolymer concentrations regardless of biopolymer types at the same curing time. It is more obvious under the curing long time, while a slight UCS decrease of GE treated clay from 551.8 kPa to 492.2 kPa can be observed with the increase of GE concentration from 1% and 2% at the short curing time (e.g., 7 days). Similarly, the UCS of 3% SA treated clay also decreases to 86.1 kPa and 1016.7 kPa at curing 0 and 5 days, respectively, compared to the UCS of 2% SA treated clay with 111.54 kPa and 1280.7 kPa, respectively. It can be explained that the biopolymer tends to be occurred in the form of gels in the soil-biopolymer matrices at higher biopolymer concentration with curing short time, causing that the strength cannot be entirely performed under this condition. Moreover, the biopolymer film with lower concentration can contact the soil particles to increase the UCS of soil-biopolymer matrices through physical interaction, hydrogen and ionic bonds even under curing short time. However, the UCS of biopolymer treated clay is larger than that of pure clay regardless of biopolymer concentration at the same curing time.

Figure 4.3 (a) illustrates that the UCS of GE treated clay obviously increases compared to pure clay, especially for 1%, which has the largest increment. To be specific, with the GE concentration increased to 1%, the UCS of SA treated clay increases from 418.2 to 551.8 kPa, from 520.3 to 673.4 kPa, from 543.7 to 723 kPa, from 557.6 to 904.4 kPa, from 482.6 to 875.9 kPa, 457.1 to 793 kPa, from 436.6 to 701.5 kPa, and from 401.5 to 664.7 kPa at the curing time 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. It corresponds to the increment of 32%, 29%, 33%, 62%, 81.5%, 73.5%, 60.7% and 65.6%, respectively. On the other hand, with the increase of GE concentration, the increment of UCS seems to be slowly. For example, with the increase of GE concentration from 1% to 3%, the UCS of GE treated clay slightly increases from 673.4 to 709 kPa, from 723 to 817.4 kPa, from 904.4 to 1042.9 kPa, from 875.9 to 1006.2 kPa, from 793 to 943.8 kPa, from 701.5 to 938.5 kPa, and from 664.7 to 871 kPa, respectively, at curing time 14, 21, 28, 35, 42, 49 and 70 days. It corresponds to the increment of 5.3%, 13%, 15.3%, 14.9%, 19%, 33.8%, and 31%, respectively, which is obviously less than that of UCS increment with the GE concentration increasing from 0 to 1%. Therefore, 1% GE concentration can be regarded as the optimum value to reinforce clay.

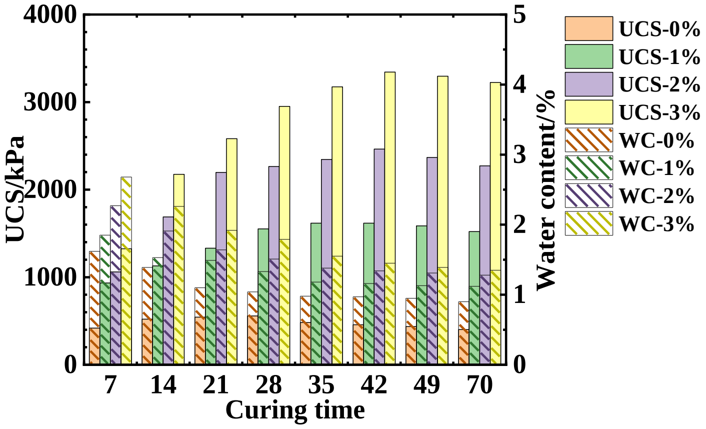
Figure 4.3 (b) illustrates the UCS of different XG concentrations treated clay at various curing times. It can be observed the obvious increase of UCS of XG treated clay compared to pure clay. Specifically, with the increase of XG concentration from 0 to 1%, the relevant UCS increases from 418.2 to 933.7 kPa, from 520.3 to 1129 kPa, from 543.7 to 1331.3 kPa, from 557.5 to 1552 kPa, from 482.6 to 1617.5 kPa, from 457.1 to 1617.4 kPa, from 436.6 to 1586.6 kPa, and from 401.5 to 1521.2 kPa at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. It corresponds to the increment value of 123%, 117%, 144.9%, 178.4%, 235%, 253.9%, 263.4% and 278.9%, respectively, compared to untreated clay. Although there is a significant increase of UCS to 1325.2, 2174.7, 2582, 2951, 3174, 3343.2, 3296, 3224.4 kPa at 3% XG treated clay with curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively, which corresponds to the increment value of 216.9%, 318%, 374.9%, 429.3%, 557.6%, 631.4%, 654.9%, 703.1%, respectively, compared to pure clay. Moreover, the UCS increment from 1% to 3% XG treated clay is 41.9%, 92.6%, 94%, 90.1%, 96.2%, 106.7%, 107.7% and 112%, respectively, which was significant less than the increment value of UCS from 0 to 1% XG treated clay. Therefore, the overall trend can be revealed that the increment degree decreases with the increase of XG concentration.

Figure 4.3 (c) illustrates the UCS of different SA concentrations treated clay with various curing times. At the initial condition, the UCS of samples is significantly smaller than that of curing long time due to the higher water content. And with the concentration increased from 0 to 0.5%, the UCS of SA treated soil increases from 15.7 to 40.4 kPa, from 329.1 to 502.7 kPa, from 520.3 to 648.3 kPa, from 543.7 to 739.8 kPa, from 557.6 to 849.5 kPa, from 482.6 to 724.1 kPa, from 457.1 to 719.5 kPa, from 436.6 to 705 kPa, and from 401.5 to 683.7 kPa, respectively, with curing 0, 5, 14, 21, 28, 35, 42, 49, 70 days. The corresponding increment values are 157.3%, 52.7%, 24.6%, 36.1%, 52.4%, 50%, 57.4%, 61.5% and 70.3%, respectively. It can be observed that although there is a significant increase of UCS under the lower SA concentration, the increment is relevant small because the lower SA concentration cannot fully reinforce the strength of the soil. However, with the SA concentration increasing to 1%, the UCS of SA treated clay significant increases to 70.7, 959.7, 1324, 1746.9, 2292.4, 2172.7, 1918.1, 1788.1, 1595.9 kPa with curing 0, 5, 14, 21, 28, 35, 42, 49, 70 days, respectively. The corresponding UCS increment values are 3.5, 1.9, 1.5, 2.2, 3.1, 3.5, 3.2, 3.1 and 3 times that of pure clay, respectively. It can be illustrated that 1% SA can fully contact soil particles through physical interaction, hydrogen and ionic bonds to cause the obvious increase of UCS along with more than 3 times, especially for curing more than 28 days. In addition, with the SA concentration increasing to 2%, the UCS significant increases to 111.54, 1280.7, 2653.5, 3549.1, 3776.9, 3723, 3549.1, 3175.7 and 2992.9 kPa with curing 0, 5, 14, 21, 28, 35, 42, 49, 70 days, respectively. The corresponding increment values are 0.57, 0.33. 1.00. 1.03. 0.65, 0.71, 0.85, 0.78 and 0.88 times that of 1% SA treated clay. It reveals that 2% SA can still keep the stability increment of UCS with more about 0.8 times than that of 1% SA treated clay. However, with the increase of SA concentration to 3%, there is limited changeable of UCS to 86.1, 1016.7, 3605.2, 4234.9, 4911.5, 4532.9, 3787.1, 3596.9 and 3238.2 kPa, respectively, with curing 0, 5, 14, 21, 28, 35, 42, 49, 70 days, respectively. Compared to the UCS of 2% SA treated clay, the corresponding increment values are -22.8, -20.6, 35.9, 19.3, 30, 21.8, 6.7, 13.3 and 8.2%, respectively. On the other hand, it can also observed that the UCS increment values from 2% to 3% SA concentration are considerable compared to the UCS of pure clay. For example, the increment value of UCS from 2% to 3% SA treated clay is 1134.6 kPa at curing 28 days, which is more 2 times than the UCS of pure clay. Overall, the optimum SA concentration to reinforce clay under this condition can be regarded as 1%-2%.

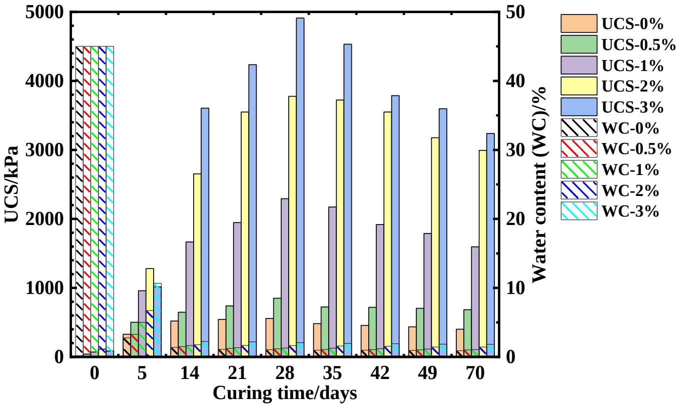
Throughout the test results of three biopolymers (e.g., GE, XG and SA) treated clay, it can be concluded that the UCS of biopolymer treated clay increases with the increase of biopolymer concentration, while the UCS increment ratio decreases with the increase of biopolymer concentration. And 1-2% can be regarded as the optimum biopolymer concentration to reinforce clay effectively and efficiency.



(a) GE



(b) XG



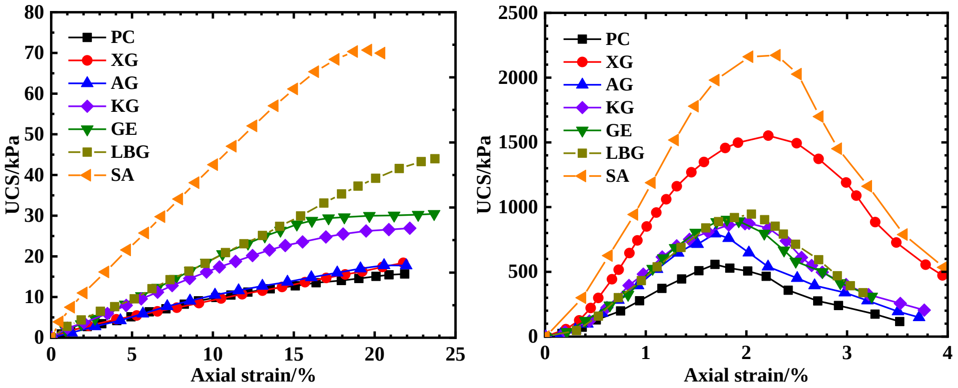
(c) SA

Figure 4.3 UCS of various biopolymer concentrations treated clay

4.2.2 Effect of biopolymer type on UCS

To illustrate the influence of biopolymer types on the strength of biopolymer treated clay, seven biopolymers (e.g., XG, AG, KG, GE, LBG and SA) with 1% concentration are selected. The stress-strain curves of these biopolymers treated clay with initial stage and curing 28 days are illustrated as shown in Figure 4.4. The strain-hardening can be observed for all conditions at the immediate stage because the maximum strength can be obtained at 20% strain and tends to keep stable after it. Due to the occurrence of biopolymer gel formed in soil-biopolymer matrices, some biopolymers cannot perform the reinforcement behaviours. For example, the UCS of XG and AG treated clay is 18.4 and 17.8 kPa, respectively, which is similar to the UCS of pure clay with 15.7 kPa. In addition, the UCS of KG, GE and LBG treated clay slightly increase to 26.9, 30.5 and 44 kPa, respectively, with the increment ratio of 71.3, 94.3 and 180.3%, respectively. Moreover, the highest strengthening biopolymer can be observed as SA, while the UCS significant increases UCS to 70.7 kPa with an increment ratio of 350.3%. On the other hand, the elastic modulus of XG and AG treated clay is similar to that of pure clay. In addition, the elastic modulus of KG, GE and LBG is similar to each other, larger than that of pure clay. Furthermore, the highest elastic modulus can be observed in SA treated clay. Overall, at the high water content condition (e.g., immediate stage), the highest efficiency reinforcement biopolymer is SA, and then LBG, GE, KG, following XG and AG as shown in Figure 4.4 (a).

The UCS of various biopolymer types treated clay with curing 28 days can be illustrated as shown in Figure 4.4 (b). The strain-softening can be observed for all conditions. Specifically, the maximum strength of pure clay can be obtained at 1.69% strain with 557.6 kPa. With the occurrence of biopolymer, the axial strain corresponding to the maximum strength normally increases to within 2.3% depending on the biopolymer types, which is much smaller than the immediate stage. Moreover, the elastic modulus of biopolymer treated clay is also larger than that of pure clay. Among these biopolymers, the SA treated clay shows the highest elastic modulus and then XG treated clay, while the other four biopolymers (e.g., AG, KG, GE and LBG) treated clay can be observed with the similar values of elastic modulus. In addition, the UCS of 1% XG, AG, KG, GE, LBG and SA treated clay with curing 28 days was 1552.1, 795.1, 874.1, 904.4, 945.9 and 2172.8 kPa, respectively, which corresponds to the UCS increment ratio with 178.4, 42.6, 56.8, 62.2, 69.6 and 289.7%, respectively, compared to untreated clay. It can be explained that the strengthening efficiency of biopolymer reinforced clay depends on the viscosity of biopolymer gel at the immediate stage. Furthermore, the connection form and bond strength attribute to the strength of biopolymer treated soil with curing long time. Meanwhile, the highest strengthening efficiency biopolymer at both hydrogen and dehydrogen conditions is SA.



(a) Immediate stage (b) Curing 28 days

Figure 4.4 Stress-strain curves of various biopolymers treated clay

For comparing the strengthening efficiency of various biopolymers treated clay, the UCS of six biopolymers treated clay with different curing time is illustrated in Figure 4.5. It can be observed that the biopolymer rank of strengthening efficiency is SA, XG, LBG, GE, KG and AG, respectively, after curing 7 days. Before curing 14 days, AG and KG treated clay show a slight increase of UCS from 418.3 to 433.6 and 440.2 kPa, respectively, at curing 7 days, from 520.3 to 541.5 and 572.4

kPa, at curing 14 days. However, SA and XG perform more strengthening efficiency under these conditions along with the UCS increasing to 1324.2 and 933.7 kPa, respectively, at curing 7 days, to 1665.3 and 1129 kPa, respectively, at curing 14 days. In addition, the UCS of other two biopolymers (e.g., LBG and GE) treated clay increases to 613 and 551.8 kPa, respectively, at curing 7 days, to 794.5 and 673.4 kPa, respectively, at curing 14 days. After 21 days, four biopolymers (e.g., AG, KG, GE and LBG) can be regarded as one group with a similar strengthening efficiency. To be specific, the UCS of AG, KG, GE and LBG treated clay increases from 543.7 to 742.8, 787.4, 875.9 and 945 kPa, respectively, at curing 21 days, which corresponds to the UCS increment ratio of 36.6, 44.8, 61.1 and 73.8%, respectively, compared to untreated clay. Normally, the increment ratio of AG, KG, GE and LBG treated clay is in the range from 36.4 to 50.5%, from 47.7 to 63.2%, from 58.6 to 70.5%, and from 69.7 to 87.1%, respectively. Overall, the UCS increment ratio of these four biopolymers treated clay is less than 90%. In terms of XG treated clay, it can be illustrated that the UCS increases to 1331.3, 1552, 1624, 1617.4, 1586.6 and 1521.2 kPa, respectively, which corresponds to the increment ratio of 144.9, 178.4, 236.5, 253.9, 263.4 and 278.9%, respectively, at curing 21, 28, 35, 42, 49 and 70 days, compared to untreated soil at the same curing time. In addition, the UCS of SA treated clay increases to 1946.9, 2292.4, 2172.7, 1998.1, 1888.1 and 1746.9 kPa, respectively, at curing 21, 28, 35, 42, 49 and 70 days, which corresponds to the increment ratio of 258.1, 311.2, 350.2, 337.2, 332.5 and 335.1%, respectively, compared to untreated soil at the same curing time.

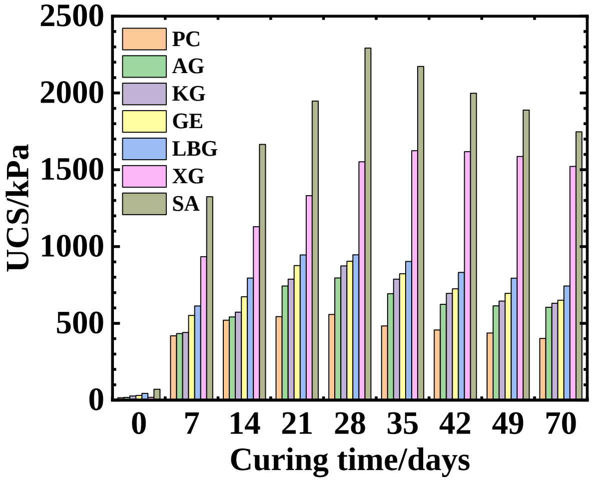
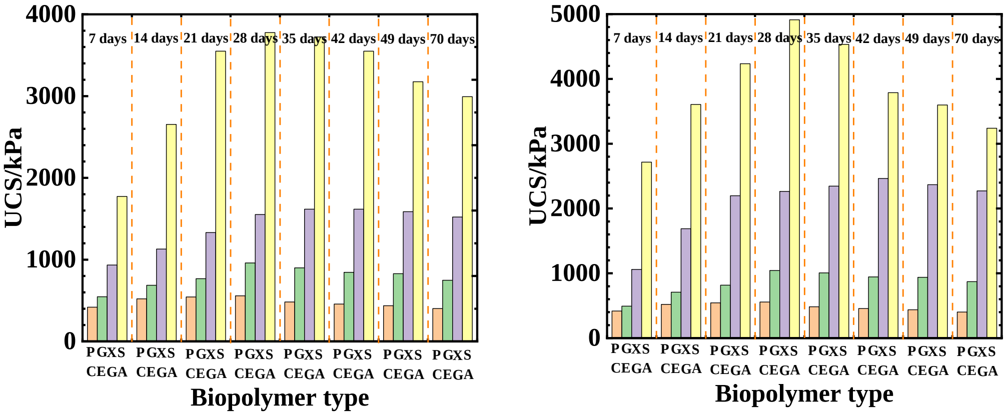


Figure 4.5 UCS of 1% various biopolymers treated clay

For comparing the UCS increment of different biopolymers treated clay, selecting GE, XG and SA as the typical biopolymers, the biopolymer concentration continuously increases to 2 and 3%, and the UCS results of three biopolymers treated clay are shown in Figure 4.6. In terms of 1% concentration, the UCS increment ratio of SA treated clay compared to XG treated clay is 41.8, 47.5, 46.2, 47.7, 33.8, 23.5, 19 and 14.8%, respectively, at curing 7, 14, 21, 28, 35, 42, 49 and 70 days. With the concentration increasing to 2%, the corresponding UCS increment ratio increases to 89.9, 135, 166.6, 143.4, 130.2, 119.4, 100.2 and 96.7%, respectively, while it decreases again to 156.1, 113.6, 92.8, 117, 93.3, 53.7, 51.9 and 42.6%, respectively, with the concentration increasing to 3%. On the other hand, compared to GE treated clay, the UCS of XG treated clay increases by 69.2, 67.7, 52, 71.6, 97.3, 123.2, 128.4 and 133.7%, respectively, at curing 7, 14, 21, 28, 35, 42, 49 and 70 days. With the concentration increasing to 2%, the increment ratio remains constant with 71, 64.4, 73.5, 61.8, 79.8, 91.4, 91.5 and 103.4%, respectively. And it significantly increases to 115.4, 138.1, 168.7, 117, 133.1, 161, 152.3 and 160.8%, respectively, under the condition of 3% biopolymer concentration treated clay.



(a) 2%

(b) 3%

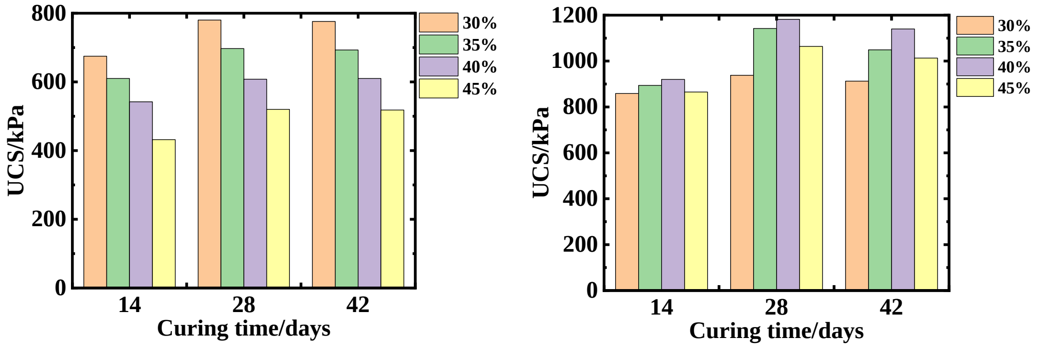
Figure 4.6 UCS of 2% and 3% various biopolymers treated clay

4.2.3 Effect of initial moisture content on UCS

4.2.3.1 XG treated clay

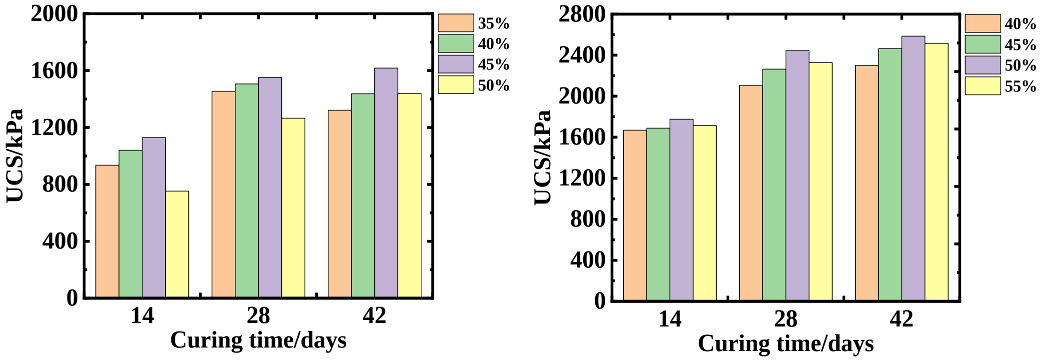
Figure 4.7 illustrates the unconfined compressive strength of untreated clay and biopolymer treated clay (e.g., 0.5, 1, 2 and 3%) with curing 14, 28 and 42 days and different initial moisture contents. In terms of untreated clay samples, the compressive strength decreases with the increase of initial water content regardless of curing time because there is no additional material added to the soil and the dry density contributes to the strength value of untreated clay. For example, the compressive strength gradually almost linear decreases from 675 kPa to 432 kPa, from 780 to 520 kPa, and from 776 to 518 kPa with the increase of initial water content from 30% to 50% at curing 14, 28 and 42 days, respectively.

For 0.5% XG treated soil, it can be observed that the UCS increases firstly and then decreases with the increase of initial water content. Specifically, the UCS increases from 858.6 to 920 kPa with the initial water content increasing from 30% to 35% at curing 14 days, and then the UCS decreases to 865 kPa with the initial water content of 45%. Moreover, the UCS increases from 938.1 to 1182 kPa, from 912.4 to 1140 kPa with the initial water content increasing from 30% to 40% at curing 28 and 42 days, respectively. And then, the UCS decreased to 1064 and 1013 kPa at curing 28 and 42 days, respectively. It shows that the optimum water content can be regarded as 40% to reach the maximum UCS.



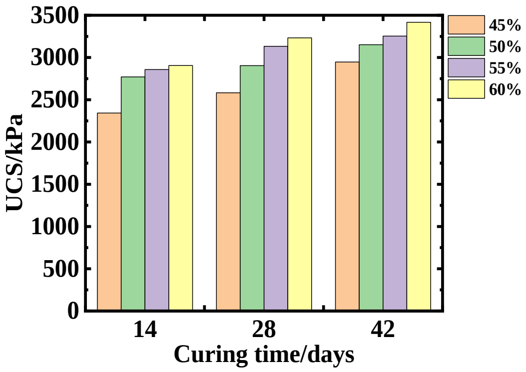
(a) untreated clay

(b) 0.5% XG treated clay



(c) 1% XG treated clay

(d) 2% XG treated clay



(e) 3% XG treated clay

Figure 4.7 UCS of XG treated clay with different initial moisture content

In terms of 1% XG treated clay, it also shows that the UCS increases firstly and then decreases with the increase of initial water content. To be specific, the UCS almost linear increases from 935 to 1129 kPa, from 1455 to 1552 kPa, and from 1321 to 1617.4 kPa with the initial water content increasing from 35% to 45% at curing 14, 28 and 42 days, respectively. And then, the UCS decreases to 753, 1265 and 1440 kPa with the initial water content of 50% at curing 14, 28 and 42 days, respectively. It can be observed that the lowest UCS reaches at curing 14 days and the initial water content of 50%. It can be explained that the higher initial water content typically tends to cost a long time for reaching the final balance water content. Moreover, the higher initial water content also leads to a lower dry density causing weak strength. In addition, it can conclude that the optimum water content is 45% to reach the maximum UCS.

Similarly, the UCS of 2% XG treated clay increases firstly and then decreases with the increase of initial water content. The value almost linear increases from 1668.3 to 1775 kPa, from 2106.4 to 2443.8 kPa, from 2298.8 to 2585.2 kPa with the increase of initial water content from 40% to 50% at curing 14, 28 and 42 days. And then, the UCS of 2% XG treated clay with the initial water content of 55% slight decreases to 1713.3, 2327.4 and 2515.9 kPa at curing 14, 28 and 42 days. It can conclude that the optimum initial moisture content is 50% to reach the maximum strength of 2% XG treated clay. In addition, under this condition, the UCS also increases with the increase of curing time regardless of initial moisture content.

For 3% XG treated clay, it can be illustrated that the UCS increases with the increase of initial moisture content. At a short curing time (e.g. 14 days), the UCS increases from 2343.2 to 2770.2 kPa with the initial water content increasing from 45% to 50%.

And then, with the initial water content continuous increasing to 60%, the UCS only margin increases to 2904.7 kPa. It can be explained that the higher water content can cause the XG to form the mixture gel in the biopolymer-soil matrices and tend to connect more soil particles. On the other hand, the higher initial water content tends to cause a lower dry density and usually costs more curing time to reach the high strength. Obviously, the short curing time is not enough to form biopolymer film for reaching the maximum strength. Therefore, the increment ratio decreases with the increase of initial water content at curing 14 days. With the increase of curing time, the increment ratio of UCS tends to increase. At curing 28 days, the USC of 3% XG treated clay is 2582, 2904, 3132.4 and 3233.2 kPa with the initial water content of 45%, 50%, 55% and 60%, respectively. Moreover, the UCS almost linear increases from 2946.9 to 3417.2 kPa with the initial water content increasing from 45% to 60% at curing 42 days. Therefore, the optimum initial moisture content is 60% to reach the maximum strength. However, it should also be noted that the highest initial water content is 60% in the preparation stage because the soil-biopolymer mixture is like the fluid status and the samples cannot be made in the moulds with an initial water content of more than 60%. In addition, under this condition, the UCS also increases with the increase of curing time regardless of initial moisture content.

Overall, the optimum initial moisture content reaching the maximum UCS of XG treated clay increases with the increase of XG concentration. There needs higher initial moisture content to obtain the complete gel solution, improving the performance of hydrogen and ionic bonding between biopolymer and fine particles with the increase of biopolymer concentration. In this study, the ideal initial moisture content corresponding to the maximum UCS of 0.5%, 1%, 2% and 3% XG treated clay was 40%, 45%, 50% and 60%, respectively, which was 1.3, 1.46, 1.67 and 2 times the optimum water content of untreated clay (30%) achieved maximum dry density. After the ideal moisture content, the UCS values decrease except for 3% XG due to the limitation of experimental tests. Moreover, it also reveals that the higher initial water content costs a long time to reach fully dried condition. For example, the UCS of 1% treated clay with the initial moisture content of 50% still increases even for samples curing 42 days.

Figure 4.8 illustrates the effectiveness of XG in enhancing soil strength at the ideal initial moisture content with different curing times. At curing 14 days, it can be illustrated that the maximum UCS is 675, 920, 1129, 1775 and 2904.7 kPa at the ideal initial moisture content and curing time with the XG concentrations of 0, 0.5, 1, 2 and 3%, respectively. It corresponds to the increment ratio of XG treated clay with 36.3, 67.3, 163 and 330.3%, respectively, compared to untreated clay. At curing 28 days, the maximum UCS is 780, 1182, 1552, 2443.8 and 3233.2 kPa at the ideal initial moisture content and curing time with the XG concentrations of 0, 0.5, 1, 2 and 3%, respectively. It corresponds to the increment ratio of XG treated clay with 51.5, 99, 213.3 and 314.5%, respectively, compared to untreated clay. With the curing time increasing to 42 days, the maximum UCS was 776, 1140, 1617.4, 2585.2 and 3417.2 kPa with XG treated clay at 0, 0.5, 1, 2 and 3%, respectively. Moreover, the UCS increment ratio of XG treated clay compared to untreated clay is 46.9, 108.4, 233.1 and 340.4%, respectively. Therefore, it can be found that there was a rough relationship between XG concentration (C_{XG}) and the UCS increment ratio (IR_{UCS}) regardless of curing time as shown in Eq. (4.1).

$$IR_{\mathrm{UCS}} = 100\ C_{\mathrm{XG}} \tag{4.1}$$

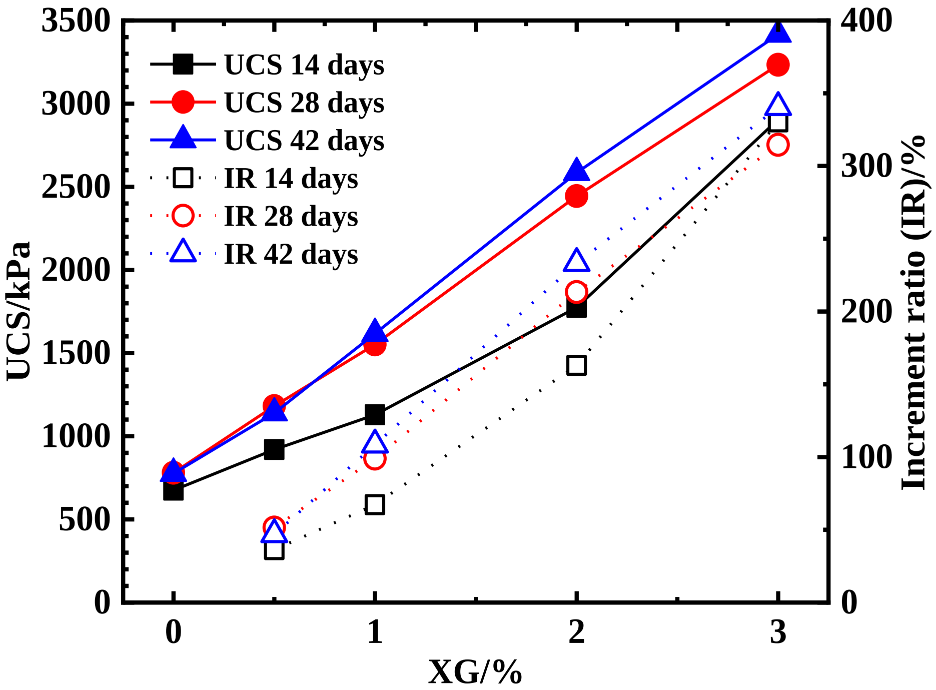


Figure 4.8 UCS and its increment ratio of XG treated clay with ideal initial moisture content and curing time

4.2.3.2 SA treated clay

Figure 4.9 illustrates the UCS of different SA concentrations (e.g., 0.5, 1, 2 and 3) treated clay with different initial moisture content at curing 14, 28 and 42 days. In terms of untreated clay, the change of UCS with the increase of initial moisture content has been illustrated in section 4.2.3.1. In terms of 0.5% SA treated clay, it can be found that the UCS increases with the increase of initial moisture content. Specifically, the UCS increases from 675.9 to 894.2 kPa, from 775.9 to 1227.6 kPa, from 716.4 to 1150.3 kPa, and from 705.7 to 964.8 kPa with the initial moisture content increased from 40% to 55% at curing 14, 28, 42 and 49 days, respectively. In addition, it can be observed that the UCS has a slight increase with the initial moisture content increased from 40% to 50% regardless of curing time, while a significant increase of UCS can be found with the initial moisture content increased from 50% to 55%. For example, with the initial water content increasing from 40% to 50%, the UCS increment ratio is 14.2, 24.1, 19.7 and 4.8% at curing 14, 28, 42 and 49 days, respectively. Correspondingly, the UCS increment ratio is 15.8%, 27.5%, 34.1% and 30.5%, respectively. Moreover, the maximum strength of 0.5% SA treated clay can be achieved at the initial moisture content of 55%. Moreover, the UCS under this condition is significantly larger than that of 0.5% SA treated clay with other initial moisture content. However, the samples of 0.5% SA treated clay with an initial water content of more than 55% cannot be made because the biopolymer-soil mixture under this condition is more like fluid status.

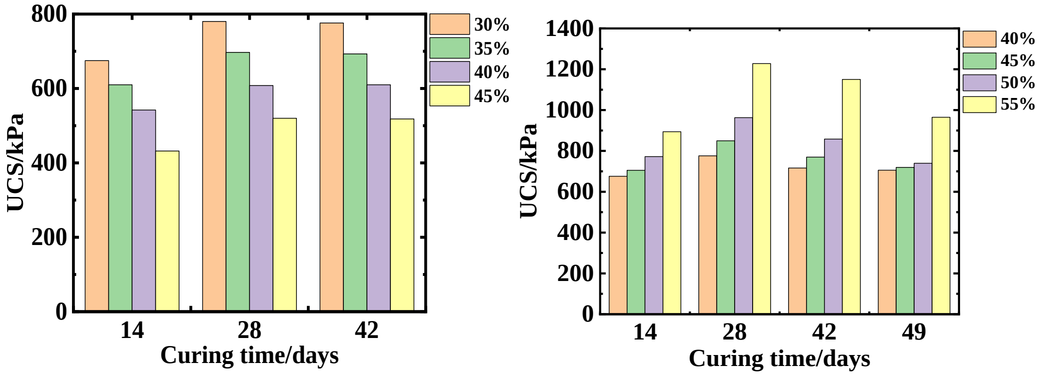
For 1% SA treated clay, the UCS increases firstly and then decreases with the increase of initial water content. To be specific, the UCS significant increases from 1544.4 to 2460.2 kPa, from 1901.1 to 3320.6 kPa, from 1877.8 to 2885.9 kPa, and from 1689.7 to 2852.4 kPa with the initial moisture content increased from 40% to 50% at curing 14, 28, 42 and 49 days, respectively. And then, the UCS obvious decreases to 1762.8, 2545.6, 1979 and 1922.4 kPa with the initial water content of 55% at curing 14, 28, 42 and 49 days, respectively. In addition, there is a limited UCS increase with the initial moisture content increasing from 40% to 45%. It can conclude that the optimum initial moisture content is 50% to reach the maximum UCS. Moreover, the corresponding UCS under this condition is significantly larger than that of 1% SA treated clay with other initial moisture content.

In terms of 2% SA treated clay, the UCS almost linear increases with the increase of initial moisture content. Specifically, the UCS increases from 2042 to 4751.3 kPa, from 2566.5 to 5405.6 kPa, from 2188.5 to 5328.1 kPa, from 1944.5 to 5072.3 kPa with the initial moisture content increased from 40% to 55% at curing 14, 28, 42 and 49 days, respectively. It can be observed that the UCS difference of 2% SA treated clay between each initial water content is obvious, which was different from other SA concentrations. The optimum moisture content of 2% SA treated clay is 55% to reach the maximum strength. However, the maximum UCS increment is at the initial water content of 50%, which is more 40% than that of the initial water content of 45% for all curing time.

For 3% SA treated clay, the UCS increases firstly and then decreases with the increase of initial water content. Specifically, with the initial water content increasing from 40% to 50%, the UCS increases from 3376.5 to 3840 kPa, from 4324.7 to 5538.9 kPa, from 3761.4 to 4915.4 kPa and from 3590.7 to 4703.4 kPa at curing 14, 28, 42 and 49 days, respectively. However, with the initial water content continuous increasing to 55%, the UCS decreases from 3840 to 3330.2 kPa, from 5538.9 to 4535.4 kPa, from 4915.4 to 4323.1 kPa, and from 4703.4 to 4104 kPa at curing 14, 28, 42 and 49 days, respectively. It can be observed that the optimum water content is 50% to reach the maximum UCS under this condition. In addition, with the increase of initial water content, the UCS increment tends to be slow. The UCS of 3% SA treated clay at the initial water content of 45% is slightly less than that of the initial water content of 50%.

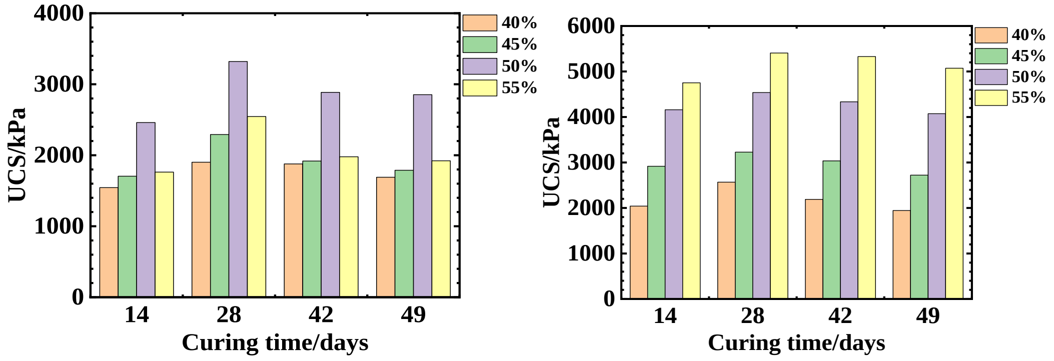
Overall, the optimum initial moisture content reaching the maximum UCS of SA treated clay is about 50% (e.g., 1% and 3%) or 55% (e.g., 0.5% and 2%). It illustrates that the stable SA gel is formed in a fixed initial moisture content (e.g., 50-55%) to strengthen the clay through hydrogen and ionic bonding regardless of SA concentrations. In the current study, the difference between the ideal initial moisture content corresponding to the maximum UCS and other initial moisture content corresponding to the UCS is relatively large. However, it decreases with the increase of SA concentration. Moreover, it also reveals that higher initial water content does not need to cost more curing time to reach a fully dried condition in SA treated clay.

All initial water contents in SA treated clay reach the maximum UCS at curing 28 days, which is different from XG treated clay.



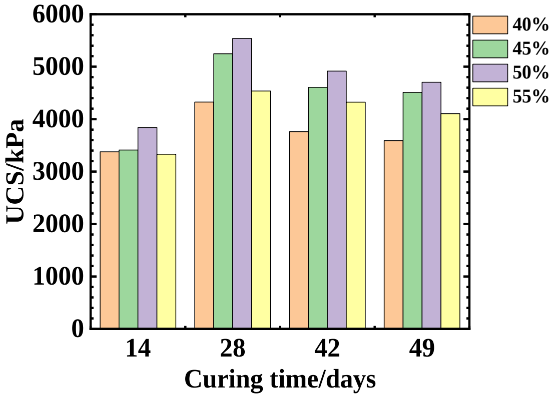
(a) untreated clay

(b) 0.5% SA treated clay



(c) 1% SA treated clay

(d) 2% SA treated clay



(e) 3% SA treated clay

Figure 4.9 UCS of SA treated clay with different initial moisture content

Figure 4.10 illustrates the effectiveness of SA in enhancing soil strength at the ideal initial moisture content with different curing times. At curing 14 days, it can be illustrated that the maximum UCS of SA treated clay at the ideal initial moisture content is 894.2, 2460.2, 4751.3 and 3840 kPa with the SA concentrations of 0.5, 1, 2 and 3%, respectively. Compared to untreated clay, the increment ratio is 32.5, 264.5, 603.9 and 468.9%, respectively. At curing 28 days, the maximum UCS of SA treated clay is 1227.6, 3320.6, 5405.6 and 5538.9 kPa with the SA concentrations of 0.5, 1, 2 and 3%, respectively. It corresponds to the increment ratio of 57.4, 325.7, 593 and 610.1%, respectively. With the curing time increasing to 42 days, the maximum UCS of SA treated clay is 1150.3, 2885.9, 5328.1 and 4915.4 kPa, respectively, with the SA concentrations of 0.5, 1, 2 and 3%, which is 0.48, 2.72, 5.87 and 5.33 times of untreated clay. At curing 49 days, the maximum UCS of SA treated clay is 964.8, 2852.4, 5072.3 and 4703.4 kPa, respectively, with the SA concentrations of 0.5, 1, 2 and 3%. It corresponds to the UCS increment ratio of 25.6, 271.4, 560.5 and 512.4%, respectively. It can be observed that the increment ratio of SA treated clay increases and then decreases with the increase of SA concentration. It can be found that there is a rough relationship between SA concentration (C_{SA}) and the UCS increment ratio (IR_{UCS}) regardless of curing time. The optimum SA concentration to strength and stabilize clay is 2%, and there is a limit UCS increment or even decrement of 3% SA treated clay compared to that of 2% SA. The phenomenon can also be found in the previous works of literature (Chang et al. 2015a, Ayeldeen et al. 2016, Latifi et al. 2018). It can be explained that the extra SA concentration has a limited effect on increasing the solution viscosity. In addition, the extra SA molecules tend to contact each other to form the SA cluster rather than biopolymer-soil matrices. Moreover, the ideal UCS of SA treated clay can be observed at curing 28 days regardless of SA concentrations. Therefore, the optimum performance of SA strengthen and stabilize clay is obtained in the ideal concentration (2%), ideal initial water content (50% or 55%) and ideal curing time (28 days).

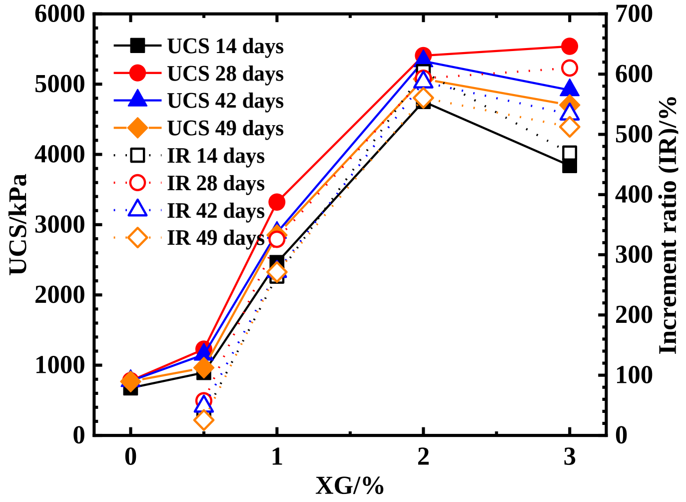
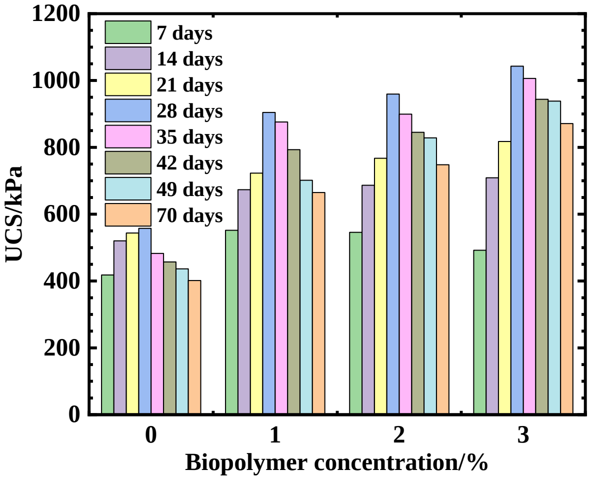


Figure 4.10 UCS and its increment ratio of SA treated clay with ideal initial moisture content and curing time

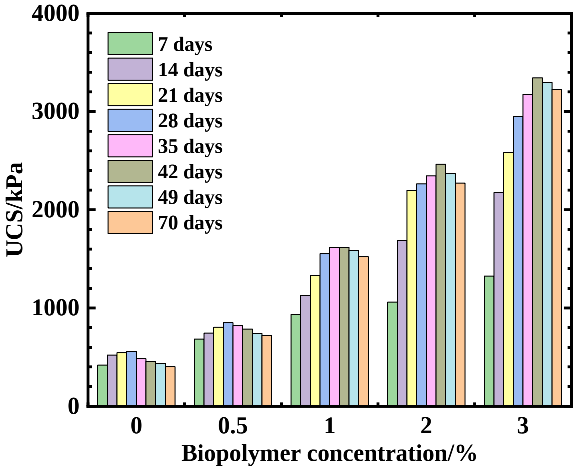
4.2.4 Effect of curing time on UCS

Three biopolymers (e.g., GE, XG and SA) treated clay with different concentrations (e.g., 0.5, 1, 2 and 3%) at an initial water content of 45% are selected to investigate the influence of curing time on its UCS. As shown in Figure 4.11, the UCS of biopolymer treated clay increases firstly and then decreases with the increase of curing time regardless of biopolymer types and concentrations. Specifically, the UCS of untreated clay increases from 418.2 kPa at curing 7 days to 557.55 kPa at curing 28 days with the decrease of UCS increment. And then the UCS obviously decreases to 482.64 kPa at curing 35 days following a slight decrease to 401.5 kPa at curing 70 days. In terms of GE treated clay, the UCS almost linear increases from 551.8 kPa, 545.8 kPa and 492.2 kPa at curing 7 days to 904.4 kPa, 959.4 kPa and 1042.9 kPa at curing 28 days with 1%, 2% and 3% concentrations, respectively. And then, the UCS almost linear decreases to 664.7 kPa, 747.8 kPa and 871 kPa at curing 70 days. Moreover, the UCS of XG treated clay has a slow increase with the increase of curing time regardless of XG concentrations. At 0.5% concentration, the UCS increases from 683.7 kPa at curing 7 days to 849.5 kPa at curing 28 days. And then, the UCS slightly linear decreases to 719.5 kPa at curing 70 days. In addition, the maximum UCS of 1% XG treated clay is obtained at curing 35 days with 1617.46 kPa, and the UCS slightly decreases to 1521.2 kPa at curing 70 days. However, the UCS of XG treated clay increases from 1060.1 kPa and 1325.2 kPa at curing 7 days to 2463.3 kPa and 3343.2 kPa at curing 42 days with 2% and 3% concentrations, respectively. Moreover, the UCS almost linear decreases to 2271.4 kPa and 3224.4 kPa, respectively. For SA treated clay, it can be observed that the UCS sharply increases from 40.4 kPa, 70.7 kPa, 111.54 kPa and 86.1 kPa at curing 0 days to 648.3 kPa, 1324.2 kPa, 2653.5 kPa and 3605.2 kPa at curing 14 days, respectively. In addition, the UCS increment decreases with the continuous increase of curing time. The maximum UCS of 0.5%, 1%, 2% and 3% SA treated is obtained at curing 28 days with 849.5 kPa, 2292.4 kPa, 3776.9 kPa and 4911.5 kPa, respectively. Additional, the UCS decreases to 683.7 kPa, 1595.9 kPa, 2992.9 kPa and 3238.2 kPa, respectively, at curing 70 days.

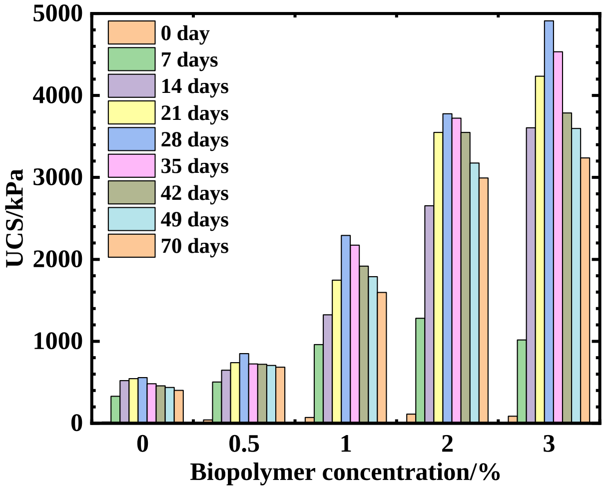
In terms of the above description, it can be explained that the fluid property still plays a prominent role compared to its adhesive bonding property of biopolymer hydrogel, and the biopolymer solution is a weak gel with a short curing time (e.g., 7 days). It means biopolymer gel-like properties still cannot be fully recognised causing easily to be broken. Therefore, biopolymer treated clay and untreated clay with the same initial water contents demonstrates a slight variation. With the increase of curing time, it can be observed that the outer part of the sample is exposed to air-dry conditions showing crystallisation and cement effect of biopolymer quickly. A significant increase in compressive strength can be observed in the first 28 days. As the water content in samples after curing 28 days is similar, the variation of the specimen's compressive strength is attributed to the dehydration of condensed biopolymers solution, especially in the inner part of the sample. Therefore, it is expected to continue slightly increasing UCS until curing 42 days at 2% and 3% XG concentrations. With the increase of biopolymer content in XG treated clay, it is expected to require more curing time to reach the maximum compressive strength, while the UCS of GE and SA treated clay obtains the maximum value at curing 28 days regardless of biopolymer concentrations. However, according to the gel property, the biopolymers gel shrank will finally form a thin film and become brittle with complete water evaporation, especially for the outer part of XG treated clay. It may lead to a change of biopolymer performances in the clay particle. It can be shown that the UCS of biopolymer treated clay slightly decreases at curing long time (e.g., >49 days).



(a) GE



(b) XG



(c) SA

Figure 4.11 UCS of biopolymers treated clay with different curing time

The UCS and increment ratio of biopolymer treated clay with ideal curing time and long curing time (e.g., 70 days) at an initial water content of 45% can be illustrated in Figure 4.12. It shows that the UCS of biopolymer treated clay decreases at curing a long time, while the increment ratio of biopolymer treated clay increases. Specifically, with the curing time increasing from ideal status to 70 days, the UCS of GE treated clay decreases from 904.4 kPa to 664.7 kPa, from 959.4 kPa to 747.8 kPa, from 1042.9 kPa to 871 kPa at 1%, 2% and 3% GE concentrations, respectively. And the decrement ratio is 26.5%, 22.1% and 16.5%, respectively. Correspondingly, the UCS of XG treated clay decreases from 949.5 kPa to 719.5 kPa, from 1617.46 kPa to 1521.2 kPa, from 2463.3 kPa to 2271.4 kPa, from 3343.2 kPa to 3224.4 kPa at 0.5%, 1%, 2% and 3% XG concentrations, respectively. Moreover, the decrement ratio is 24.2%, 5.95%, 7.79% and 3.55%, respectively. Moreover, the UCS of SA treated clay decreases from

1449.5 kPa to 883.7 kPa, from 2292.4 kPa to 1595.9 kPa, from 3776.9 kPa to 2992.9 kPa, from 4911.5 kPa to 3738.2 kPa at 0.5%, 1%, 2% and 3% SA concentrations, respectively. And its decrement ratio is 39.03%, 30.38%, 20.76% and 23.89%, respectively. It also illustrates that the UCS decrement ratio of biopolymer treated clay at curing a long time decreases with the increase of biopolymer concentration. Furthermore, the XG tends to have the smallest UCS decrease due to the stability of the XG gel. However, with the curing time increasing from ideal status to 70 days, compared to untreated clay, the UCS increment ratio of GE treated clay slightly increases from 62.21% to 65.55%, from 72.07% to 86.25%, from 87.05% to 116.9% at 1%, 2% and 3% GE concentrations, respectively. And the UCS increment ratio of XG treated clay obviously increases from 70.3% to 79.2%, from 190.1% to 278.9%, from 341.8% to 465.7%, and from 499.6% to 703.1% at 0.5%, 1%, 2% and 3% XG concentrations, respectively. Meanwhile, the UCS increment ratio of SA concentration also almost keeps constant with the values changing from 159.98% to 120.1%, from 311.16% to 297.48%, from 577.41% to 645.43%, from 780.9% to 831.1% at 0.5%, 1%, 2% and 3% SA concentrations, respectively. It can be illustrated that the reinforced performance of biopolymer treated clay cannot decrease and even can be continuous increase at curing a long time, especially for XG.

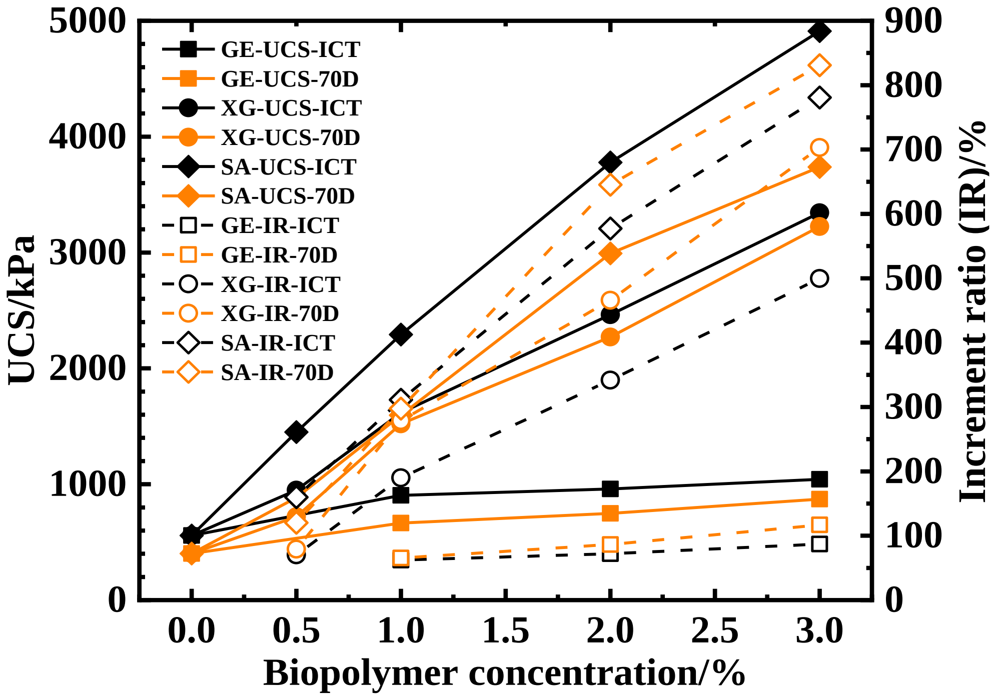


Figure 4.12 UCS and its increment ratio of biopolymers treated clay with ideal conditions

4.2.5 Effect of durability on UCS

To illustrate the durability of biopolymer treated clay, the samples are still cured at room temperature until 378 days (54 weeks). Figure 4.13 illustrates the UCS of XG treated clay and untreated clay with different initial water contents and XG concentrations at curing 378 days. It shows that the UCS of XG treated clay at an initial water content of 30% decreases from 784.6 kPa to 646.4 kPa, from 1046.1 kPa to 923 kPa, from 1401.6 kPa to 1039.3 kPa, and from 1825 kPa to 1696.4 kPa at 0% (untreated clay), 0.5%, 1% and 2% XG concentrations, respectively, with the curing time increasing from ideal status to 378 days. The UCS decrement ratio is 17.61%, 11.77%, 25.85% and 7.05%, respectively. At the same long curing time, the UCS of XG treated under this condition is about 1.43, 1.61 and 2.62 times that of untreated clay.

At an initial water content of 35%, the UCS decreases from 656.9 kPa to 600.6 kPa, from 1103.9 kPa to 1045.8 kPa, from 1476.7 kPa to 1203.6 kPa, from 2053.8 kPa to 1869.3 kPa at 0% (untreated clay), 0.5%, 1% and 2% XG concentrations, respectively, with the curing time increasing from ideal status to 378 days. The UCS decrement ratio is 8.57%, 5.26%, 18.49% and 8.98%, respectively. Under this condition, the UCS of XG treated clay with curing 378 days is 1.74, 2.0 and 3.11 times that of untreated clay at 0.5%, 1% and 2% XG concentrations, respectively.

At an initial water content of 40%, the UCS of XG treated clay decreases from 553.5 kPa to 497.5 kPa, from 1240.6 kPa to 1187.9 kPa, from 1682.8 kPa to 1375.5 kPa, from 2298.8 kPa to 2141.9 kPa at 0% (untreated clay), 0.5%, 1% and 2% XG concentrations, respectively, with the curing time increasing from ideal status to 378 days. The UCS decrement ratio is 10.12%, 4.25%, 18.26% and 6.83%, respectively. In this case, the UCS of XG treated clay with curing 378 days is 2.39, 2.76 and 4.31 times that of untreated clay at 0.5%, 1% and 2% XG concentrations, respectively.

At an initial water content of 45%, the UCS of XG treated clay decreases from 488 kPa to 385.1 kPa, from 1143 kPa to 981.9 kPa, from 1806.3 kPa to 1551.5 kPa, from 2463.3 kPa to 2190 kPa at 0% (untreated clay), 0.5%, 1% and 2% XG concentrations, respectively, with the curing time increasing from ideal status to 378 days. The UCS decrement ratio is 21.09%, 14.09%, 14.11% and 11.09%, respectively. Under this condition, the UCS of XG treated clay with curing 378 days is 2.55, 4.03 and 5.69 times that of untreated clay at 0.5%, 1% and 2% XG concentrations, respectively.

At an initial water content of 50%, the UCS of XG treated clay decreases from 435.9 kPa to 326.2 kPa, from 1113.6 kPa to 889.7 kPa, from 1609.4 kPa to 1218.8 kPa, from 2585.2 kPa to 2202.4 kPa at 0% (untreated clay), 0.5%, 1% and 2% XG concentrations, respectively, with the curing time increasing from ideal status to 378 days. The UCS decrement ratio is 25.17%, 20.1%, 24.27% and 14.81%, respectively. Under this condition, the UCS of XG treated clay with curing 378 days is 2.73, 3.74 and 6.75 times that of untreated clay at 0.5%, 1% and 2% XG concentrations, respectively.

Therefore, it can be shown that the XG can still have good durability in reinforcement and stabilization clay. Moreover, the most UCS decrement ratio of XG treated clay is about 25%, and the minor decrement ratio is only about 7%. Especially for higher initial water content, the XG treated clay tends to obtain a higher UCS, while the UCS of untreated clay significantly decreases. Importantly, the UCS increment ratio of XG treated clay at curing 378 days compared to untreated soil increases with the increase of initial water content.

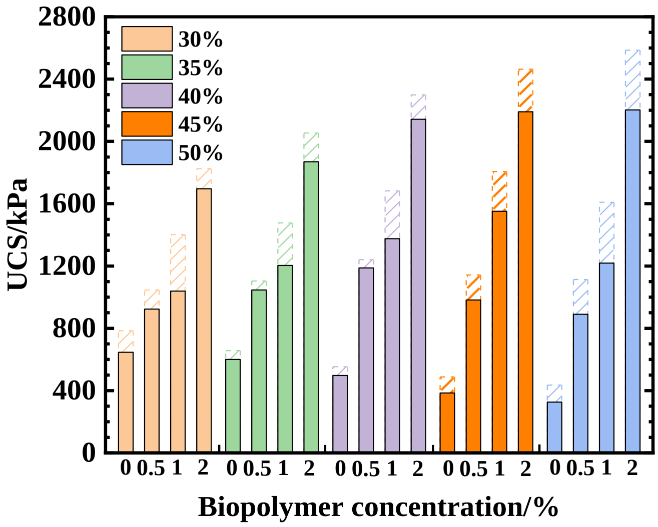


Figure 4.13 UCS of XG treated clay with curing 378 days

As shown in Figure 4.14, the durability of biopolymer treated clay under different conditions (e.g., mixing method, biopolymer type, biopolymer concentration and initial water content) is illustrated. It shows that the UCS of biopolymer treated clay decreases with the long curing time regardless of conditions. The decrement ratio is about in the range of 11.1-26.7%. However, the UCS of biopolymer treated clay is still significantly larger than that of untreated clay, which is in the range of 1.67-7.83 times. Specifically, at an initial water content of 40%, the UCS of XG and SA treated clay only decrease by about 13.2% and 11.3%, while the UCS of XG and SA treated clay is more 4 times than that of untreated clay. At an initial water content of 45%, the UCS of XG and SA treated clay are more 5.5 times than that of untreated clay. In addition, the UCS of 1% XG treated clay under the hot water-dry mixing method and 1% KG treated clay under the hot water-wet mixing method is about 3.9 and 2.6 times of untreated clay, respectively. Moreover, the 1% AG treated clay under hot water-wet mixing method and 1% GE treated clay under room temperature water-wet mixing method tends to have weak performance. Their UCS is only 1.95 and 1.67 times that of untreated clay. At an initial water content of 50%, the 1% SA and 2% XG under room temperature water-dry mixing method has the best durability on reinforcement clay that the UCS of them are 7.83 and 6.54 times that of untreated clay.

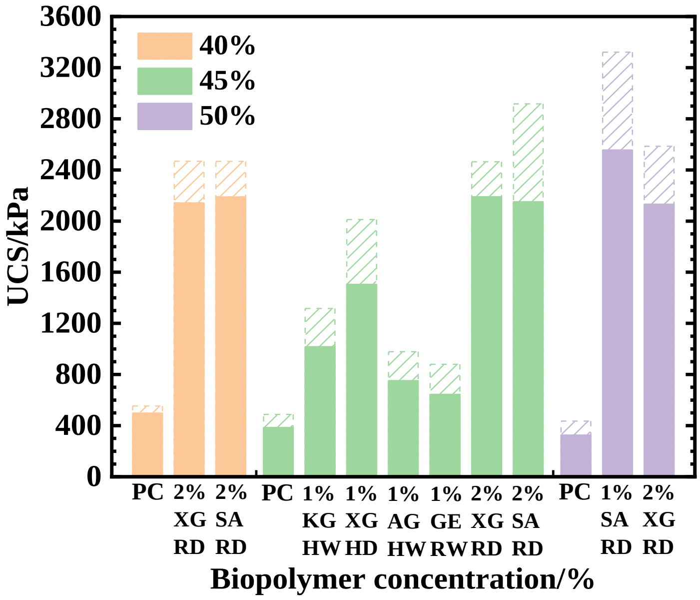


Figure 4.14 UCS of biopolymers treated clay with curing 378 days

Figure 4.15 illustrates the UCS of 1% XG treated clay at an initial water content of 45% with different rewetting-drying cycles. It should be noted that the untreated clay samples are broken and crushed when soaking in water for more than 2 hours. The untreated clay cannot undertake even one rewetting-drying cycle. Therefore, the UCS of untreated clay under rewetting-drying can be ignored. In terms of XG treated clay, the UCS was 1552 kPa, 1397.4 kPa, 1285.9 kPa and 1197.7 kPa with the rewetting-drying cycles of 0, 1, 2 and 3, respectively. Compared to the highest UCS of XG treated clay without rewetting-drying, the decrement ratio was 9.96%, 17.15% and 22.83% with the rewetting-drying cycles of 1, 2 and 3, respectively. It can be shown that the decrement ratio decreases with the increase of rewetting-drying, and it tends to keep constant after certain rewetting-drying cycles. However, the UCS of XG treated clay after rewetting-drying cycles is still obviously larger than that of the highest UCS of untreated clay (curing 28 days), which is 2.51, 2.31 and 2.15 times with 1, 2 and 3 cycles of rewetting-drying, respectively. Therefore, the XG treated clay has excellent durability in undertaking climate change.

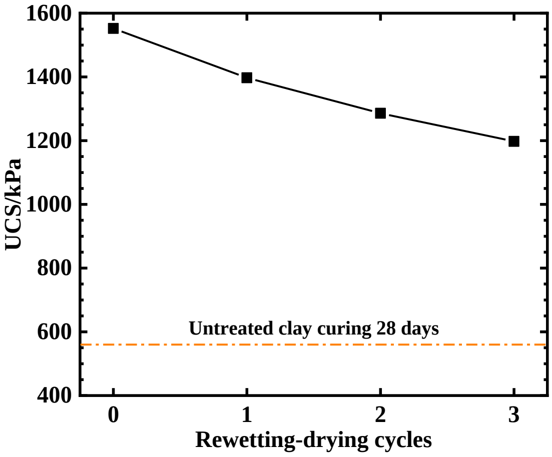


Figure 4.15 UCS of various XG concentrations treated clay

4.2.6 Effect of cross-linking on UCS

Cross-linking means that two types of biopolymer are mixed together and can be reacted in the process. For example, according to the description of production, xanthan gum can be added to agar gum and kappa carrageenan to form a more stable gel. Therefore, taking XG-AG, XG-KG and XG-LBG as examples, this part illustrates the UCS of biopolymer treated clay by considering cross-linking under different curing time. As shown in Figure 4.16, it shows that the UCS of XG-AG treated clay increases with the increase of XG content. Moreover, there is the threshold ratio value at XG-AG with 1:4, in which the UCS of XG-AG treated clay is significantly larger than that of other conditions when the ratio of XG-AG is higher than 1:4. Furthermore, the AG treated clay has the lowest UCS regardless of curing time. In addition, the most XG-AG treated clay obtains the highest UCS at curing 35 days, except for XG-AG with the ratio of 1:4. As mentioned before, the UCS of XG-AG treated clay decreases with the increase of curing time. Specifically, compared to untreated clay, the UCS of XG-AG with the ratio of 1:4 increases from 418.2 kPa to 451.4 kPa, from 520.3 kPa to 549.4 kPa, from 543.7 kPa to 640.4 kPa, from 557.55 kPa to 795.1 kPa, from 482.64 kPa to 711.8 kPa, from 457.07 kPa to 703.6 kPa, from 436.59 kPa to 659.2 kPa, from 401.5 kPa to 628.9 kPa at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. Moreover, the UCS of XG-AG treated clay almost linear increases from 643.6 kPa to 838.1 kPa, from 883.8 kPa to 1141.1 kPa, from 1057.6 kPa to 1366 kPa, from 1187.9 kPa to 1497.5 kPa, from 1218.4 kPa to 1629.6 kPa, from 1076.9 kPa to 1530.5 kPa, from 889.4 kPa to 1469.6 kPa, from 730.4 kPa to 1393.4 kPa with the ratio changing from 2:3 to 4:1 at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. It can be observed that the UCS of XG-AG treated clay with the ratio of 4:1 at curing 14, 21 and 35 days is even larger than the USC of XG treated clay at the same curing day.

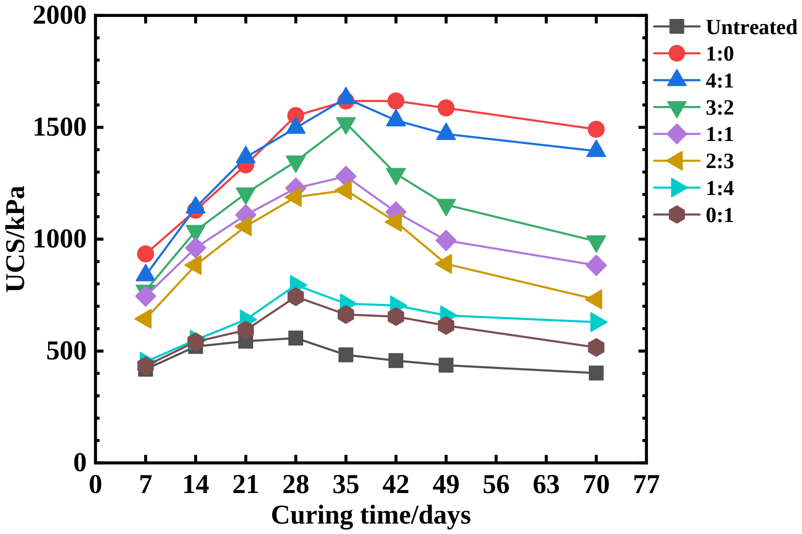


Figure 4.16 UCS of XG-AG treated clay

As shown in Figure 4.17, it can be found that the UCS of XG-KG treated clay has a linear increase with the condition changing from untreated clay to the ratio of 1:4. Moreover, there is the threshold ratio value at XG-KG with 1:4, while the UCS of XG-KG treated clay is obviously larger than untreated clay beyond this ratio. In addition, the XG-KG ratio of 1:1 obtains the highest UCS value. Moreover, with the ratio changing from 2:3 to 4:1, 3:2 and 1:1, the corresponding UCS almost linear increases. At the initial curing time (7 days), the UCS of only XG-KG with 1:1 treated clay is larger than that of pure XG treated clay. With the increase of curing time, the UCS of other conditions (e.g. the ratio beyond 1:4) is gradually larger than the pure

XG treated clay. Under the curing 35 days, the USC of XG-KG treated clay with all ratios beyond 1:4 is larger than the pure XG treated clay. At the same time, as mentioned before, the UCS of XG-KG treated clay increases first and then decreases with the increase of curing time that it reaches the highest value at curing 28 or 35 days. Specifically, with the XG-KG ratio decreasing from 4:1 to 1:1, the UCS almost linear increases from 757.2 to 1042.2 kPa, from 1065.8 to 1029.3 kPa, from 1370.8 to 1597.2 kPa, from 1598.7 to 1790.5 kPa, from 1826.2 to 1949.4 kPa, from 1707.18 to 1846.7 kPa, from 1627.6 to 1775.3 kPa, from 1554.2 to 1690.5 kPa at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. On the other hand, with the ratio decreasing from 1:1 to 1:4, the UCS decrement value gradually arises, and the UCS finally decreases to 451.6, 654.1, 807.7, 1024.6, 1234.9, 1182.2, 1067.7 and 982.4 kPa at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. Even under the ratio of 1:4, the UCS is obviously larger than that of untreated clay, which the increment of 7.99%, 25.72%, 48.56%, 83.77%, 155.86%, 158.65%, 144.55% and 144.68% at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively.

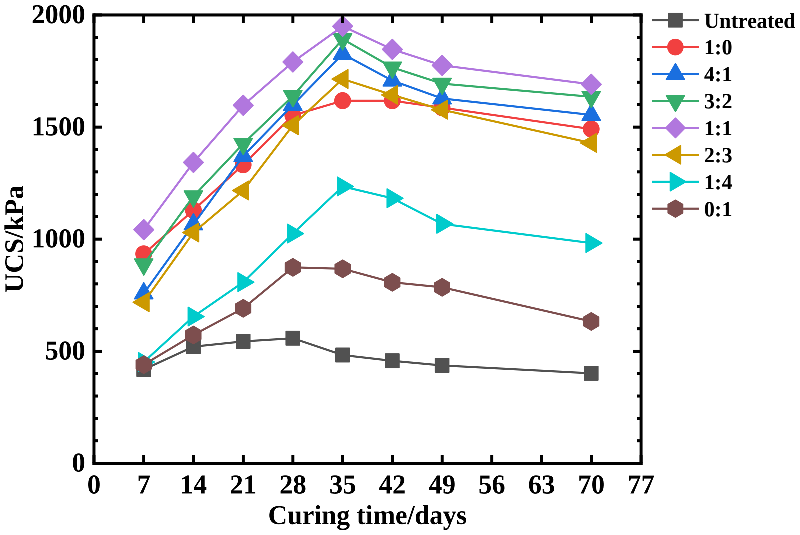


Figure 4.17 UCS of XG-KG treated clay

Figure 4.18 illustrates the UCS of XG-LBG treated clay at different ration and curing time. It can be shown that with the XG-LBG ratio decreasing from 4:1 to 1:4, the UCS also decreases. Moreover, the highest UCS can be reached at curing 28 or 35 days. To be specific, the UCS increases from 418.2 to 650.8 kPa, from 520.3 to 828.4 kPa, from 543.7 to 990.3 kPa, from 557.55 to 1161.5 kPa, from 482.64 to 1129.5 kPa, from 457.07 to 1090.2 kPa, from 436.59 to 1048.8 kPa, from 401.5 to 909.6 kPa with the condition changing from untreated clay to the XG-LBG ratio of 1:4 at curing 7, 14, 21, 28, 35, 42, 49 and 70 days, respectively. It corresponds the UCS increment ratio of 55.62%, 59.22%, 82.14%, 108.32%, 134.03%, 138.52%, 140.22% and 126.55%, respectively. And then, with the ratio increasing to 4:1, the UCS increases to 952.5, 1202.6, 1385.6, 1557.2, 1656.1, 1569.3, 1488.4 and 1391.9 kPa at curing , 14, 21, 28, 35, 42, 49 and 70 days, respectively, which corresponds to the UCS increment ratio of 127.76%, 131.14%, 154.85%, 179.29%, 243.13%, 243.34%, 240.92% and 246.68%, respectively. Obviously, the UCS of XG-LBG treated clay with the ratio of 4:1 is slightly larger than pure XG treated clay at curing smaller than 35 days.

Overall, the UCS of XG-AG/KG/LBG treated clay is always larger than pure AG/KG/LBG treated clay. Among these three biopolymers, even though the UCS of pure AG treated clay is the smallest, the XG-AG ratio of 4:1 at curing 35 days reaches the highest UCS value, which is even larger than that of the pure XG treated clay. Moreover, the XG-AG of 1:4 is the threshold ratio, and the UCS of XG-AG treated clay is significantly larger than untreated clay beyond this ratio. Moreover, the highest UCS of pure LBG treated clay is larger than that of pure AG/KG treated clay, while the UCS of XG-LBG is slightly larger than that of pure XG treated clay with the ratio of 4:1 at curing smaller than 35 days. In addition, with the ratio increasing from 1:4 to 4:1, the UCS of XG-LBG treated clay gradually increases. Regarding XG-KG treated clay, it has a good performance on the influence of biopolymer cross-link on the UCS of treated clay. It can be observed that the UCS of XG-KG treated clay with the ratio of 1:1 is always larger than that of pure XG treated clay. Furthermore, the highest UCS value of other XG-KG ratios from 4:1 to 2:3 treated clay is also larger than the highest UCS of XG treated clay with the increase of curing time. Meanwhile, although the UCS of XG-KG with the ratio of 1:4 is significantly larger than that of untreated clay, this ratio can be regarded as the threshold value that the UCS of XG-KG beyond this ratio gradually continues to increase and is significantly larger than that of the XG-KG ratio of 1:4.

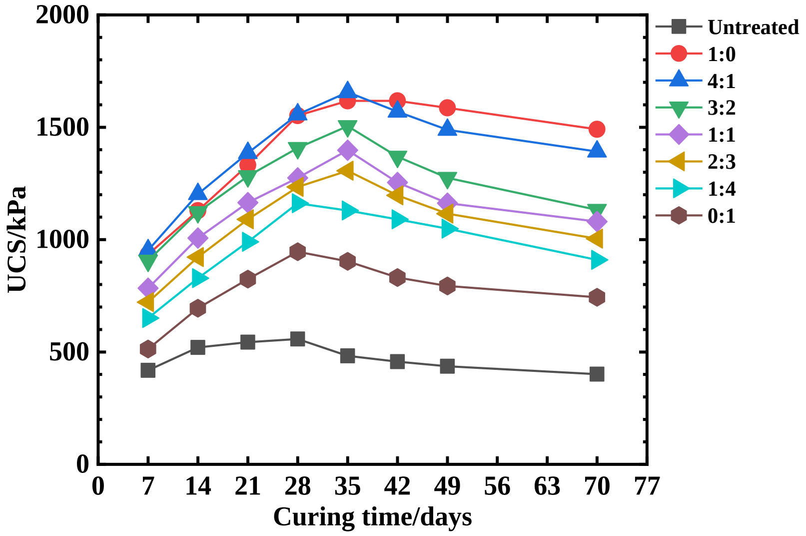


Figure 4.18 UCS of XG-LBG treated clay

4.2.7 Effect of mixing method on UCS

This part illustrates the effect of various mixing methods (e.g. room temperature water-dry (RDM), 100 °C hot water-dry (HDM), room temperature water-wet (RWM), and 100 °C hot water-wet (HWM)) with considering biopolymer type, biopolymer concentration, biopolymer cross-link and curing time. Figure 4.19 shows that dry mixing is more effective than wet mixing based on the compressive strength test results on the 7th, 14th, 28th, 35th and 49th days regardless of water temperature. For example, the UCS increases from 670.6 to 933.7 kPa, from 906 to 1129 kPa, from 1206.6 to 1552 kPa, from 1189.6 to 1723.98 kPa, from 1161.4 to 1586.61 kPa at curing 7, 14, 28, 35 and 49 days, respectively, when the mixing method is changing from RWM to RDM. Similarly, the UCS increases from 631.5 to 1004.9 kPa, from 860.3 to 1258.3 kPa, from 1179 to 1732.4 kPa, from 1056.4 to 2012.1 kPa, from 956.4 to 1825.3 kPa at curing 7, 14, 28, 35 and 49 days, respectively, when the mixing method is changing from HWM to HDM. Moreover, the UCS of XG treated clay at RWM and HWM has a little difference, while the UCS of XG treated at HDM is significantly larger than that of HWM. Therefore, the HDM can be regarded as the most effective mixing method in the field application of XG treated clay. Compared to untreated clay in RDM/RWM, the increment value is 140.29%, 141.84%, 210.72%, 316.89% and 318.08% at curing 7, 14, 28, 35 and 49 days, respectively.

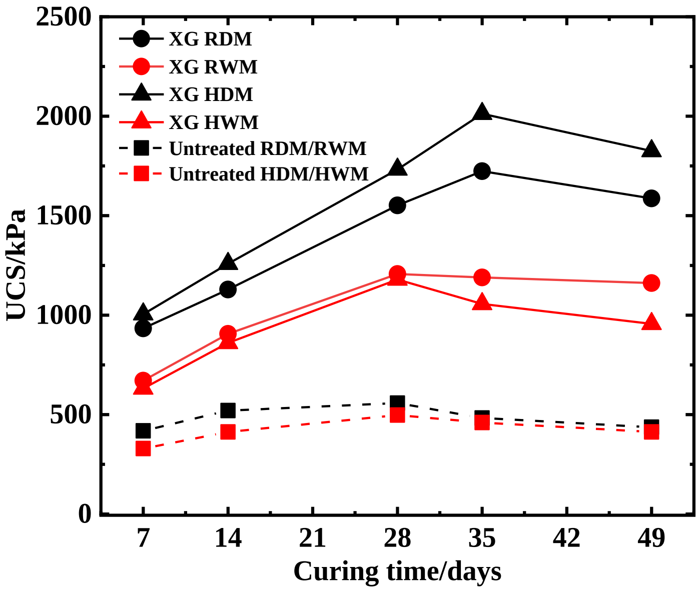


Figure 4.19 UCS of XG treated clay with different mixing methods

Similar findings can also be illustrated in the SA treated clay as shown in Figure 4.20, which exhibits the UCS of SA treated clay under different mixing methods. The dry mixing method is more effective in increasing UCS of SA treated clay than the wet mixing method regardless of water temperature. With the mixing method changing from RWM to RDM, the UCS increases from 1210.6 to 1324.2 kPa, from 1507 to 1665.3 kPa, from 2050 to 2292.4 kPa, from 1926 to 2172.7 kPa, from 1673.2 to 1888.1 kPa at curing 7, 14, 28, 35 and 49 days, respectively. And with the mixing method changing from HWM to HDM, the UCS increases from 1190.4 to 1515.9 kPa, from 1437 to 1809.3 kPa, from 2028.6 to 2446.4 kPa, from 1874.2 to 2354.1 kPa, from 1630.6 to 2105.3 kPa at curing 7, 14, 28, 35 and 49 days, respectively. At the same time, the UCS of SA treated clay under the RWM has limited difference with HWM. Moreover, the UCS of SA treated clay under the RDM is significantly larger than that of the HDM. Therefore, the HDM can also be regarded as the most effective way in the field application of SA treated clay. Compared to untreated clay under RDM/RWM, the UCS increment value is 262.48%, 247.74%, 338.78%, 387.75% and 382.21% at curing 7, 14, 28, 35 and 49 days, respectively.

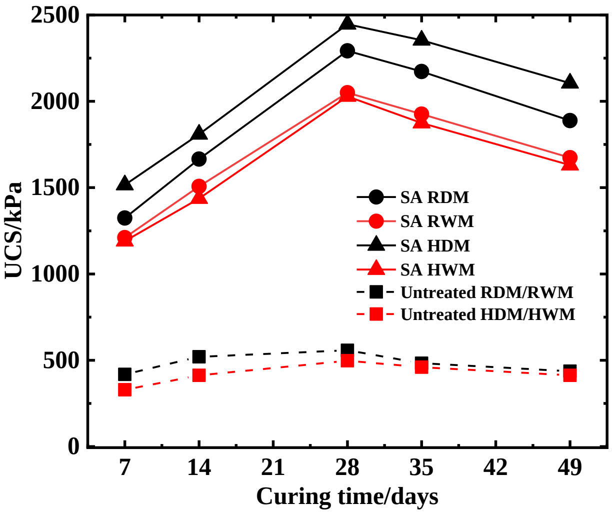


Figure 4.20 UCS of SA treated clay with different mixing methods

In terms of the above findings, it can be explained by the solubility and viscosity of XG and SA in water. Taking XG as an example, Chang et al. (2015) illustrated that 1.4% XG content relative to water was the solubility point of XG for thorough dissolution. Moreover, higher XG content in water is complicated due to the increased viscosity of the XG solution. In this study, a value of 1% XG relative to the quantity of soil causes about 2.2% of XG to water, which is significantly higher than the solubility point. Thus, it is not easy to generate the uniform biopolymer-soil matrix by mixing XG into the water, while dry mixing provides a well-distributed XG in soil. It implies that dry mixing would be more appropriate for practical applications in the field.

On the other hand, the solubility of biopolymer increased with an increase of temperature (García-Ochoa et al. 2000), and it is assumed that 1% biopolymer can be fully dissolved in water with 100°C. However, it revealed that the UCS of biopolymer treated soil could be obtained the maximum value at curing 60°C (Fatehi et al. 2018; Chang and Cho 2012). Moreover, excessively high temperature can decrease and disturb the strength evolution of biopolymer to interrupt its strengthening function. In addition, it was also easy to be decomposed to amino acids causing a loose structure and separated fibrils (Fatehi et al. 2018; Chang and Cho 2012). Therefore, under the contradictory roles of the water temperature, the UCS of XG and SA treated clay with HWM is similar to that of the RWM. Additionally, both were smaller than that of the RDM, even for the former mixing method obtaining a more uniform distribution of biopolymer-soil matrices. In terms of HDM, pouring hot water (100°C) into the biopolymer-soil mixture can quickly reduce the water temperature in the mixture at about optimum temperature. Therefore, it can further increase the solubility of biopolymer in water and provide the suitable temperature condition to interact more effectively and make more resistant bonds between biopolymer and soil particles. Therefore, it can be observed that the HDM can provide the highest compressive strength, even for curing more time. Due to the viscosity of the SA solution being higher than the XG solution, the UCS of SA treated clay is larger than that of XG treated clay at the same preparation conditions and curing time.

Figure 4.21 illustrates the UCS of SA treated clay with different concentrations under different mixing methods. It can be observed that the UCS of SA treated clay in the RDM is higher than RWM regardless of SA concentrations. Specifically, the UCS of 1% SA treated clay at RDM is 1665.3 kPa, 2292.4 kPa, 1788.1 kPa and 1704.3 kPa at curing 7, 28, 42 and 70 days, respectively, while the UCS of 1% SA treated clay at RWM is 1557 kPa, 2050 kPa, 1756 kPa and 1673.2 kPa, respectively. Moreover, the UCS of 2% SA treated clay at RDM is 2653.5 kPa, 4119.7 kPa, 3599.1 kPa and 3275.7 kPa at curing 7, 28, 42 and 70 days, respectively, while the UCS of 2% SA treated clay at RWM is 2211.2 kPa, 3938.4 kPa, 3483.7 kPa and 3160.2 kPa, respectively. In addition, the UCS of 3% SA treated clay at RDM is 3238.2 kPa, 4911.5 kPa, 4334.9 kPa and 3787.1 kPa at curing 7, 28, 42 and 70 days, respectively, while the UCS of 3% SA treated clay at RWM is 2692.1 kPa, 4731.2 kPa, 4169.3 kPa and 3598.1 kPa, respectively.

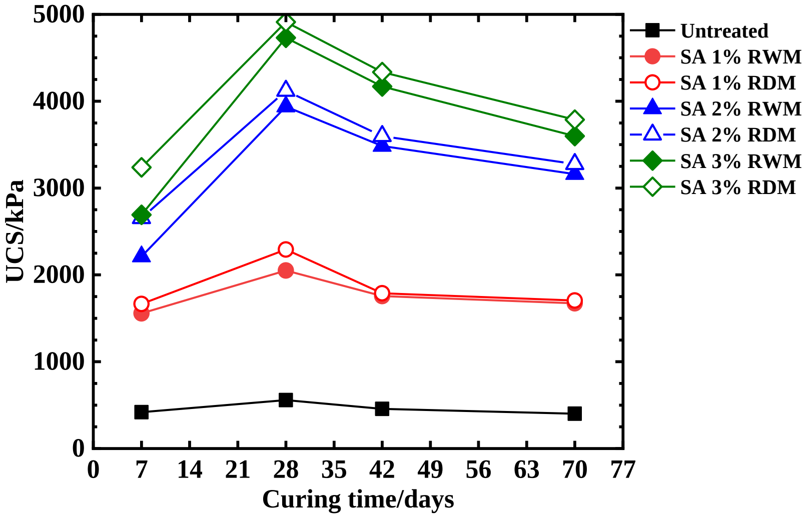


Figure 4.21 UCS of SA treated clay with different mixing methods

Figure 4.22 illustrates the UCS of AG treated clay at different curing times with considering mixing methods. It can be shown that the highest UCS is obtained at HWM following the RDM. Moreover, the UCS of AG treated clay with the HDM is the smallest, even lower than that of untreated clay. The dry mixing method is more suitable in room-temperature water, while the wet mixing method is more suitable in hot water. Specifically, the UCS of AG treated clay with the HWM is 538.9 kPa, 729.5 kPa, 978.43 kPa, 887.1 kPa and 822.8 kPa at curing 7, 14, 28, 35 and 49 days, respectively. In addition, the UCS of AG treated clay with the RDM is 433.6 kPa, 541.6 kPa, 795.1 kPa, 693 kPa and 613.9 kPa at curing 7, 14, 28, 35 and 49 days, respectively. Moreover, the UCS of AG treated with RWM is slightly lower than that of RDM, which is 430.7 kPa, 470.5 kPa, 699.5 kPa, 619.6 kPa and 530 kPa at curing 7, 14, 28, 35 and 49 days, respectively. And the UCS of AG treated with HDM is 220.1 kPa, 357.5 kPa, 396.9 kPa, 288.6 kPa and 254.2 kPa at curing 7, 14, 28, 35 and 49 days, respectively.

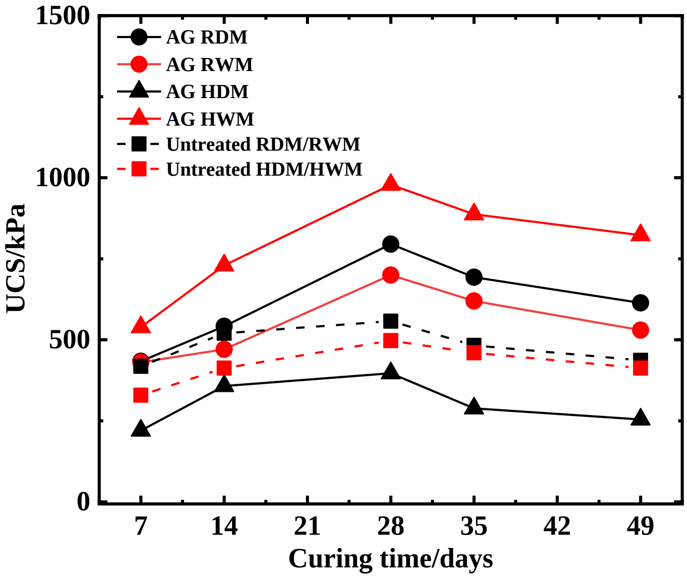


Figure 4.22 UCS of AG treated clay with different mixing methods

Figure 4.23 illustrates the UCS of GE treated clay with different mixing methods. Similarly, the highest UCS of GE treated clay is obtained in HWM following RDM. Moreover, the smallest UCS of GE treated clay is obtained in HDM, which is still higher than untreated clay. The dry mixing method is more suitable in room-temperature water, while the wet mixing method is more suitable in hot water. Specifically, the UCS of GE treated clay with HWM is 736.3 kPa, 950.1 kPa, 1143.8 kPa, 1071.6 kPa and 1018.2 kPa at curing 7, 14, 28, 35 and 49 days, respectively. In addition, the UCS of GE treated clay with the RDM is 551.8 kPa, 673.4 kPa, 904.4 kPa, 823 kPa and 694.7 kPa at curing 7, 14, 28, 35 and 49 days, respectively. Moreover, the UCS of GE treated with RWM is 441.7 kPa, 604.4 kPa, 880.1 kPa, 737.5 kPa and 585.1 kPa at curing 7, 14, 28, 35 and 49 days, respectively, which is slightly lower than that of RDM at the same curing time. And the UCS of GE treated with HDM is 473.5 kPa, 604.8 kPa, 831.3 kPa, 663.7 kPa and 530.8 kPa at curing 7, 14, 28, 35 and 49 days, respectively.

It can be explained that the solubility and viscosity are poor at room temperature. However, it is normally challenging to generate the uniform biopolymer solution with DWM, while dry mixing can provide a relative well-distributed AG in the soil to increase the viscosity of biopolymer-soil matrices. It implies that dry mixing in room temperature water would be more appropriate for practical applications in the field. However, the solution increases in hot water, and the melt temperature is about 85-95°C. Therefore, the HWM can promote the solubility of AG in water. The uniformly AG-clay matrices can significantly increase the UCS. On the other hand, the clay is more easily bound with hot water molecules than AG in the HDM. The AG cannot play the role of increasing UCS under this condition, and the clay combined with hot water can reduce the UCS. Thus, the HDM observes the smallest UCS of AG treated clay.

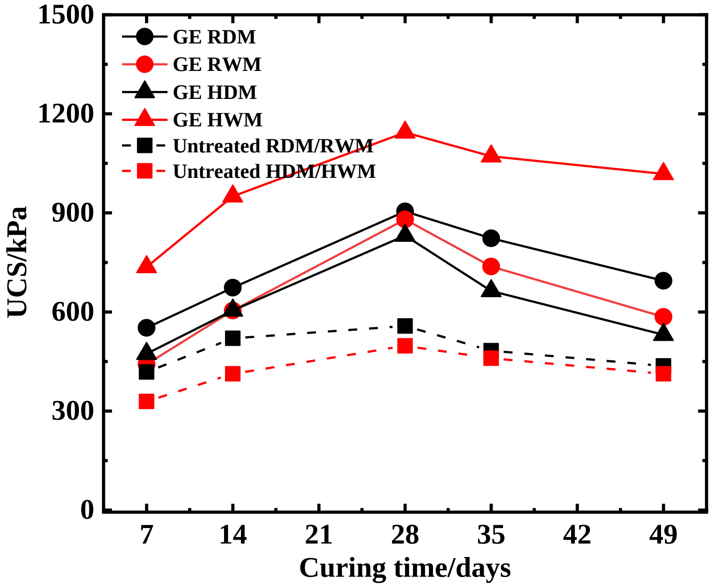


Figure 4.23 UCS of GE treated clay with different mixing methods

Figure 4.24 illustrates the UCS of KG treated clay with different mixing methods. It can be observed that the UCS of KG treated clay using hot water mixed is higher than that of room-temperature water regardless of hot and dry mixing. On the other hand, the dry mixing method is more efficient than the wet mixing method. Therefore, the HDM of KG treated clay can obtain the highest UCS following HWM. Furthermore, the smallest UCS of KG treated clay is observed with the RWM, which is still larger than untreated clay. Specifically, the UCS of KG treated clay with the HDM is 860.5 kPa, 1127.1 kPa, 1537.9 kPa, 1366 kPa and 1166 kPa at curing 7, 14, 28, 35 and 49 days, respectively. In addition, the UCS of KG treated clay with the HWM is 783.6 kPa, 1016.9 kPa, 1316.5 kPa, 1224.5 kPa and 1139.8 kPa at curing 7, 14, 28, 35 and 49 days, respectively. The UCS of KG treated clay with the RDM is 440.2 kPa, 572.4 kPa, 874.1 kPa, 867.5 kPa and 785 kPa at curing 7, 14, 28, 35 and 49 days, respectively. Additional, the UCS of KG treated clay with the RWM is 400.5 kPa, 542.1 kPa, 675.8 kPa, 621 kPa and 600.3 kPa at curing 7, 14, 28, 35 and 49 days, respectively.

It can be explained that it is ordinarily difficult to generate a uniform biopolymer solution with the wet mixing method. In contrast, dry mixing can provide a relative well-distributed KG in the soil to increase the viscosity of biopolymer-soil matrices regardless of water temperature. It implies that the dry mixing method would be more appropriate for practical applications in the field. With the increase in water temperature, the KG solubility increased as well. Moreover, the wet mixing method in hot water can also provide uniformly biopolymer-soil matrices. However, the melt temperature of KG is about 70 °C. Thus, the excessively high temperature can decrease and disturb the strength evolution of biopolymer to interrupt its strengthening function. However, in terms of the HDM, pouring hot water (100°C) into the biopolymer-soil mixture can quickly reduce the water temperature in the mixture to the optimum mixing temperature. Therefore, under the contradictory roles of the water temperature, the UCS of KG treated clay with the HDM is higher than that of the HWM. It revealed that properly increasing the water temperature can efficiently improve the UCS of KG treated clay.

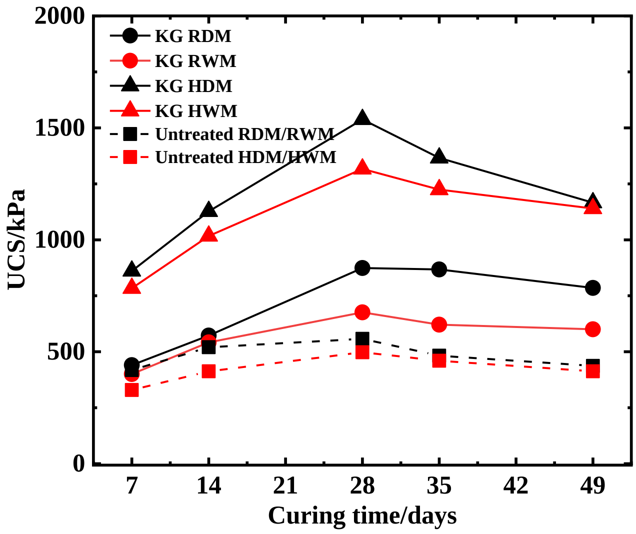


Figure 4.24 UCS of KG treated clay with different mixing methods

Figure 4.25 illustrates the UCS of LBG treated clay with considering different mixing methods. It can be observed that the hot water temperature was more suitable for LBG treated clay. Moreover, the UCS of LBG treated clay using the wet mixing method is also higher than that of the dry mixing method. Specifically, the UCS of LBG treated clay with the HWM is 602.7 kPa, 830.2 kPa, 1148.7 kPa, 956.5 kPa and 838.9 kPa with curing 7, 14, 28, 35 and 49 days, respectively. In addition, the UCS of LBG treated clay with the RWM is 517.7 kPa, 739.6 kPa, 1106.3 kPa, 932.8 kPa and 831.7 kPa at curing 7, 14, 28, 35 and 49 days, respectively. At the same curing time, the UCS of LBG treated clay with the HDM is 558.5 kPa, 758.8 kPa, 1014.8 kPa, 922.9 kPa and 801.6 kPa, respectively. The UCS of LBG treated clay with the RDM is 513 kPa, 694.5 kPa, 945.9 kPa, 903.1 kPa and 793.7 kPa, respectively.

It can be explained that a value of 1% XG relative to the quantity of soil causes about 2.2% of LBG to water, which is lower than the solubility point of LBG. Therefore, the wet mixing method can obtain the uniform biopolymer solution firstly. And then, the uniform biopolymer solution can be mixed into soil for generating the well-distributed biopolymer-soil matrices. On the other hand, the viscosity of LBG solution can increase with the increase in water temperature. Moreover, the melting point of LBG was more than 90 °C. Thus, the highest UCS of LBG treated clay can be observed at HWM. However, the HDM has a limited viscosity increase in LBG solution. Therefore, the UCS of LBG treated clay with the RWM was higher than that of the HDM. Moreover, the smallest UCS of LBG treated clay is observed in the RDM.

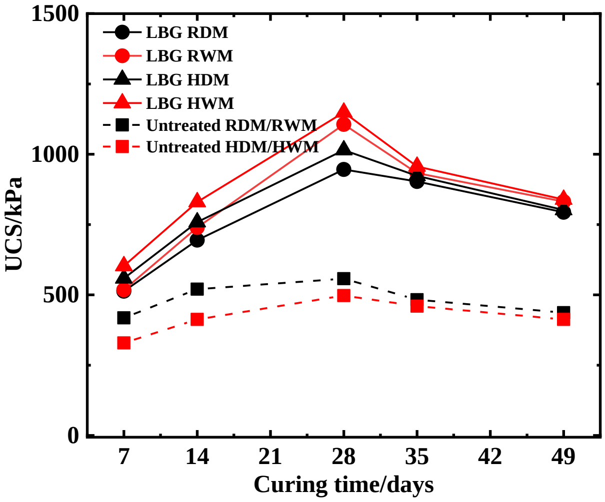


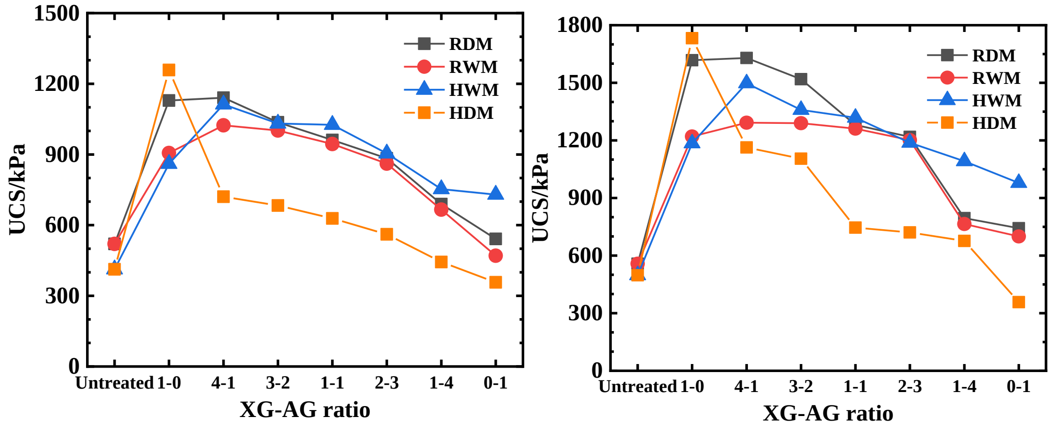
Figure 4.25 UCS of LBG treated clay with different mixing methods

Considering biopolymer cross-linking, the influence of the mixing method on the UCS of biopolymer treated clay is changeable. As mentioned before, the optimum mixing method of XG and AG treated clay is HDM and HWM, respectively, while the lowest UCS of XG and AG treated clay is observed in HWM and HDM, respectively. Meanwhile, the RDM performs a higher UCS than the RWM for XG and AG treated clay. Combing with the properties of two biopolymers, the UCS of XG-AG treated clay obtains the highest value with the RDM at a higher XG-AG ratio (e.g., 4:1 and 3:2). And then, with the decrease in XG-AG ratio, the dominant role of AG is observed in XG-AG mixing biopolymer that the highest UCS of XG-AG treated clay is observed in HWM, especially for the XG-AG ratio of 1:4 and 0:1 regardless of curing time. In addition, with curing a long time, the highest UCS of XG-AG treated clay at the ratio of 1:1 and 2:3 is observed in RDM or RWM. Overall, the UCS of XG-AG treated clay with HDM, RDM and RWM is almost the same in the XG-AG ratio of 3:2, 1:1 and 2:3.

Specifically, as shown in Figure 4.26 (a), the UCS of XG-AG treated clay is about 1100 kPa, 1000 kPa, 950 kPa, 880 kPa and 690 kPa at the ratio of 4:1, 3:2, 1:1, 2:3 and 1:4, respectively, at curing 14 days, while the UCS of XG-AG treated clay in HDM gradually decreases from 720.6 kPa to 443.5 kPa with the XG-AG ratio decreasing from 4:1 to 1:4. With the curing time increasing to 28 days as shown in Figure 4.26 (b), the UCS of XG-AG treated clay in the ratio of 4:1 is 1629.6

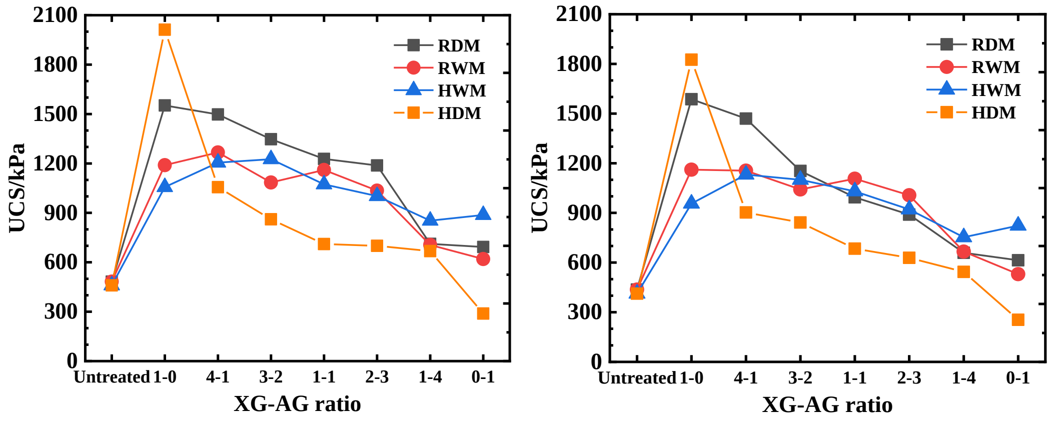
kPa, 1497.5 kPa, 1292.4 kPa and 1163.1 kPa with the RDM, HWM, RWM and HDM, respectively. Similarly, the UCS of XG-AG treated clay in the ratio of 3:2 is 1518.7 kPa, 1358.68 kPa, 1289.7 kPa and 1104.6 kPa with the RDM, HWM, RWM and HDM, respectively. However, the UCS of XG-AG treated clay with the RDM, RWM and HWM is about 1280 kPa and 1200 kPa at the XG-AG ratio of 1:1 and 2:3, respectively. Moreover, the UCS of XG-AG treated clay at the ratio of 1:4 is about 1091.66 kPa in the HWM, which is significantly larger than that of RDM and RWM (e.g., about 780 kPa). The UCS of XG-AG treated clay almost keeps constant at 720 kPa with the ratio decreasing from 1:1 to 1:4.

As shown in Figure 4.26 (c), with the curing time increasing to 35 days, the highest UCS of XG-AG treated clay gradually decreases from 1497.4 kPa to 711.8 kPa with the XG-AG ratio decreasing from 4:1 to 1:4, respectively, in RDM. Similarly, the lowest UCS of XG-AG treated clay gradually decreases from 1205.3 kPa to 887.1 kPa. However, the UCS of XG-AG treated clay with RDM and RWM is similar with 1230 kPa, 1120 kPa, 1100 kPa, 1020 kPa and 780 kPa in the XG-AG ratio of 4:1, 3:2, 1:1, 2:3 and 1:4, respectively. With the curing time increasing to 49 days as shown in Figure 4.26 (d), the UCS of XG-AG treated clay is 1469.6 kPa, 1154.9 kPa, 1131.6 kPa and 902.7 kPa in the RDM, RWM, HWM and HDM, respectively. In addition, the UCS of XG-AG treated clay in the RDM, RWM and HWM in the ratio of 3:2, 1:1, 2:3 and 1:4 seems to keep constant with 1100 kPa, 1000 kPa, 920 kPa and 700 kPa, respectively. In terms of the HDM, the UCS of XG-AG treated clay is also the smallest value, which gradually decreases from 842.2 kPa to 543.5 kPa with the ratio decreasing from 3:2 to 1:4, respectively.



(a) Curing 14 days

(b) Curing 28 days



(c) Curing 35 days

(d) Curing 49 days

Figure 4.26 UCS of XG-AG treated clay with different mixing methods

4.3 Triaxial shear test results

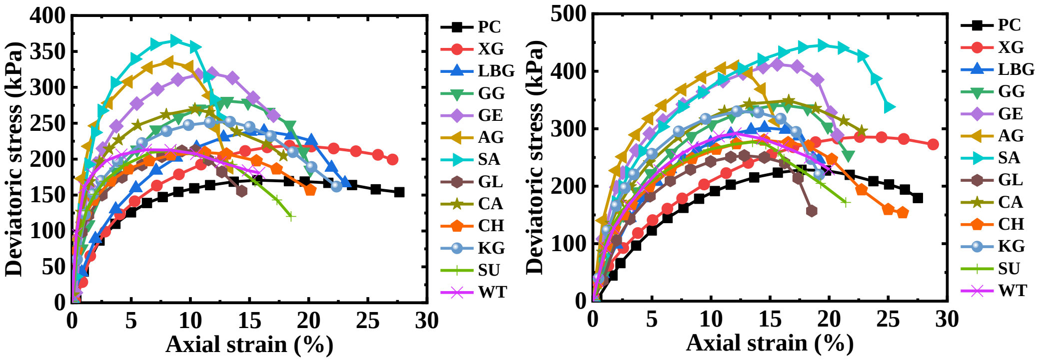
4.3.1 Effect of biopolymer type on strength characteristics of clay

4.3.1.1 Behaviour of stress-strain curve

Figure 4.27 illustrates the typical stress-strain curve of twelve biopolymer types treated clay. It can be observed that the deviatoric shear stress gradually increases to the peak point and then has a slight decrease with the increase of axial strain. Moreover, there is strain-softening behaviour for untreated clay under lower confining pressure. For biopolymer treated clay, the deviatoric shear stress significant increases to the peak point and then gradual decreases with the increases of axial strain. Moreover, the corresponding axial strain obtains peak shear stress increases with the increase of confining pressure for all conditions. In addition, this value of biopolymer treated clay is even more significant than untreated clay under higher confining pressure.

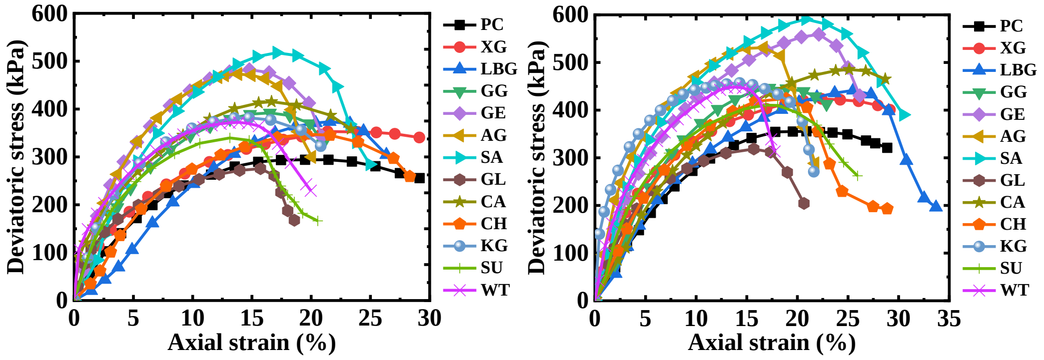
To be specific, the peak deviatoric stress of 1% XG, LBG, GG, GE, AG, SA, GL, CA, CH, KG, SU, WT treated clay is 218.7 kPa, 239.1 kPa, 280.9 kPa, 319.4 kPa, 335.2 kPa, 364.7 kPa, 212.1 kPa, 270 kPa, 209.4 kPa, 252 kPa, 212.7 kPa and 213 kPa with the increment of 28.1%, 40.1%, 64.6%, 87.1%, 96.4%, 113.7%, 24.3%, 58.2%, 22.7%, 47.6%, 24.6%, 24.8%, respectively, compared to untreated clay (170.7 kPa), under the confining pressure of 100 kPa. Under the confining pressure of 200 kPa, the peak deviatoric stress of 1% XG, LBG, GG, GE, AG, SA, GL, CA, CH, KG, SU, WT treated clay is 285.6 kPa, 301.5 kPa, 340.2 kPa, 411.9 kPa, 408.4

kPa, 445.1 kPa, 253.2 kPa, 348.8 kPa, 280.1 kPa, 330.2 kPa, 277 kPa and 291.8 kPa, respectively, which corresponds to the increment of 25%, 32%, 48.9%, 80.3%, 78.8%, 94.9%, 10.9%, 52.7%, 22.6%, 44.6%. 21.3% and 27.8%, respectively, compared to untreated clay (228.4 kPa). With the confining pressure increasing to 300 kPa, the peak deviatoric stress of each biopolymer treated clay is 353.2 kPa, 373.5 kPa, 392.1 kPa, 482.3 kPa, 473.2 kPa, 517.6 kPa, 275.6 kPa, 415.5 kPa, 347.7 kPa, 381.6 kPa, 339.7 kPa and 372.2 kPa, respectively, corresponding to the increment of 20.1%, 27%, 33.3%, 64%, 60.9%, 76%, -6.3%, 41.3%, 18.2%, 29.8%, 15.5% and 26.6%, respectively, compared to untreated clay (294.1 kPa). Under the confining pressure of 400 kPa, the peak deviatoric stress of each biopolymer treated clay is 423.7 kPa, 441.5 kPa, 446.6 kPa, 558.9 kPa, 531 kPa, 590.9 kPa, 318.5 kPa, 485.3 kPa, 424.3 kPa, 456.8 kPa, 410.4 kPa and 448.3 kPa, respectively, which corresponds to the increment of 19.2%, 24.2%, 25.6%, 57.2%, 49.3%, 66.2%, -10.4%, 36.5%, 19.3%, 28.5%, 15.4% and 26.1%, respectively, compared to untreated clay (355.6 kPa). It should be noted that the effectiveness of all biopolymer treated clay decreases with the increase of confining pressure. Furthermore, the peak shear stress of GL treated clay is even smaller than that of untreated clay under the confining pressure of 300 and 400 kPa because GL as a liquid polymer can increase the initial water content of treated clay. Normally, the dry density of soil tends to decrease with the continuous increase of water content after optimum water content causing a decrease in shear stress. On the other hand, the higher water content causes the polymer gels to reduce the surface roughness.



(a) 100 kPa

(b) 200 kPa



(c) 300 kPa

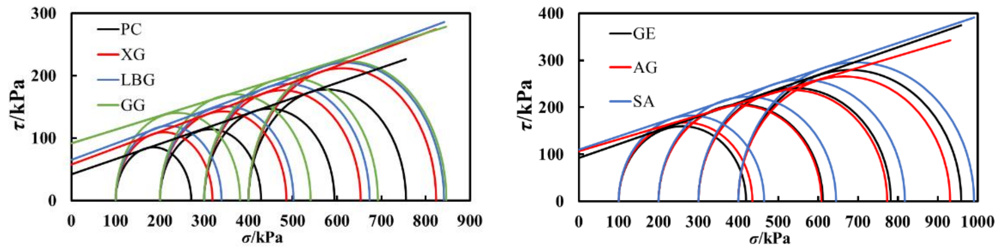
(d) 400 kPa

Figure 4.27 Various biopolymers (1%) treated clay

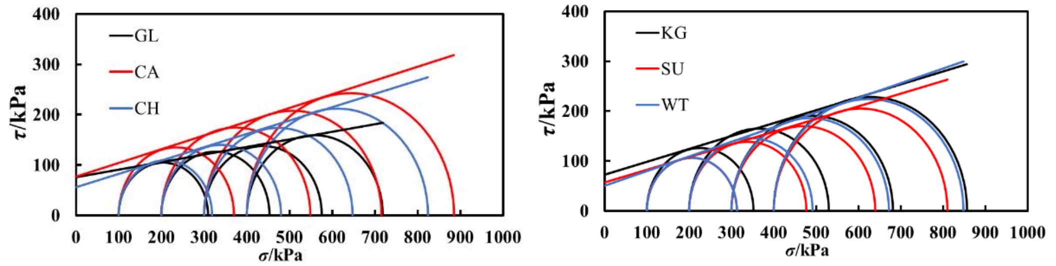
Compared with the results of all biopolymers treated clay, SA is the most efficient biopolymer to enhance the mechanical properties of soil, following AG and GE under the hydraulic condition. CA, GG, KG, and LBG also significantly strengthen and stabilise the soil. Moreover, XG, CH, SU and WT treated soil show a similar enhancement effect at the current condition, and GL treated soil shows the worst results.

4.3.1.2 Shear Strength Parameters

The Mohr-coulomb circles are drawn in Figure 4.28 to obtain the shear parameters of each biopolymer treated clay. Meanwhile, the cohesion and internal friction angle are summerized in Figure 4.29. It can be illustrated that all biopolymers treated clay increase cohesion compared to untreated clay (42.1 kPa). Specifically, the cohesion of 1% XG, LBG, GG, GE, AG, SA, GL, CA, CH, KG, SU, WT treated clay is 57.7 kPa, 65.2 kPa, 91.5 kPa, 91.9 kPa, 106.5 kPa, 110.3 kPa, 76 kPa, 77.1 kPa, 56.4 kPa, 73 kPa, 56.7 kPa and 50.4 kPa, respectively, along with the increment of 37.1%, 54.9%, 117.3%, 118.3%, 153%, 162%, 80.5%, 83.1%, 34%, 73.4%, 34.7% and 19.7%, respectively. The cohesion developed is due to the enhanced binding between the soil particles and the viscous nature of the hydrogel. Obviously, it can be divided into four categories. Firstly, SA, AG, GE and GG are the most effective biopolymer to increase soil cohesion with all biopolymer treated clay increasing more than 110% compared to untreated clay. And then KG, GL and CA have a similar effect on enhancing soil cohesion. Thirdly, LBG, XG and SU can be regarded as the third level to strengthen soil cohesion, while CH and WT treated soil has a limited increase in the soil cohesion.

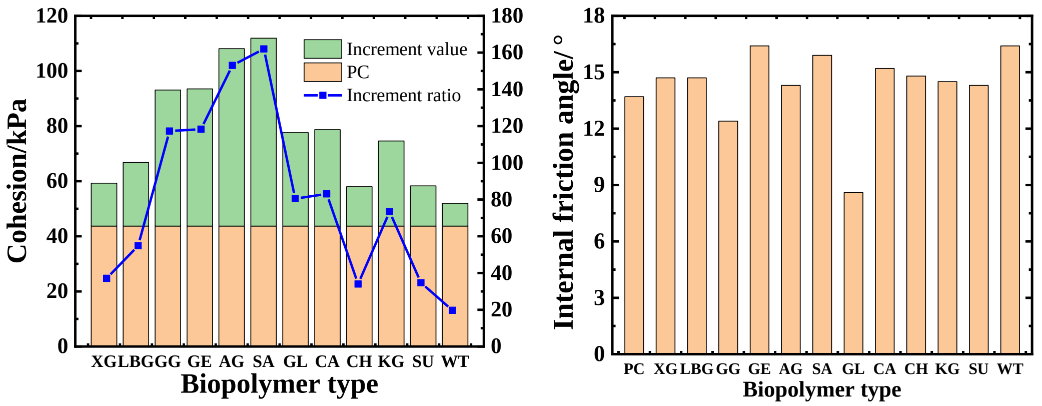


(a) Mohr-coulomb circles (PC, XG, LBG, GG) (b) Mohr-coulomb circles (GE, AG, SA)



(c) Mohr-coulomb circles (GL, CA, CH) (d) Mohr-coulomb circles (KG, SU, WT)

Figure 4.28 Mohr-coulomb circles of biopolymers (1%) treated clay



(a) Cohesion (b) Internal friction angle

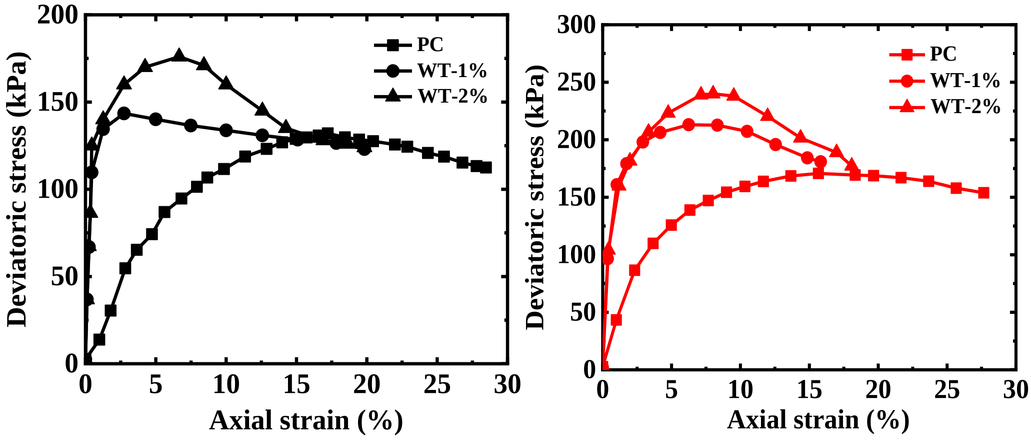
Figure 4.29 Shear strength parameters of various biopolymers treated clay

On the other hand, similarly to the results of soil cohesion, most biopolymers treated soil also increases the internal friction angle of soil, except for GG and GL treated soil. It can be illustrated that GL as a liquid polymer has a limited effect on aggregate soil particles and a significant effect on reducing surface roughness. Moreover, GG is a non-ionic and neutrally charged polysaccharide with numerous hydroxyl (-OH) groups that form hydrogen bonds between GG and soil particles. It results in the formation of hydrogen bonds that have higher bonding energy (kJ/mol) between the guar gum solution and the clay particles. It inhibits the aggregation of particles and only induces slight aggregation, thereby controlling the void size (Chen et al., 2013). In terms of other conditions, the evaluation of the internal friction angle of treated soils at different content and types shows that the internal friction angle of 1% XG, LBG, GE, AG, SA, CA, CH, KG, SU and WT increases to 14.7 °, 14.7 °, 16.4 °, 14.3 °, 15.9 °, 15.2 °, 14.8 °, 14.5 °, 14.3 ° and 16.4 °, respectively, compared to untreated clay (13.7 °). Overall, there is a limited change of internal friction angle for all untreated and treated clay under hydraulic conditions. Nevertheless, biopolymer hydrogel is known to produce a coating over the soil grains, reducing the angularity and surface roughness. Also, the hydrogel occupying the void spaces would reduce the friction. However, the internal friction angle of other biopolymers treated soil was higher than untreated soil due to the increasing stiffness of hydrogel. The gel would be converted to a firm plastic material connecting the soil particles that resist the shear stresses (Latifi et al. 2018, Chang and Cho 2019, Soldo et al. 2020). This interaction can be motivated by the electrical charge of fine-grained particles of the soil such that biopolymer monomers are bonded through cationic bonding or hydrogen bonding between carboxylic acid (–COOH) and/or hydroxyl groups (-OH) to the electrically charged soil particles. As a result, interconnections between biopolymer and particles increase the inter-particle contacts, which in turn leads to improved resistance.

4.3.2 Effect of biopolymer concentration on strength characteristics of clay

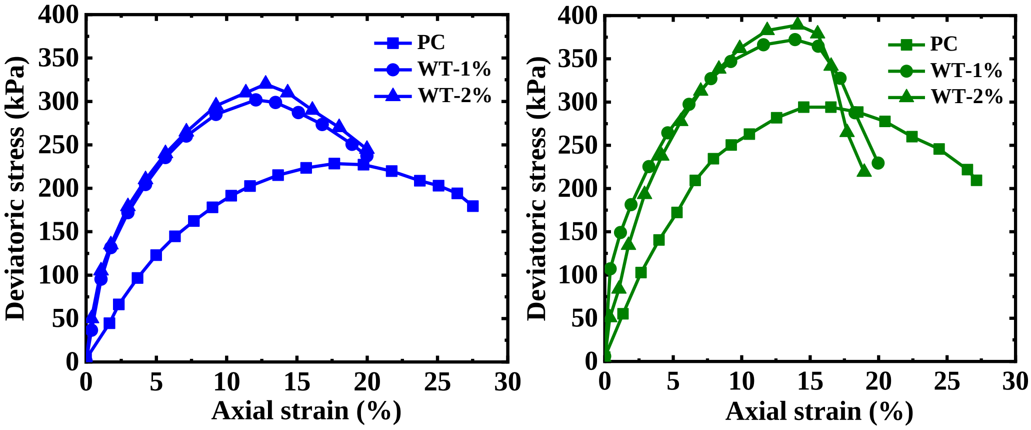
4.3.2.1 Behaviour of stress-strain curve

It can be observed that untreated clay exhibits obvious strain-hardening behaviours, and the peak shear strength is obtained at a strain of about 16% regardless of confining pressure. Moreover, the peak deviatoric stress of untreated clay is 132, 170.7, 228.4, 294.1 and 355.6 kPa under the confining pressure of 30, 100, 200, 300, 400 kPa, respectively, as shown in Figure 4.30. With the addition of WT, the stress-strain curve can be still observed in elastic-plastic behaviour under the low confining pressure, while there is the strain-softening behaviour for WT treated clay under high confining pressure. Moreover, the corresponding strain for obtaining the peak deviatoric stress increases with the increase of confining pressure, and there is no noticeable difference with the increase of concentration. Furthermore, the peak deviatoric stress of 1% and 2% WT treated clay increases to 143.5, 213, 301.8, 372.2 and 428.3 kPa, as well as 176, 240, 320, 389.1 and 439.5 kPa under the confining pressure of 30, 100, 200, 300 and 400 kPa, respectively. It is revealed that the shear strength increases with the increase of WT concentration, although the increment is limited in higher concentration, especially for high confining pressure.



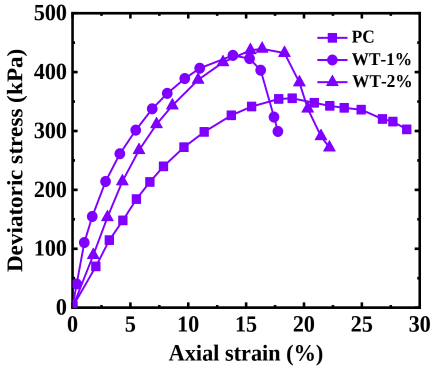
(a) 30 kPa

(b) 100 kPa



(c) 200 kPa

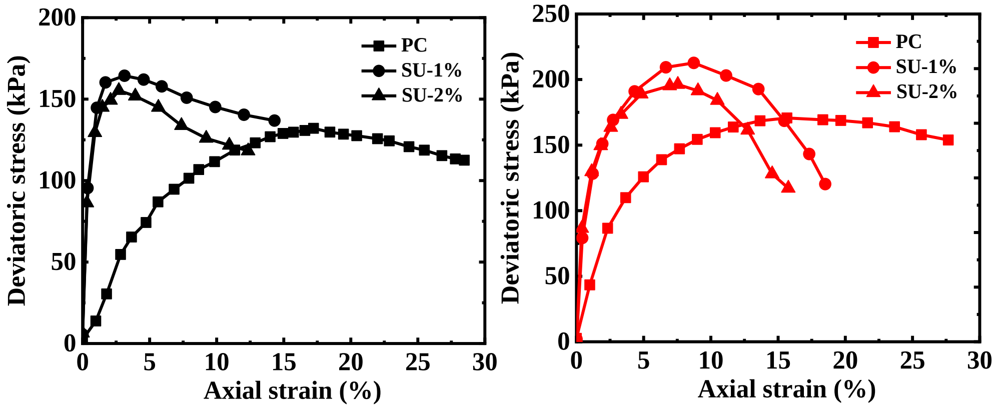
(d) 300 kPa



(e) 400 kPa

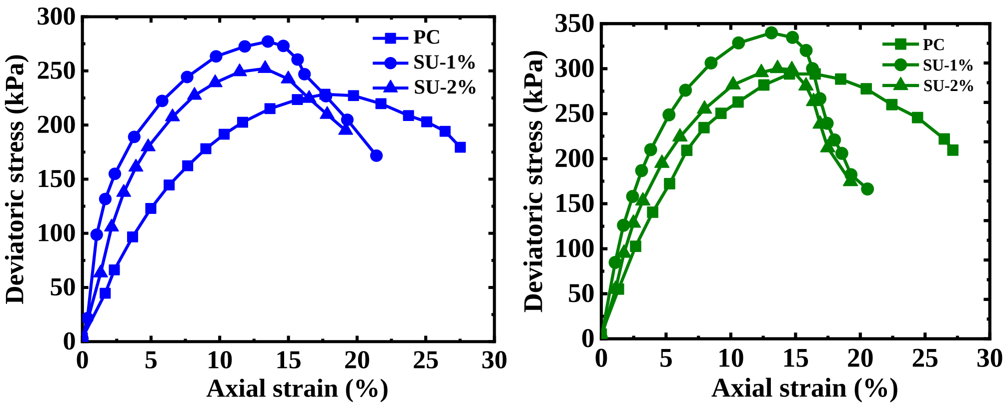
Figure 4.300 WT treated clay

The stress-strain curve of SU treated clay shows strain-softening behaviour regardless of confining pressure as shown in Figure 4.31. Moreover, SU treated clay strengthens shear properties compared to untreated clay. To be specific, the peak shear stress of 1% and 2% SU treated clay is 164.4, 212.7, 277, 339.7 and 410.4 kPa, as well as 155.3, 196.3, 252.1, 300.1 and 348.4 kPa under the confining pressure of 30, 100, 200, 300 and 400 kPa, respectively, as shown in Figure 4.30. Significantly, the shear strength of 1% SU treated clay is larger than that of 2% SU treated clay. Moreover, the difference between the two conditions increases with the increase of confining pressure. It can be illustrated that there is limited stabilization soil for higher SU at hydraulic conditions under high confining pressure. However, the strain corresponding to the peak shear stress has a limited difference with the increase of SU concentration.



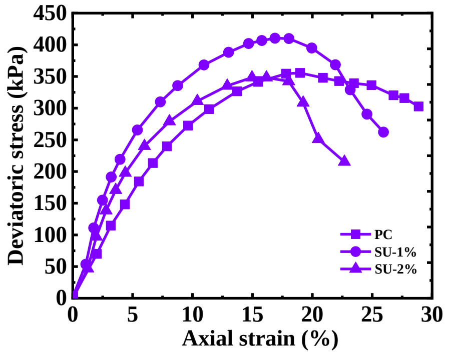
(a) 30 kPa

(b) 100 kPa



(c) 200 kPa

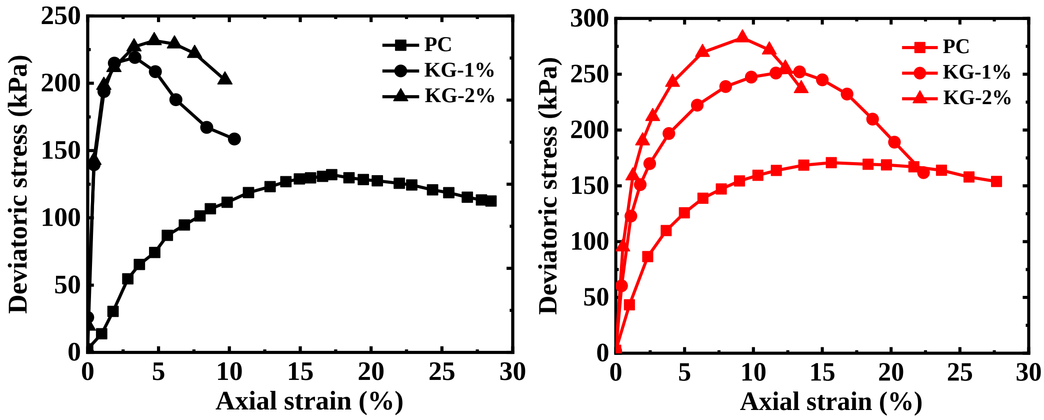
(d) 300 kPa



(e) 400 kPa

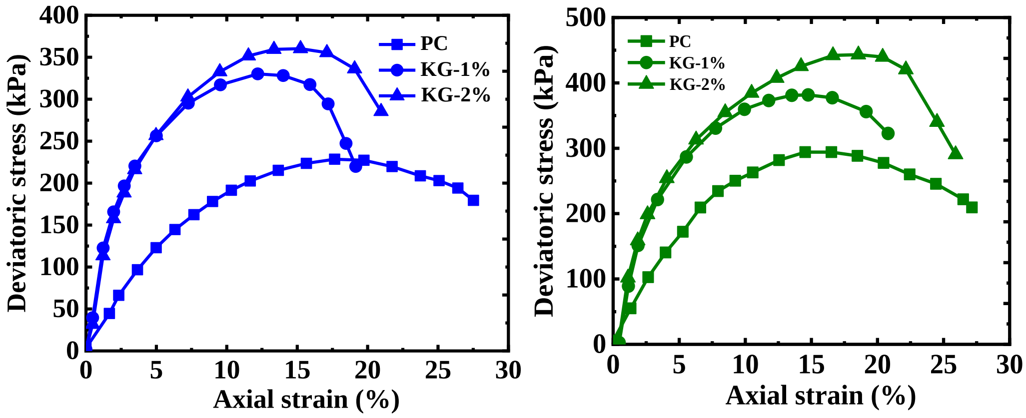
Figure 4.311 SU treated clay

As shown in Figure 4.32, there is an obvious soil improvement for 1% KG treated soil. Moreover, with the increase of KG concentration, the shear strength and the strain for obtaining the peak shear strength of KG treated soil have also slightly increased, and the increment between two concentrations can be significantly observed with the increase of confining pressure. It is illustrated that the higher KG concentration seems to be useful in hydraulic conditions under high confining pressure. To be specific, the peak shear strength of 1% and 2% KG treated soil is 219.1, 252, 330.2, 381.6 and 456.8 kPa, as well as 231.7, 282.6, 360.3, 443.2 and 520 kPa under the confining pressure of 30, 100, 200, 300, 400 kPa, respectively. Moreover, all KG treated clay shows strain-softening behaviour regardless of confining pressure and biopolymer concentration.



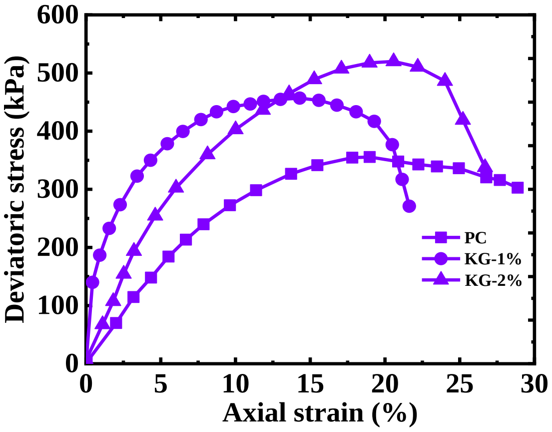
(a) 30 kPa

(b) 100 kPa



(c) 200 kPa

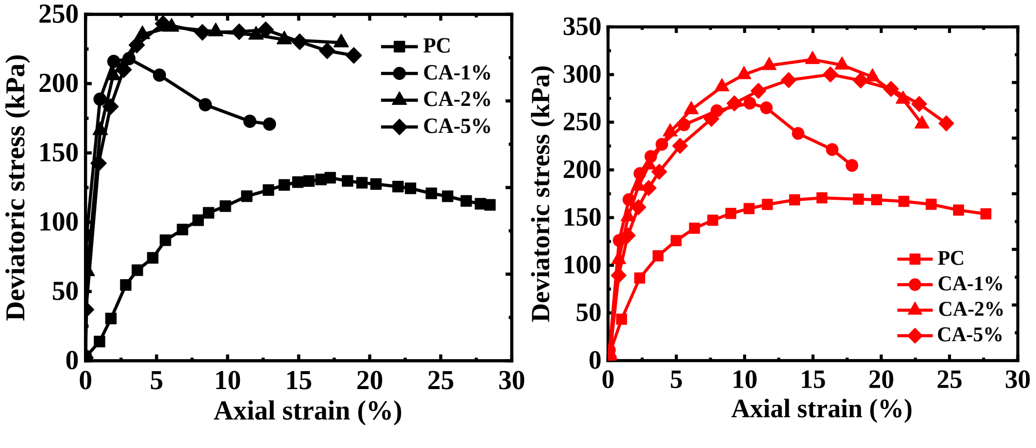
(d) 300 kPa



(e) 400 kPa

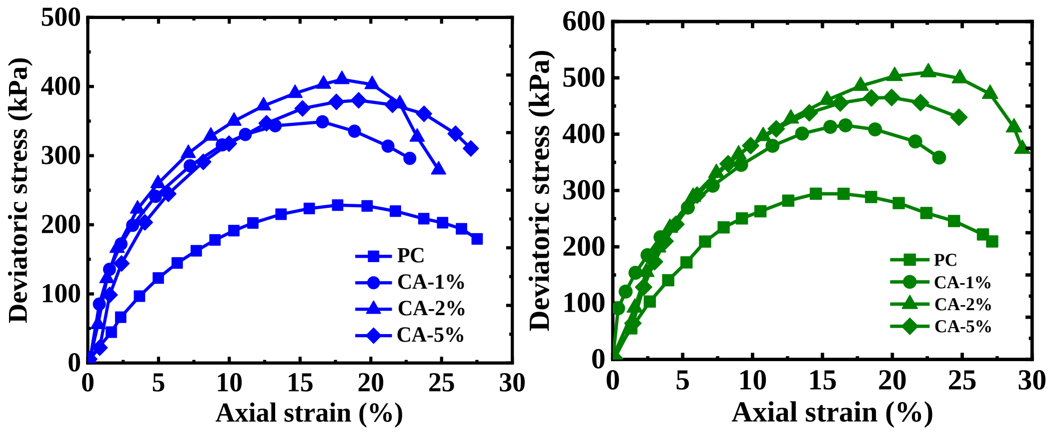
Figure 4.322 KG treated clay

In terms of CA treated clay, it can be revealed that CA has a significant strengthening to clay, and there is strain-hardening behaviour for high concentration under low confining pressure or low concentration under high confining pressure. With the increase of CA concentration, the shear strength and the strain corresponding to the peak shear strength increase firstly and then decrease, as shown in Figure 4.33. Specifically, the peak shear strength of 1% CA concentration treated clay is 218.1, 270, 348.8, 415.5 and 485.3 kPa under the confining pressure of 30, 100, 200, 300 and 400 kPa. With the CA concentration increasing to 2%, the corresponding peak shear strength increases to 240.9, 315.8, 410.2, 509.7 and 590.7 kPa, respectively. However, the corresponding peak shear strength slight decreases to 238.8, 300, 380, 465 and 531.3 kPa, respectively, with CA concentration increasing to 5%. Therefore, the optimum CA concentration can be regarded as 2% at the hydraulic condition to obtain the maximum strength properties.

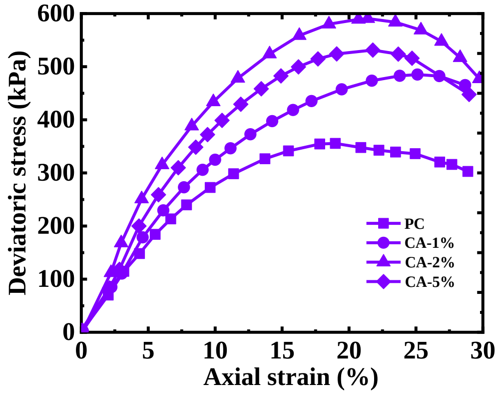


(a) 30 kPa

(b) 100 kPa



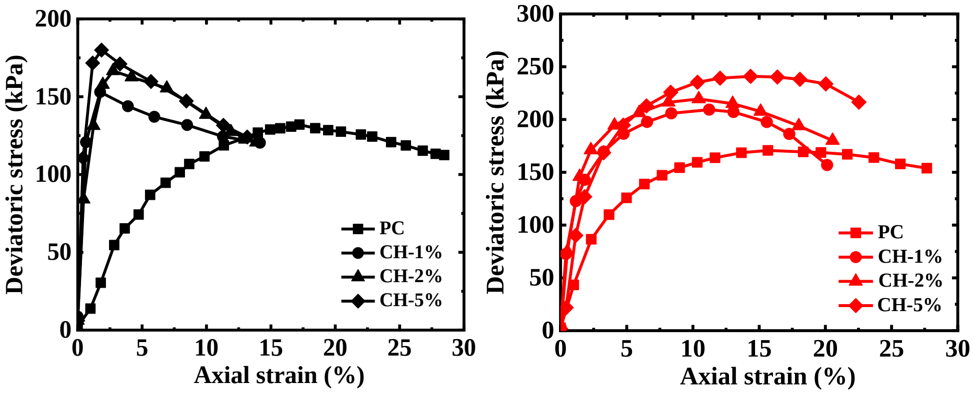
(c) 200 kPa (d) 300 kPa



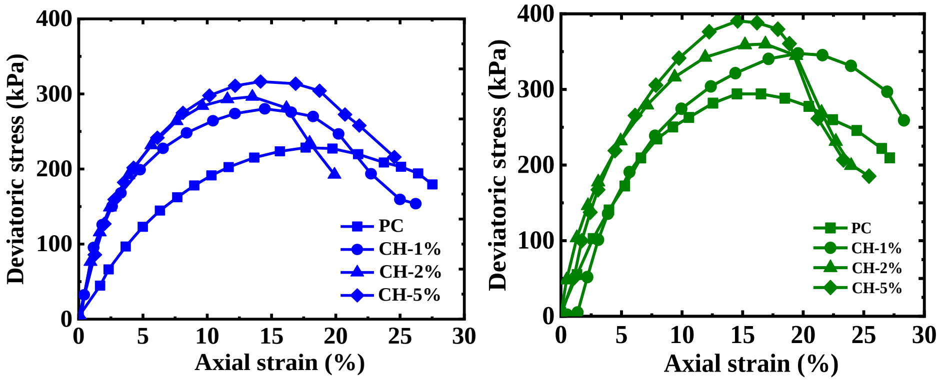
(e) 400 kPa

Figure 4.333 CA treated clay

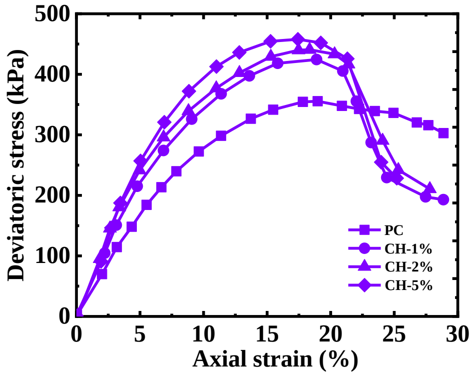
Figure 4.34 illustrates the stress-strain curves of CH treated clay with various biopolymer concentrations and confining pressure. It can be observed the strain-softening behaviours for all conditions. Moreover, the shear strength of CH treated clay is even smaller than that of untreated soil in the residual stage under high confining pressure. However, the shear strength of CH treated clay before reaching peak point is still large than that of untreated soil. Moreover, the peak shear strength increases with the increase of CH concentration, while the corresponding strain has little change. Specifically, the peak shear strength of 1% CH treated clay is 153, 209.3, 280.1, 347.7 and 424.3 kPa under confining pressure of 30, 100, 200, 300 and 400 kPa, respectively. Furthermore, with the concentration increasing to 2% and 5%, the corresponding value slightly increases to 166.6, 219.4, 296.3, 360.1, 440.6 kPa, and 180, 240.9 316.5, 390.6 and 457.8 kPa, respectively. It can be observed that even though there is a significant concentration increment from 1% to 5%, the increment of shear strength is minimal. Therefore, 1% CH concentration may be more reasonable to enhance soil under the hydraulic condition.



(a) 30 kPa (b) 100 kPa



(c) 200 kPa (d) 300 kPa

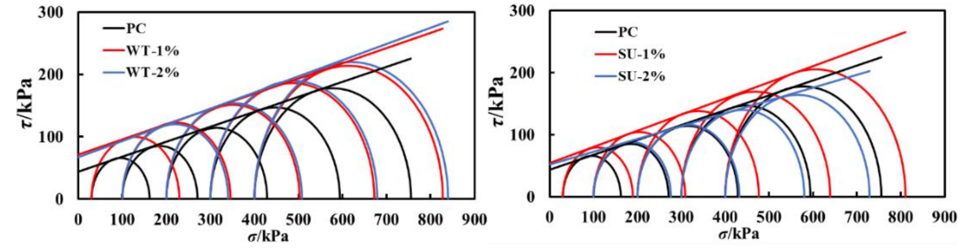


(e) 400 kPa

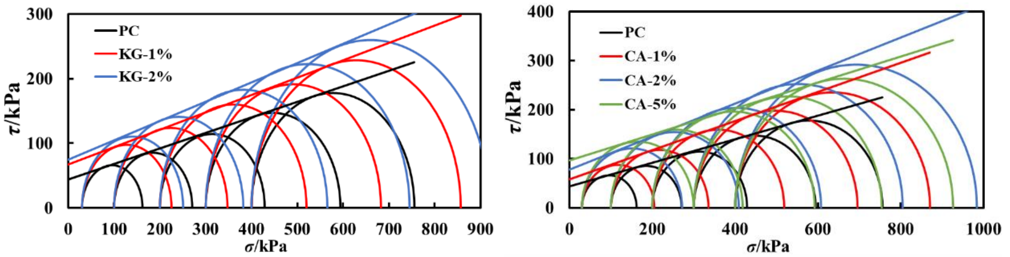
Figure 4.344 CH treated clay

4.3.2.2 Parameters of shear behaviour

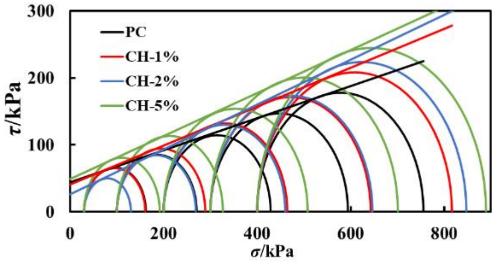
For any soil, cohesion and internal friction angle are the basic engineering properties that provide an idea of the characteristics of that soil. Any variations of these properties can significantly alter its strength and stability. The Mohr-coulomb circles are drawn in Figure 4.35 to obtain the shear parameters of the above five biopolymers treated clay at various concentrations. The cohesion and internal friction angle are plotted in Figure 4.36. It can be observed that the cohesion of all biopolymers increases with the increase of biopolymer concentration. However, the internal friction angle varies with the biopolymer type and concentration. Specifically, the cohesion and internal friction angle of untreated clay are 43.8 kPa and 13.5 °, respectively. Moreover, the cohesion of WT, SU and KG treated clay increases from 49.7 to 63 kPa, from 56.4 to 58.1 kPa, from 75.9 to 77 kPa with the concentration increasing from 1% to 2%, respectively. In addition, the cohesion of CH and CA increases from 75.7 to 81.6 kPa, from 51 to 61.6 kPa with the concentration increasing from 1% to 5%, respectively. However, the internal friction angle of WT, SU treated clay decreases from 16.2 to 15.3 °, from 14.3 to 11.9 °, with the concentration increasing from 1% to 2%. On the other hand, the internal friction angle of KG, CA treated clay decreases from 14.1 to 16.4 °, from 15.4 to 18.8 °, with the concentration increasing from 1% to 2%, while the internal friction angle of 5% CA treated clay decreases to 16.6 °, respectively. However, the internal friction angle of CH treated clay still slight increases from 15.4 to 15.8 ° with the concentration increasing from 1% to 5%.



(a) WT (b) SU



(c) KG (d) CA



(e) CH

Figure 4.355 Mohr-coulomb circles

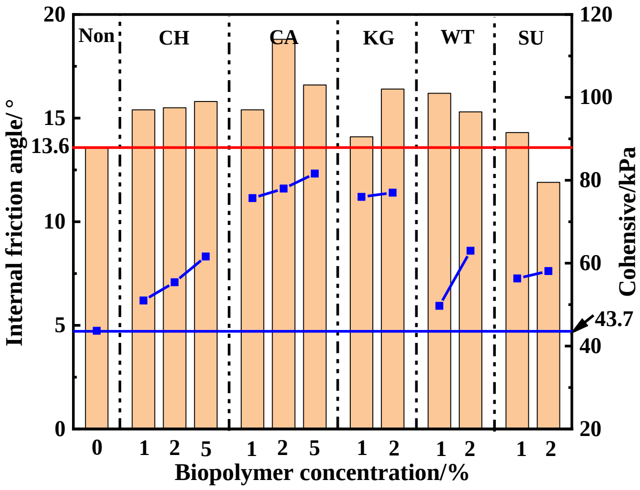


Figure 4.366 Triaxial shear parameters biopolymer treated clay

4.3.3 Effect of water condition

Adequate shear strength is vital for assessing the likelihood of ultimate limit state failure in geotechnical engineering structures (Fatehi et al. 2018, Latifi et al. 2016a). The typical stress-strain curves of 1% XG treated clay and reference specimens are shown in Figure 4.37. In terms of initial water content (curing 0 days), the maximum deviatoric shear strength values of untreated clay are 132, 170.7, 228.8, 294.1 and 355.6 kPa under the confining stress of 30, 100, 200, 300 and 400 kPa, respectively. Moreover, adding 1% XG concentration shows a slight increase in the soil strength under every vertical stress with 174, 218.7, 285.6, 353.2 and 423.7 kPa, respectively. As a result, a cohesion value of 43.8 and 58.7 kPa, a friction angle of 13.5 and 14.6 °for untreated clay and 1% XG concentration treated clay, respectively, are derived from the experiment’s analysis. It can be explained that the solid hydrophilic property of biopolymer interacts with water to form highly viscous pseudoplastic hydrogels. Meanwhile, three-dimensional electrical and hydrogen bonding can be formed to change void fills, and it contributes to the conglomeration of fine particles to form partially conglomerated aggregates (Chang and Cho 2019, Hataf et al. 2018, Smitha et al. 2021). Therefore, the presence of a small amount of XG (e.g., 1%) in clay immediately induces a remarkable increase in cohesion and internal friction angle increasing peak deviatoric shear strength. Moreover, XG gel introduces some degree of ductility to the treated soil matrix, and the biopolymer treated soil exhibits a strain-hardening behaviour (Lee et al. 2019c). It indicates that the hydrogels can induce the strengthening effect in soil that persists at a high strain.

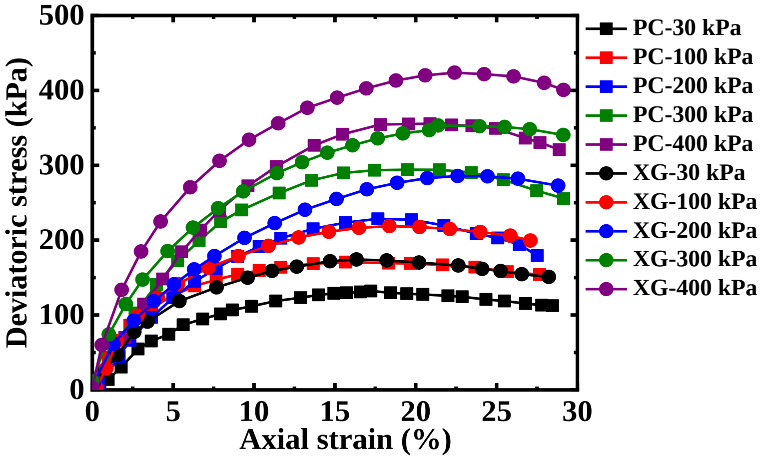
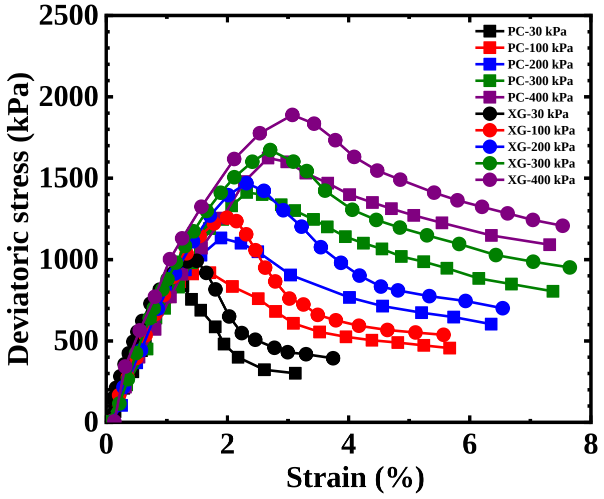
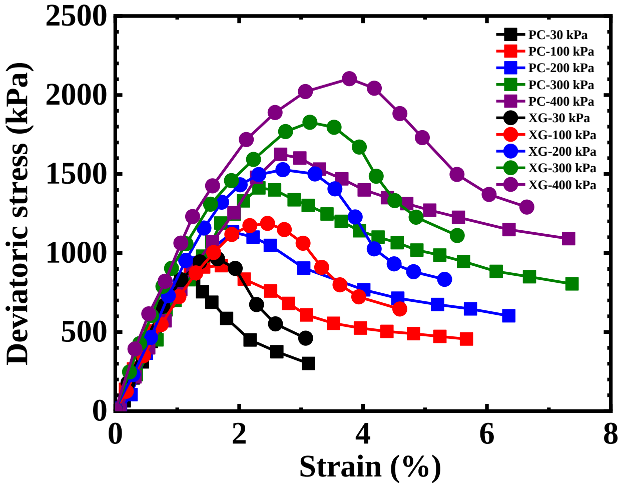


Figure 4.377 Initial stage of XG treated clay

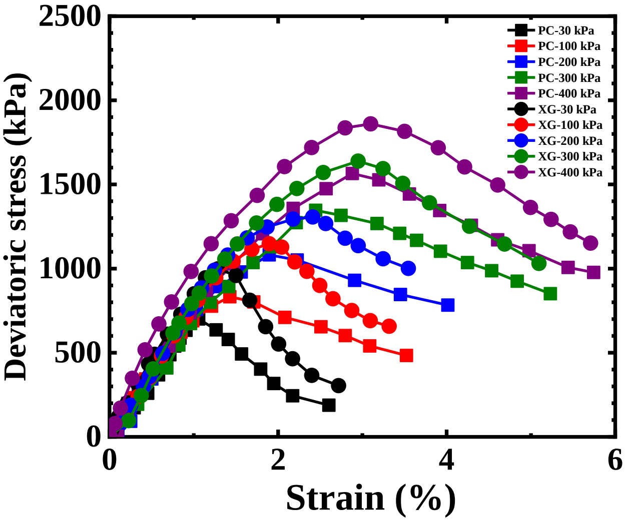
Figures 4.38-4.40 illustrate the deviatoric stress, Mohr-**coulomb circles** and shear parameters, respectively. It can be shown that the maximum deviatoric stress of untreated soil is 839.2, 919.6, 1133.1, 1412.1 and 1624.2 kPa with curing 21 days under the confining pressure 30, 100, 200, 300 and 400 kPa, respectively, while the corresponding maximum deviatoric stress of 1% XG treated clay is 992, 1257, 1470, 1673 and 1889 kPa. Figure 4.37 illustrates that the internal friction angle (IFA) and cohesion (*C*) increase from 31.7 to 32.7 °, from 202.9 to 265.5 kPa, respectively, at this stage. The dehydration of XG solution gradually leads to dried biopolymer fibres anchored on the clay particles to improve grain contact characteristics through connection and entanglement with others (Khatami and O'Kelly 2013). Moreover, the more elasticity membrane structure in the mixture can be achieved with the more liquid fraction of the specimens evaporated. This mechanism is time-independent at the curing state. Meanwhile, the high gel viscosity and adhesive properties are recognized due to the polymeric matrix creating a cross-link between the clay particles with more water evaporated, especially for the outer part of samples at room temperature. Therefore, biopolymer bonding and conglomeration properties during the shear process gradually enhance the internal friction angle and cohesion of treated clay.



(a) Stress-strain curves (21 days)



(b) Stress-strain curves (42 days)



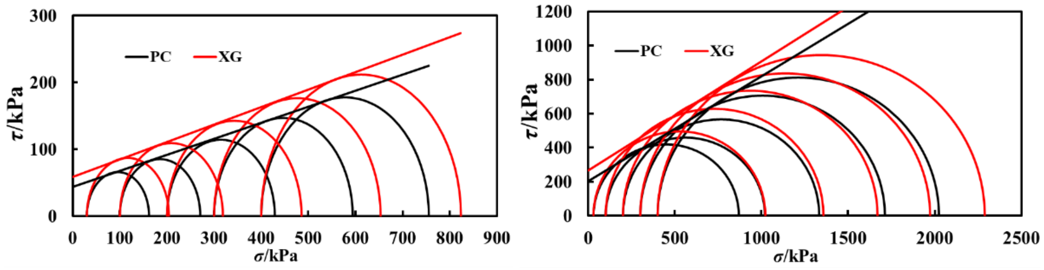
(c) Stress-strain curves (70 days)

Figure 4.388 Triaxial test results at curing stage

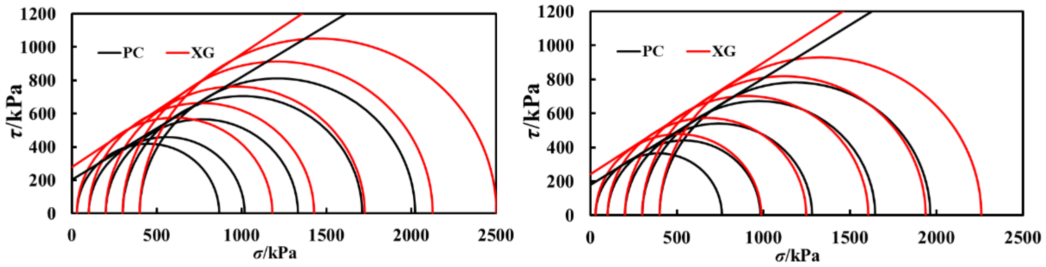
With the increase of curing time (e.g., 42 days), there is no significant increase in maximum deviatoric stress of untreated soil. In terms of 1% XG treated clay, the maximum deviatoric stress has a slight increase to 1152, 1328, 1527, 1827 and 2103 kPa under the confining pressure of 30, 100, 200, 300 and 400 kPa, respectively, along with the internal friction angle and cohesion increase from 32 to 34.2 °, 207.8 to 280.4 kPa, respectively, for untreated soil and XG treated soil at curing 42 days. Typically, the XG solution on the outer surface of samples would quickly show its crystallization and cementation effect due to air-dry conditions while also slowing down the cementation process in the inner part of the samples. However, the inside of the samples is still moist weak-link gel at curing 21 days. Therefore, the slight increase of XG treated soil at curing 42 days can be attributed to the formation of the new cementitious products in the inner part of the samples to make an interlock structure for the soil.

After drying over time (e.g., 70 days), the internal friction angle of untreated clay still almost keeps constant, and the cohesion slight decreases to 181.6 kPa. Similarly, the maximum deviatoric stress of XG treated soil decreases to 997.9, 1147.8, 1306.5, 1638.4 and 1860.1 kPa under the confining pressure of 30, 100, 200, 300 and 400 kPa, respectively. Correspondingly, the internal friction angle and cohesion of XG treated clay decrease to 32.9 ° and 244.7 kPa, respectively, compared to the values at curing 21 days. It can be explained that the external gel gradually spreads into the concentrated gel and then become the thin layer with long-term water evaporation. During this process, the mobility of biopolymer gradually decreases to zero. Moreover, the fixed thin film attached to the soil particle cannot shrink in each direction and is unable to present fluidity. With continually shrinking, the crack is generated to form the fracture surface. Therefore, some surface connections between the soil particles and biopolymer become brittle, leading to a slight decrease in maximum deviatoric stress in long-term curing. However, the maximum deviatoric stress is still significantly higher than untreated clay.

In the residual stage, it can be seen obviously the strain-soft behaviour in untreated and treated samples. Condensed biopolymer gels break into fragments under large strains, which are expected to behave as frictional materials to improve interlocking between soil particles at the initial failure stage. Therefore, the maximum deviatoric stress of XG treated clay is still higher than that of untreated soil through the interface of attractive adhesive forces between soil surfaces and viscous gels.



(a) 0 days (b) 21 days



(c) 42 days (d) 70 days

Figure 4.399 Mohr-coulomb circles of XG treated clay

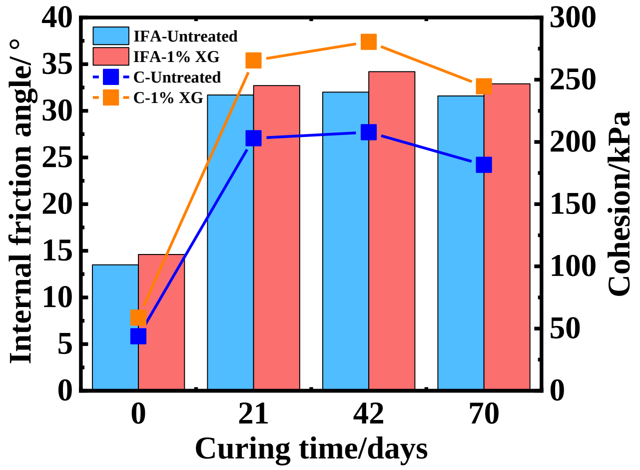
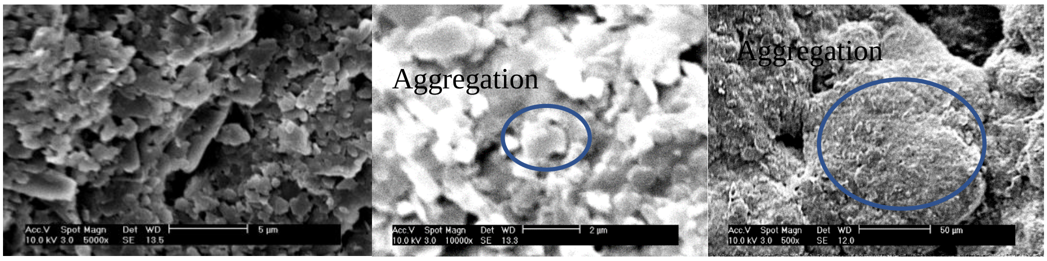


Figure 4.40 Shear strength parameters of various conditions

4.4 Feasibility analysis

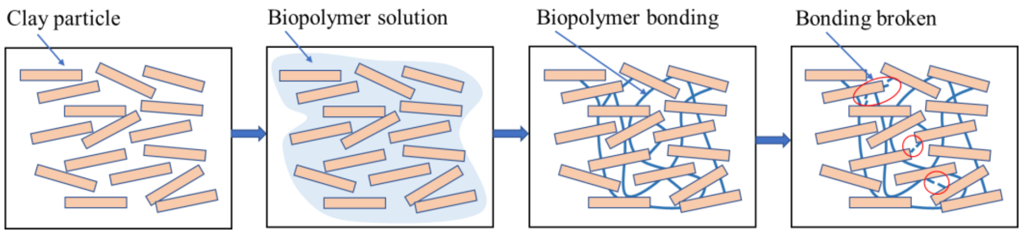
4.4.1 Reinforcement mechanism

Figure 4.41 illustrates the SEM images of untreated clay, XG treated clay and SA treated clay (the most efficient biopolymers on strengthening clay). It shows that the biopolymer can significantly make soil aggregation to form big particle sizes and connect clay particles through bonds strength. Therefore, the reinforcement mechanism of biopolymer treated clay can be explained as shown in Figure 4.42. At the initial condition (Figure 4.42 (b)), it forms uniformly dispersed and high viscosity biopolymer hydrogels immediately with a relatively flat and smooth surface structure (Chang and Cho 2019). Therefore, it has a limited effect on the mechanical behaviours of soil properties (e.g. strength, stiffness, and modulus) due to high water content in the biopolymer-soil matrix. When the primary rigid biopolymer hydrogel is subjected to dehydration, the thickened gels begin to coagulate around the clay particles, while the decrease in volumetric moisture content leads to the formation of discrete air voids with filling the biopolymer gels. Meanwhile, the hypothesis of biopolymer-soil micro behaviour is associated with anionic characteristics and chemical functional groups of biopolymer, which provides an electrical interaction and the hydrogen bonding between the biopolymer and the diffuse double layer of clay minerals that governs the interparticle behaviour of the treated clay. Once the biopolymer gels are dried, condensed film-like biopolymer gels enhance the inter-particle through biopolymer matrix formation among the clay particles (Figure 4.42 (c)). The dried biopolymer gels finally can improve the compressive strength, cohesion and shear strength of biopolymer treated soil. Nevertheless, with the continuous water evaporation, the gel gradually spreads into the concentrated gel and then becomes a thin layer and shranks, especially for the outer surface of biopolymer treated specimens drying in room temperature conditions. With continually shrinking, the crack is generated to form the fracture surface. During this process, the mobility of biopolymer gradually decreased to zero, causing the thin film of biopolymer to break easily, as shown in Figure 4.42 (d). Thus, a part of the surface connections between the soil particles and biopolymer become brittle.



(a) untreated clay (b) XG treated clay (c) SA treated clay

Figure 4.41 SEM images



(a) untreated clay (b) initial stage (c) drying process (d) long-term curing stage

Figure 4.42 Treatment process of XG treated clay

4.4.2 Economic analysis

Compared to other current soil improvement materials (e.g., cement, lime), the present high cost of biopolymers restricts their use in geotechnical engineering as shown in Table 4.2. However, the economic efficiency of biopolymers is increasing rapidly due to new manufacturing methods (i.e., bio-refineries) and environmental regulations (e.g., CO_2 emission). For soil improvement in geotechnical engineering, Chang and Cho (2012) illustrated that the total economical price for 1 ton of soil improvement by using 0.49% b-1,3/1,6-glucan polymer treatment was $1576, which was significantly lower than the 10% cement mixture ($2848). Chang et al. (2016b) also performed economic feasibilities on xanthan gum treated soil compared to cement. It shown that the total cost for 1 ton soil treatment by using 0.5% xanthan gum treatment was 12.95 USD, which was only 3.6% more expensive than 10% cement treatment (12.50 USD).

In this study, 1% ratio of biopolymer to the weight of soil can provide significant greater strengthening effect than that of a 10% Ordinary Portland Cement (OPC) (Chang and Cho 2012). For an equal unit (1 ton) of soil treatment, the material cost at current price of employing biopolymer is uneconomical compared to conventional cement mixing, such as SA being 140% more expensive (SA treatment: 30 USD/ton of soil; cement: 12.5 USD/ton of soil). However, biopolymer treatment soil becomes remarkably competitive when this CO2 emission trading is considered. Specifically, with the emphasis on environmental protection, the CO_2 emission trade price rapidly increases from 22 USD/ton of CO_2, in 2012 to 90 USD/ton of CO_2, in 2022 in last decade years (Böhringer et al. 2022). Therefore, the most biopolymers of total economical price (direct material cost + indirect CO_2 emission expense) for 1 ton of soil improvement is significantly lower than 10% cement mixture (23.75 USD), such as XG, GG and AG, while the price of SA treated soil (25.5 USD) is also similar to traiditonal material treated soil.

Moreover, in recent studies, all biopolymers used for soil improvement are mostly bacteriological or of food-grade quality, which requires high purity and a very hygienic production environment. Due to the high quality of biopolymer produced, the market price of the finished product would also be high. Therefore, if it is produced exclusively for stabilization purposes, the price would be drastically reduced. For example, the price of XG has a significant decrease by more than 90% in the last decade year. Overall, biopolymers have high potential to replace high carbon emitting soil treatment materials, especially when considering the aim of environment-friendly construction and development.

Table 4.2 Economic feasibility of XG in geotechnical engineering

Material	Price (USD/kg)	Required amount (kg/ton soil)	Material price (USD/ton soil)	CO_2 emission parameters			Total cost (USD)
				Per 1kg material production (kg)	Related (kg/ton soil)	Trade (USD/ton soil)[c]	
OPC	0.125[a]	100	12.5	+1.25	+125	+11.25	23.75
XG	1.75[b]	10	17.5	-5	-50	-4.5	13
LBG	9[b]	10	90				85.5
GG	2[b]	10	20				15.5
GE	10[b]	10	100				95.5
AG	2[b]	10	20				15.5
SA	3[b]	10	30				25.5
GL	0.9[b]	10	9				4.5
CA	8[b]	10	80				75.5
CH	3.5[b]	10	35				30.5
KG	4[b]	10	40				35.5
SU	30[b]	10	300				295.5
WT	10[b]	10	100				95.5

[a] Depicts the price of cement in the United States, in 2021 (www.statista.com); [b] Depicts the average price of sodium alginate, in 2022 (market price: www.alibaba.com); [c] EU ETS (European Union Emission Trading Scheme) carbon emission trade: 90 USD/ton of CO2,

in 2022 (https://blogs.imf.org/2022/07/21/more-countries-are-pricing-carbon-but-emissions-are-still-too-cheap/).

4.5 Possible implementation

In this part, the fundamental mechanisms of biopolymer treated clay are revealed. The engineering parameters, including UCS and shear strength parameters, were illustrated by considering biopolymer content, biopolymer type, initial water content, curing time, durability, cross-linking and mixing method. Herein, simple empirical models with the fitting parameters are suggested. The biopolymer treated clay can significantly increase strength even under biopolymer concentrations lower than 3%. Biopolymer treatment clay has special merits regarding its strengthening performance, low environmental impact, and quickness of function. It indicates that biopolymer has excellent potential and feasibility as new soil treatment materials in various geotechnical engineering fields regardless of hydraulic condition, especially as a temporary additive for shallow depth stabilisation, such as soil pavement, slope surface and surface erosion control. However, the durability of biopolymers is a critical issue due to their biodegradable and hydro sensitive behaviour. Thus, the long-term behaviour of biopolymer treated clay has to be verified to define its serviceability, especially for cyclic loading and climate change (e.g. rewetting-drying). In addition, it can also be utilized as a grout material in compaction grouting or deep cement mixing method due to its high viscosity when mixed with water and soil grains. Although the usage of biopolymers has numerous benefits for soil improvement/stabilization, each biopolymer has different advantages to soils because of their conditions, such as soil-biopolymer ratio, temperature and reaction with water. Overall, it is expected to better understand the physical and chemical properties of biopolymers treated soil and then correctly apply the biopolymers that fit geographical characteristics shortly. However, to be practically and economically applicable in site fields, various factors such as workability, cost, proper equipment and environmental issues need to be further assessed.

4.6 Summary

For meeting the gaps on the mechanical properties of biopolymer treated clay, this chapter mainly illustrates the unconfined compressive strength of biopolymer with considering various factors including biopolymer concentration (0.5%, 1%, 2%, 3%, 4% and 5%), biopolymer type (XG, SA, GE, LBG, KG, AG), initial water content (30%-60%), curing time (0-70 days), durability (long-term curing and rewetting-drying), cross-linking (XG-AG, XG-KG and XG-LBG) and mixing method (RDM, RWM, HDM and HWM). In addition, triaxial shear tests are conducted to investigate the shear behaviours (cohesion and internal friction angle) of various biopolymers (e.g., XG, BG, GG, GE, AG, SA, GL, CA, CH, KG, SU and WT) treated clay under hydraulic and dehydrated conditions. Lastly, the feasibility analysis, including reinforcement mechanism and economic analysis of biopolymer treated clay, is illustrated. Some conclusions are obtained as follows.

(1) The UCS of biopolymer treated clay is more significant than that of untreated clay (e.g., more than 5 times) and typically increases with the increase of biopolymer concentration, especially for after curing certain days (e.g., > 7 days). The most effective concentration of biopolymer treated clay is 1-2%. At hydrated and dehydrated conditions, the highest UCS is obtained in SA treated clay, following by XG treated clay. In addition, LBG, GE, KG and AG have a similar strengthening efficiency after curing 28 days that the UCS increment ratio of these four biopolymers treated clay is less than 90%. Moreover, the UCS of biopolymer treated clay increases firstly and then decreases with the increase of curing time, and the optimum curing time is normally 28-42 days depending on biopolymer type and concentration, and initial water content. However, the UCS increment ratio can even continuously increase at curing a long time.

(2) The UCS of untreated clay decreases with the increase of initial water content, while the UCS of biopolymer treated clay fluctuates. The optimum initial water content of 0.5%, 1%, 2% and 3% XG treated clay is 40%, 45%, 50% and 60%, respectively, which is 1.3, 1.46, 1.67 and 2 times of the optimum water content of untreated clay (30%). It illustrates that higher XG concentrations need more initial moisture content to obtain the full gel solution to improve the performance of hydrogen and ionic bonding between biopolymer and fine particles. There is a rough relationship between XG concentration (C_{XG}) and the UCS increment ratio (IR_{UCS}) regardless of curing time as $IR_{\mathrm{UCS}} = 100\ C_{\mathrm{XG}}$. On the other hand, the optimum initial moisture content of SA treated clay is 50-55% to form the stable SA gels strengthening

the clay through hydrogen and ionic bonding. In addition, the stable XG gels cause the smallest reduction of UCS at below 10%, while the UCS of SA treated clay has a decrement ratio of more than 20% at curing 70 days. Even under curing 54 weeks, the UCS decrement ratio is only 7-26% compared to the maximum value, and the biopolymer can still have good durability in reinforcement and stabilization clay that the UCS of biopolymer treated clay is 1.43-7.83 times of untreated clay.

(3) Under rewetting-drying conditions, the samples of untreated clay are broken and crushed when soaking in water for more than 2 hours, while the UCS of XG treated clay is still obviously larger than that of the highest UCS of untreated clay that it is 2.51, 2.31 and 2.15 times after 1, 2 and 3 cycles, respectively. Compared to the highest UCS of XG treated clay, the UCS decrement ratio is 9.96%, 17.15% and 22.83% with the rewetting-drying cycles of 1, 2 and 3, respectively. It can be shown that the UCS decrement ratio decreases with the increase of rewetting-drying cycles, and it tends to keep constant after certain rewetting-drying cycles. The UCS of XG-AG or XG-LBG treated clay increases with the increase of XG content, while the XG-KG with the ratio of 1:1 obtains the maximum UCS. Moreover, there is a threshold ratio value at XG-AG and XG-KG with 1:4 to significantly increase soil strength beyond this ratio. With the increase of curing time, the UCS of XG-AG or XG-KG treated clay is gradually larger than the pure XG treated clay, while the UCS of XG-LBG with the ratio of 4:1 is slightly larger than that of pure XG treated clay at curing smaller than 35 days.

(4) The optimum mixing method of XG/SA treated clay is HDM, and then RDM, which are significantly larger than that of XG treated clay mixing with RWM and HWM. It can be found that the dry mixing method is more effective than the wet mixing method to increase the UCS of XG/SA treated clay. In addition, the highest UCS of AG/GE treated clay is obtained at HWM following RDM and the UCS of AG/GE treated clay with HDM is the smallest. Therefore, in terms of AG/GE treated clay, the dry mixing method is more suitable in room-temperature water, while the wet mixing method is more suitable in hot water. In addition, the UCS of KG treated clay using hot water mixed is higher than that of room-temperature water. Furthermore, the dry mixing method is more efficient than the wet mixing method. Therefore, the highest UCS of KG treated clay is obtained by using HDM following HWM, and the smallest UCS of KG treated clay is observed with RWM. In terms of

LBG treated clay, the hot water temperature and wet mixing method are more suitable. Thus, the highest UCS of LBG treated clay is obtained by adopting HWM following RWM. In addition, the smallest UCS of LBG treated clay is observed in RDM. Considering the cross-linking of biopolymer, the highest UCS of XG-AG treated clay is achieved in RDM at higher XG-AG ratio (e.g., 4:1 and 3:2), while the optimum mixing method of XG-AG treated clay is HWM at low XG-AG ratio (e.g., 1:4 and 0:1). Under curing a long time, the highest UCS of XG-AG treated clay at the ratio of 1:1 and 2:3 is observed in RDM or RWM. Overall, the UCS of XG-AG treated clay with HDM, RDM and RWM is almost the same in the XG-AG ratio of 3:2, 1:1 and 2:3.

(5) Biopolymer significantly increases peak deviatoric stress for strengthening and stabilising clay at hydraulic conditions. Moreover, the cohesion increases due to the formation of biopolymer gel, while the internal friction angle has little change between untreated and treated clay. SA, AG, GE and GG are the most effective biopolymer to increase soil cohesion among all biopolymers treated clay, increasing more than 110% compared to untreated clay. And then KG, GL and CA have a similar effect on enhancing soil cohesion. In addition, BG, XG and SU can be regarded as the third level to strengthen soil cohesion, while CH and WT treated soil have limited increase in the soil cohesion. All of these depend on the electrical charge, chemical groups and viscosity of the biopolymer. With the increase of biopolymer concentration, the cohesion of biopolymer treated clay increases due to the formation of highly viscous hydrogels regardless of biopolymer type. However, this increment decreases, while the internal friction angle varies with the increase of biopolymer concentration because there are the contradictory effects with aggregating soil particles to change particle size distribution for increasing the internal friction of soil particles and the viscous biopolymer gel reducing the surface roughness to decrease the internal friction of soil particle. Moreover, the internal friction angle of untreated clay is 31.7 °, 32 ° and 31.6 ° at curing 21, 42 and 70 days, respectively, while the internal friction angle of 1% XG treated clay is 32.7 °, 34.2 ° and 32.9 °, respectively. Meanwhile, the cohesion of untreated clay is 202.9 kPa, 207.8 kPa and 181.6 kPa at curing 21, 42 and 70 days, respectively, while the cohesion of 1% XG treated clay is 265.5 kPa, 280.4 kPa, 244.7 kPa, respectively.

(6) At hydraulic conditions, the uniformly dispersed and high viscosity biopolymer hydrogels are formed immediately. And then, the thickened biopolymer gels begin to coagulate around the soil particles under the electrical interaction and the hydrogen bonding between the biopolymer chains and the diffuse double layer of clay minerals. After dehydration, the condensed film-like biopolymer gels enhance the inter-particle. However, after long-term curing with water evaporation, the gel gradually spreads into the concentrated gel and becomes a thin layer. During this process, the mobility of biopolymer gradually decreased to zero, causing the thin film of biopolymer to break easily with a slight decrease in strength. In terms of economic analysis, the present high cost of biopolymers restricts their application in geotechnical engineering compared to other current soil improvement materials (e.g., cement, lime). However, with environmental impact, some biopolymer (e.g., XG, GG, AG and SA) is competitive. Moreover, with the development of biopolymer production and reducing the quality requirement of biopolymers, it is expected that the price of biopolymers can still have a significant decrease in the future.

Chapter 5 Mechanical Properties of Biopolymer Treated Sand/Sand-clay Mixture

5.1 Materials and Method

5.1.1 Soil

5.1.1.1 Sand

Two types of sand (e.g. paving joint sand (S1) and sharp sand (S2)) were purchased from Building & Timber Supplies. The S1 and S2 grains' specific gravity was 2.65 and 2.66, respectively. The grain size distribution curves of both soils can be depicted in Figure 5.1. The basic properties of S1 were described as D_{50} = 0.36 mm, C_u = 1.70 and C_c = 1.02. The S1 is classified as poorly graded sand (SP) according to the ASTM D-2487. In addition, the basic properties of S2 were described as D_{50} = 0.43 mm, C_u = 1.74 and C_c = 0.97. Therefore, the S2 is also classified as poorly graded sand (SP) according to the ASTM D-2487.

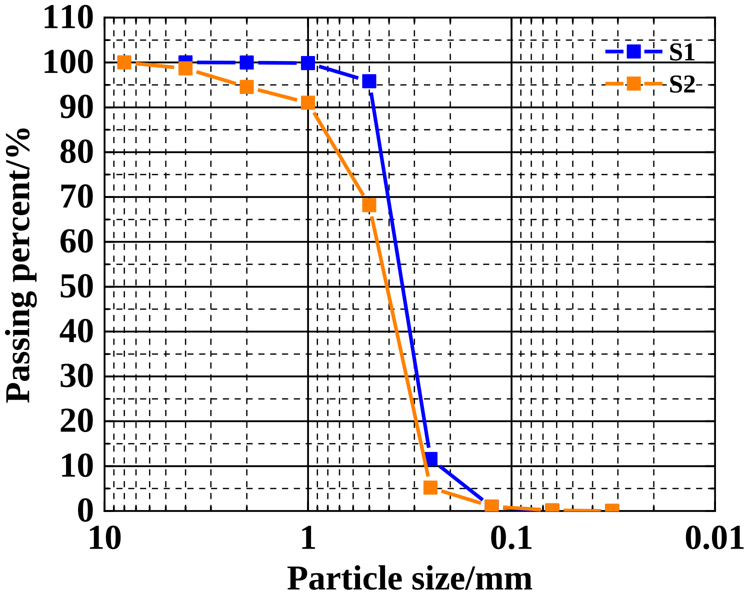


Figure 5.1 Grading curves of two types of sand

5.1.1.2 Clay-sand mixtures

Clean clay and sand were dried in an oven before specimen preparation. Different clay-sand mixtures were obtained by uniformly mixing dry sand and clay at the specific mass ratios (i.e., m_c/m_S; the clay-to-soil ratio in mass, where m_c/m_S=1.0 indicates pure clay) listed in Table 5.1.

Table 5.1 Clay-sand mixtures

m_c/m_s	Soil (%)	
	Sand	Clay
0	100	0
0.2	80	20
0.5	50	50
0.8	20	80
1	0	100

5.1.2 Biopolymer

Six biopolymers, e.g. carrageenan kappa gum (KG, CAS No: 90000-07-1), locust bean gum (LBG, CAS No: 9000-40-2), xanthan gum (XG, CAS No: 11138-66-2), agar gum (AG, CAS No: 9002-18-0), sodium alginate (SA, CAS No: 9005-38-3) and gellan gum (GE, CAS No: 71010-52-1) were used in the present study. The details can be found in section 3.1.2.

5.2 Sample preparation and experimental programme

To evaluate the engineering properties of the soil-biopolymer mixture, unconfined compressive tests were performed on biopolymer treated sand. The uniform biopolymer-soil mixture was compacted into three-part cylinder moulds with a diameter of 50 mm height of 100 mm. The details of sample preparation are illustrated in section 3.1.3. Table 5.2 lists the program details for the experimental test of untreated/biopolymer treated sand. The experimental programme of the unconfined compression test can be found in section 3.1.4.

Table 5.2 Experimental program summary

Soil	Biopolymer	Concentration/%	Curing time/days	Initial water content/%	Water condition	Mixing method
S1, S2	SA, XG, LBG, GE, KG, AG	1, 2, 3	14, 28	10-20	DC	DM

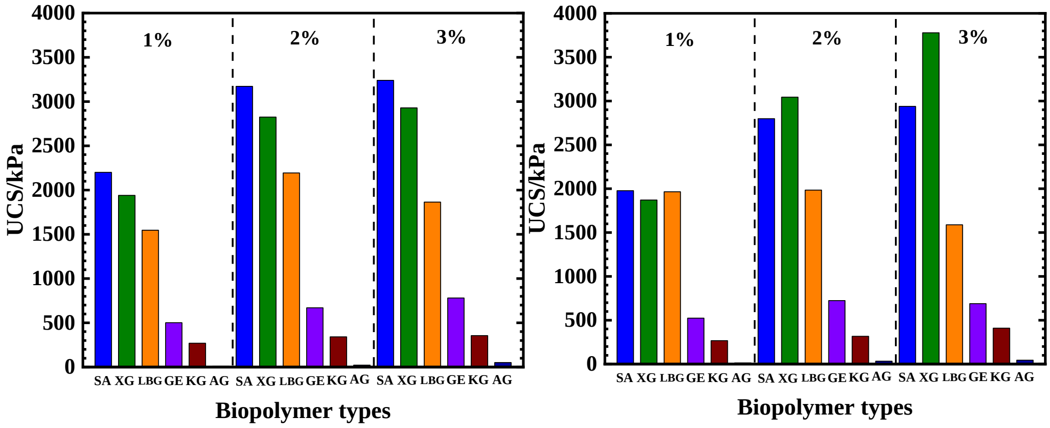
Clay-S1 (4-1)	XG	0.8, 1, 1.6, 2.4	14, 28, 35, 42, 49, 70	39	DC	DM
Clay-S1 (1-1)		0.5, 1, 1.5		30		
Clay-S1 (1-4)		0.2, 0.4, 0.6, 1		21		
Clay-S2 (4-1)	XG	1, 2, 3	14, 28	39	DC	DM
Clay-S2 (1-1)		1, 2, 3		30		
Clay-S2 (1-4)		1, 2, 3		21		
Clay-S2 (4-1)	SA	1, 2, 3	7, 28, 42, 49	43/44	DC	DM
Clay-S2 (1-1)		1, 2, 3		32.5/35		
Clay-S2 (1-4)		1, 2, 3		25.5/26		

5.3 Unconfined compressive test results

5.3.1 Effect of biopolymer type

It should be noted that the UCS of untreated sand can be almost neglected due to the cohesionless between sand particles regardless of curing time. Furthermore, Figure 5.2 illustrates the UCS of six typical biopolymer types (e.g., SA, XG, LBG, GE, KG and AG) treated S1. At curing 14 days, as shown in Figure 5.2 (a), the SA treated S1 obtained the highest UCS value regardless of biopolymer concentration, followed by XG treated S1. Subsequently, the performance of biopolymer on reinforcing the UCS of S1 was ranked as LBG, GE, KG and AG regardless of biopolymer concentration. However, although the UCS of AG was the smallest among these biopolymers, it can also significantly increase the UCS of S1. Specifically, the UCS of SA, XG, LBG, GE, KG and AG treated S1 at 1% concentration was 2199.9 kPa, 1940.5 kPa, 1546.8 kPa, 500.6 kPa, 268.8 kPa and 10.3 kPa that the UCS of SA treated S1 was 1.13, 1.42, 4.39, 8.18 and 213.58 times than that of XG, LBG, GE, KG and AG, respectively. Moreover, SA, XG, LBG, GE, KG, and AG treated S1 at 2% concentration was 3171.5 kPa, 2824.1 kPa, 2193.2 kPa, 669.5 kPa, 341.4 kPa and 21.9 kPa, respectively. Under this condition, the UCS of SA treated S1 was 1.12, 1.45, 4.74, 9.29 and 144.8 times that of XG, LBG, GE, KG and AG, respectively. In addition, the UCS of SA, XG, LBG, GE, KG and AG treated S1 at 3% concentration was 3239.7 kPa, 2928.8 kPa, 1863.8 kPa, 780.9 kPa, 355.2 kPa and 50.8 kPa, respectively. Moreover, the UCS of SA treated S1 was 1.11, 1.74, 4.15, 9.12, and 63.78 times that of XG, LBG, GE, KG and AG treated S1. Overall, the UCS of SA was about 1.11-1.13, 1.42-1.74, 4.15-4.74 and 8.18-9.29 times of XG, LBG, GE and KG treated S1, while the UCS of SA was significantly more extensive than that of AG treated S1 variety in a wide range from 63.78 to 213.58 times.

Figure 5.2 (b) illustrated the UCS of six typical biopolymer types treated with S1 for 28 days. It can be found that although the SA treated S1 obtained the highest UCS value at 1% that it was only a margin larger than that of LBG and XG treated S1. At 2% and 3% concentrations, the maximum UCS was obtained in XG treated S1, SA treated S1 and LBG treated S1. Obviously, the UCS of XG, SA and LBG treated S1 was more significant than that of GE, KG and AG treated S1. Similarly, the UCS of AG treated S1 was also most minor, more extensive than that of untreated S1. In addition, the highest UCS was obtained at 3% XG treated S1 at curing 28 days. Specifically, the UCS of SA, XG, LBG, GE, KG and AG treated S1 at 1% concentration was 1977.2 kPa, 1871.2 kPa, 1964.8 kPa, 523.6 kPa, 266.5 kPa and 13.6 kPa, respectively. Moreover, the UCS of SA treated S1 was 1.06, 1.01, 3.78, 7.42, and 145.38 times that of XG, LBG, GE, KG and AG treated S1. Moreover, the UCS of SA, XG, LBG, GE, KG and AG treated S1 at 2% concentration was 2799.2 kPa, 3044.3 kPa, 1984.5 kPa, 723.8 kPa, 316.4 kPa and 32.6 kPa, respectively. Under this condition, the UCS of XG treated S1 was about 1.09, 1.53, 4.21, 9.62 and 93.38 times that of SA, LBG, GE, KG and AG treated S1. In addition, the UCS of SA, XG, LBG, GE, KG and AG treated S1 at 3% concentration was 2938.6 kPa, 3778 kPa, 1587.9 kPa, 688.4 kPa, 409.2 kPa and 43.7 kPa, respectively, which the UCS of XG treated S1 was 1.29, 2.38, 5.49, 9.23 and 86.45 times of SA, LBG, GE, KG and AG treated S1. Overall, at low biopolymer concentration (e.g., 1%), the UCS of SA, XG and LBG treated S1 was almost identical, and the UCS of SA treated S1 only 1.01-1.06 times that of LBG and XG treated S1. Moreover, with the increase of biopolymer concentration, the UCS XG treated S1 more than that of SA and LBG increased. Meanwhile, compared to the best performance of biopolymer reinforcing S1 (e.g., SA or XG), the UCS decrement time of GE treated S1 continuously increased with the increase of biopolymer concentration, while the UCS decrement time of AG treated S1 decreased. Moreover, the UCS decrement time of KG treated S1 increased firstly and then tended to keep constant with the increase of biopolymer concentration.



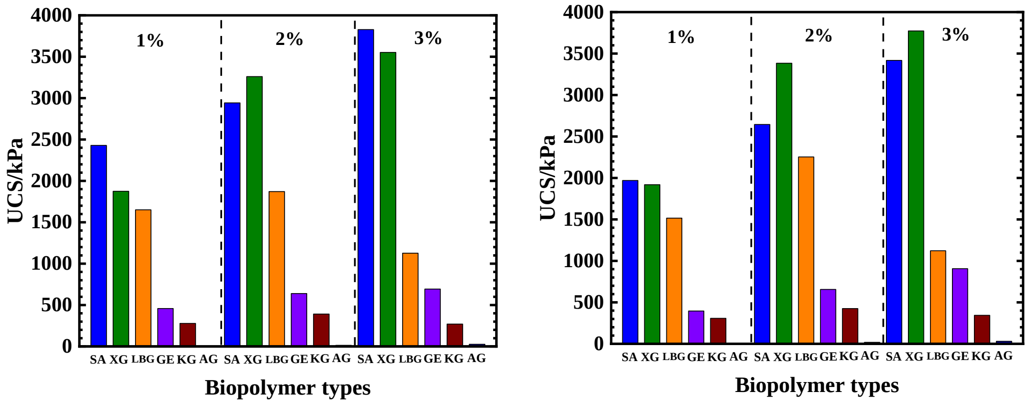
(a) 14 days (b) 28 days

Figure 5.2 Various biopolymer types treated S1

Figure 5.3 illustrates the UCS of various biopolymer types treated S2. It can be observed that the highest UCS can be achieved in 3% SA treated S2 with curing 14 days (3828.5 kPa) and 3% XG treated S2 with curing 28 days (3772.8 kPa). In addition, the results show that at curing 14 days, the SA treated S2 can be observed with the highest UCS value with 1%, and 3% concentrations, followed by XG and LBG treated S2. However, the XG treated S2 can be observed with the highest UCS value with a 2% concentration, following by SA and LBG treated S2. Therefore, the SA and XG can be regarded as efficient biopolymers for reinforcement of the UCS of S2. However, the difference between the UCS of LBG treated S2 and SA, or XG treated S2 increased with the increase of biopolymer concentration. In addition, compared to the former three biopolymers, the GE, KG and AG treated S2 had the lower UCS, especially for AG treated S2, regardless of biopolymer concentrations. Specifically, the UCS of SA, XG, LBG, GE, KG and AG treated S2 at 1% concentration was 2428.8 kPa, 1875 kPa, 1650.2 kPa, 458.5 kPa, 278.1 kPa and 5.9 kPa, respectively. In this condition, the UCS of SA treated S2 was about 1.30, 1.47, 5.30, 8.73 and 411.66 times that of the XG, LBG, GE, KG and AG, respectively. Moreover, the UCS of SA, XG, LBG, GE, KG and AG treated S2 at 2% was 2942.3 kPa, 3260.6 kPa, 1871.2 kPa, 639.6 kPa, 390.9 kPa and 13.8 kPa, respectively. The UCS of XG treated S2 was about 1.11, 1.74, 5.10, 8.34, and 236.28 times that of the SA, LBG, GE, KG and AG treated S2. Meanwhile, the UCS of SA, XG, LBG, GE, KG and AG treated S2 at 3% was 3828.5 kPa, 3552.4 kPa, 1126.5 kPa, 693.7 kPa, 270.7 kPa and 25.5 kPa, respectively. Under this condition, SA treated S2 was 1.08, 3.40, 5.53, 14.14, and 150.14 times the XG, LBG, GE, KG and AG treated S2.

As shown in Figure 5.3 (b), with curing 28 days, the highest UCS can be observed at SA treated S2 at 1% concentration, followed by XG, LBG, GE, KG and AG treated S2, while the XG treated S2 obtained the highest UCS value at 2% and 3% concentrations following by SA, LBG, GE, KG and AG treated S2. Especially at 1% concentration, the difference UCS between the SA, XG and LBG treated S2 was limited, while the difference UCS of LBG treated S2 compared to SA/XG treated S2 increased with the increase of biopolymer concentration. In addition, the UCS of GE, KG and AG treated S2 was relatively small, while they still performed good properties on increasing UCS compared to untreated S2. Specifically, the UCS of SA, XG, LBG, GE, KG, and AG treated S2 at 1% concentration was 1969 kPa, 1918.7 kPa, 1515.6 kPa, 396.2 kPa, 307.8 kPa and 8.1 kPa, respectively. In this condition, the UCS of SA was 1.03, 1.30, 4.97, 6.40 and 243.09 times that of XG, LGB, GE, KG and AG treated S2, respectively. Furthermore, the UCS of SA, XG, LBG, GE, KG and AG treated S2 at 2% concentration was 2644.8 kPa, 3384 kPa, 2253.7 kPa, 655.6 kPa, 425.3 kPa and 18.4 kPa, respectively. The UCS of XG treated S2 was 1.28, 1.50, 5.16, 7.96 and 183.91 times that of SA, LBG, GE, KG and AG treated S2. Moreover, the UCS of SA, XG, LBG, GE, KG and AG treated was 3417.6 kPa, 3772.8 kPa, 1122 kPa, 906.6 kPa, 343.4 kPa and 30.8 kPa, respectively. Under this case, the UCS of XG treated SA was 1.10, 3.36, 4.16, 10.99 and 122.49 times that of SA, LBG, GE, KG and AG treated S2.

Overall, the highest UCS of biopolymer treated S2 was similar to the secondary UCS value of biopolymer treated S2 (e.g., 1.03-1.30 times). Meanwhile, compared to the best performance of biopolymer, the UCS decrement of LBG and KG treated S2 increased, and the UCS decrement of AG treated S2 decreased with the increase of biopolymer concentration, while the UCS change of GE treated S2 tended to keep constant.



(a) 14 days

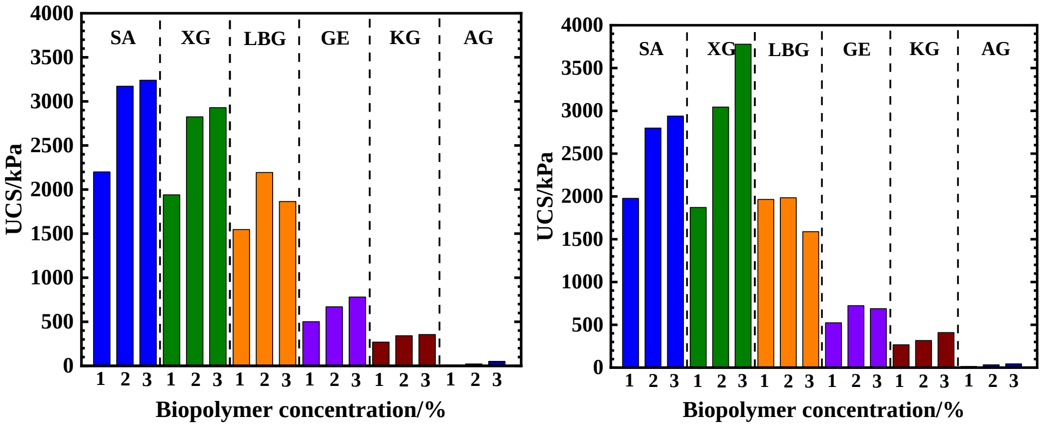
(b) 28 days

Figure 5.3 Various biopolymer types treated S2

5.3.2 Effect of biopolymer concentration

Figure 5.4 shows the UCS of various biopolymers treated S1 (e.g., SA, XG, LBG, GE, KG and AG) at 1%, 2% and 3% concentrations with curing 14 days and 28 days to illustrate the influence of biopolymer concentration on the reinforcement effect. It is shown that the UCS of 1% biopolymer treated S1 had a considerable increase compared to untreated S1. And then, with the biopolymer concentration increased to 2%, the UCS of biopolymer treated S1 still had a significant increase regardless of curing time. However, the UCS of 3% biopolymer treated S1 had a margin increase, even lower than 2% biopolymer treated S1. Therefore, it can be regarded that only 1% biopolymer can reach the excellent reinforcement effect for S1. Meanwhile, the optimum biopolymer concentration (e.g., 2%) was obtained to obtain the best performance. Specifically, with the biopolymer concentration increasing from 1% to 2% and the samples curing for 14 days, the UCS increment ratio of SA, XG, LBG, GE, KG and AG treated S1 was 44.17%, 45.53%, 41.79%, 33.74%, 27.01% and 112.62%, respectively, while the UCS increment ratio of SA, XG, LBG, GE, KG and AG treated S1 was 2.15%, 3.71%, -15.02%, 16.64%, 4.04% and 131.96%, respectively, with the biopolymer increasing from 2% to 3%. It should be noted that although AG treated S1 still kept the continuous significantly increase with the increase of biopolymer concentration, the UCS value of AG treated S1 was obviously smaller than other biopolymers treated S1.

As shown in Figure 5.4 (b), at curing 28 days, the UCS increment ratio of SA, XG, LBG, GE, KG and AG treated S1 with the biopolymer concentration increasing from 1% to 2% was 41.57%, 62.69%, 1.00%, 38.24%, 18.72% and 139.71%, respectively. And with the biopolymer concentration increasing from 2% to 3%, the UCS increment ratio of SA, XG, LBG, GE, KG and AG was 4.98%, 24.1%, -19.98%, -4.89%, 29.33% and 34.05%, respectively. It can be observed that the increment ratio decreased with the increase of biopolymer concentration except for KG, while the KG treated S1 can still keep good performance on reinforcing S1. In addition, the UCS of 3% LBG and GE treated S1 was even lower than that of 2% biopolymer concentration.



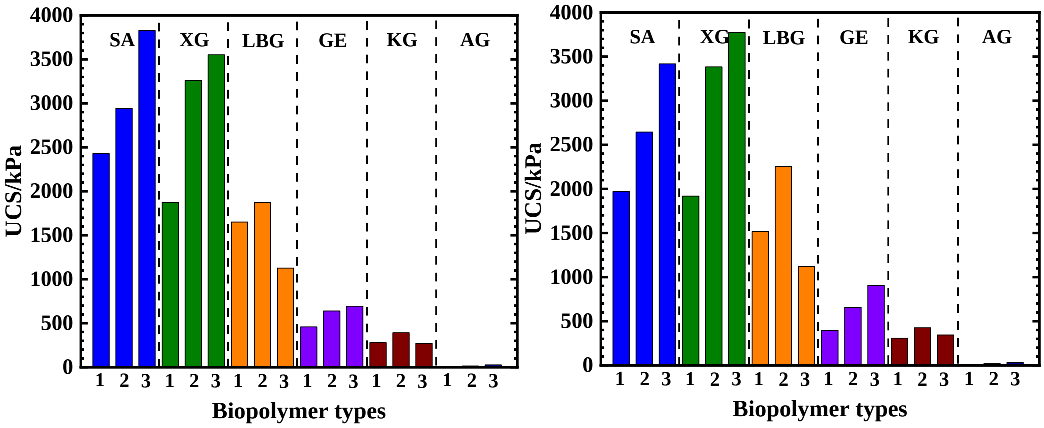
(a) 14 days

(b) 28 days

Figure 5.4 Various biopolymer types treated S1

Figure 5.5 illustrated that the UCS of six typical biopolymers (e.g., SA, XG, LBG, GE, KG and AG) treated S1 with increased of biopolymer concentration from 1% to 3% at curing 14 and 28 days. It can be observed that the UCS of SA treated S1 continuous increased with the increase of biopolymer concentration, and the corresponding increment ratio also kept constant or even increased regardless of curing time. On the other hand, the UCS of XG, GE and AG treated S2 also increased with biopolymer concentration, while the UCS increment ratio decreased. However, the UCS of LBG and KG treated S2 increased firstly with the biopolymer concentration increasing from 1% to 2% and then decreased with the biopolymer concentration increasing to 3%. Therefore, it can be concluded that the small biopolymer concentration (e.g., 1%) can better improve the strength of S2, and there was the optimum biopolymer concentration (e.g., 2%) for most biopolymer types. In comparison, SA treated S2 can still keep the excellent reinforcement effect even at 3% concentration.

Specifically, as shown in Figure 5.5 (a), under curing 14 days, the UCS increment ratio of SA, XG, LBG, GE, KG and AG treated S2 was about 21.14%, 73.90%, 13.39%, 39.50%, 40.56% and 133.90%, respectively, with the biopolymer concentration increasing from 1% to 2%. Moreover, the UCS increment ratio of SA, XG, LBG, GE, KG and AG treated S2 was about 30.12%, 8.95%, -39.80%, 8.46%, -30.75% and 84.78%, respectively, with the biopolymer concentration increasing from 2% to 3%. On the other hand, as shown in Figure 5.5 (b), under curing 28 days, the UCS increment ratio of SA, XG, LBG, GE, KG and AG treated SA was 34.32%, 76.37%, 48.70%, 65.47%, 38.17% and 127.16%, respectively, with the biopolymer concentration increasing from 1% to 2%. And the increment ratio of SA, XG, LBG, GE, KG and AG treated S2 was 29.22%, 11.49%, -50.22%, 38.29%, -19.26% and 67.39%, respectively, with the biopolymer concentration increasing from 2% to 3%.



(a) 14 days

(b) 28 days

Figure 5.5 Various biopolymer types treated S2

Taking the typical biopolymer (e.g., XG) as an example, Figures 5.6-5.8 illustrate the UCS of XG treated with different sand-clay mixture (e.g., 4:1, 1:1, 1:4) with considering different biopolymer concentrations at curing 14, 28, 35, 42, 49 and 70 days. Chang et al. (2020) illustrated that the clay content was critical in the total soil weight for revealing the reinforcement effect of biopolymer treated on the soil. Therefore, the biopolymer concentration was selected with two methods in this study. On the one hand, the ratio of biopolymer to total soil weight was 1%, 2%

and 3%, respectively. On the other hand, the biopolymer ratio to clay content was 1%, 2% and 3%, respectively. For example, in terms of sand-clay mixture with 4:1, the ratio of biopolymer to total soil with 0.2% can be regarded as the ratio of biopolymer to clay content with 1%. Table 5.1 illustrates the corresponding biopolymer concentration compared to the total soil and clay content.

Table 5.3 Biopolymer concentrations

Biopolymer	Sand-clay mixture ratio	***BC*$_{ts}$**	***BC*$_c$**
XG	4:1	0.2	1
		0.4	2
		0.6	3
	1:1	0.5	1
		1	2
		1.5	3
	1:4	0.8	1
		1.6	2
		2.4	3

Note: ***BC*$_{ts}$** is the ratio of biopolymer weight to total soil weight.

***BC*$_c$** is the ratio of biopolymer weight to clay content weight.

As shown in Figure 5.6, the UCS of XG treated sand-clay mixture with 4:1 increased with the increase of BC_c in the range of 1-3% concentration and the UCS increment ratio decreased regardless of curing time. Specifically, the UCS of untreated sand 1-clay mixture with 4:1 (S_1C_{4-1}) was 179.3 kPa, 224.4 kPa, 200.3 kPa, 183.7 kPa, 175.5 kPa and 132.1 kPa at curing 14. 28, 35, 42, 49 and 70 days, respectively. And the UCS of 1% BC_c treated SC_{4-1} was 672.2 kPa, 746.2 kPa, 741 kPa, 707.3 kPa, 675.7 kPa and 653.8 kPa at curing 14. 28, 35, 42, 49 and 70 days, respectively, which represented the increment ratio of 274.9%, 232.5%, 269.9%, 285.0%, 285.0% and 394.9%, respectively, compared to untreated soil. Moreover, the UCS of 2% BC_c treated SC_{4-1} was 1073.9 kPa, 1253.2 kPa, 1121.9 kPa, 1051.8 kPa, 1018.3 kPa and 988.5 kPa at curing 14. 28, 35, 42, 49 and 70 days, respectively. Compared to 1% BC_c treated SC_{4-1}, the UCS increment ratio was 59.8%, 67.9%, 51.4%, 48.7%, 50.7% and 51.2%, respectively. In addition, the

UCS of 3% BC_c treated S_1C_{4-1} was 1073.9 kPa, 1253.2 kPa, 1121.9 kPa, 1051.8 kPa, 1018.3 kPa and 988.5 kPa at curing 14. 28, 35, 42, 49 and 70 days, respectively. Compared to 2% BC_c treated SC_{4-1}, the UCS increment ratio was only about 10.8%, 10.9%, 10.3%, 6.3%, 4.7% and 4.9%, respectively.

Considering the biopolymer ratio to total soil weight, it can be observed that the UCS of XG treated S_1C_{4-1} sharply increased to 1352.8 kPa, 1676.9 kPa, 1429.4 kPa, 1388 kPa, 1172.6 kPa and 1068.9 kPa with the BC_{ts} increasing to 1% at curing 14, 28, 35, 42, 49 and 70 days, respectively, which illustrated the UCS increment ratio of 654.5%, 647.3%, 613.6%, 655.6%, 568.1% and 709.2%, respectively. For curing 14 days, the UCS of 2% and 3% BC_{ts} slightly decreased to 1312.1 kPa and 1290.8 kPa, respectively. Under other conditions, the UCS of 2% BC_{ts} slightly increased to 1790 kPa, 1616.8 kPa, 1614.7 kPa, 1442.3 kPa and 1413.6 kPa at curing 28, 35, 42, 49 and 70 days, respectively. Compared to 1% BC_{ts} treated soil, the UCS increment ratio was only 6.7%, 13.1%, 16.3%, 23.0% and 32.2%, respectively. However, with the BC_{ts} increasing to 3%, the UCS again significantly increased to 2665.1 kPa, 2580.3 kPa, 2169.3 kPa, 1973.2 kPa and 1913.1 kPa at curing 28, 35, 42, 49 and 70 days, respectively. Compared to 2% BC_{ts} treated soil, the UCS increment ratio was 48.9%, 59.6%, 34.3%, 36.8% and 35.3%, respectively.

Overall, it can be illustrated that only a tiny biopolymer concentration (e.g., 0.2% BC_{ts}) can significantly increase the UCS of soil, which presented the highest UCS increment ratio and was more than 5.68-7.09 times of untreated soil. And then, with the increase of BC_{ts}, the UCS increase ratio tended to decrease firstly and then increase. It can be observed that there was another significant increase stage from 2% BC_{ts} to 3% BC_{ts}. In addition, with less curing time, the UCS of higher BC_{ts} (e.g., 2% and 3%) treated soil may be less than the lower BC_{ts} (e.g., 1%) treated soil because the higher BC_{ts} had good water retention, and there was not enough time to form the stable biopolymer-soil matrices performing the lower UCS.

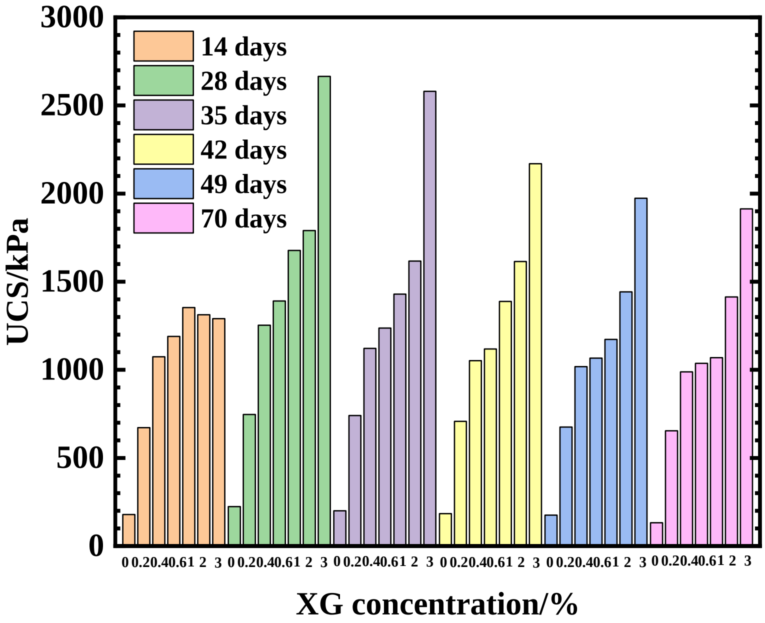


Figure 5.6 XG treated S_1C_{4-1}

Figure 5.7 illustrated the UCS of various XG concentration treated S1-clay mixture with the ratio of 1:1 (S_1C_{1-1}) at different curing time. Considering the ratio of XG weight to clay content (BC_c), it illustrated that the UCS of XG treated S_1C_{1-1} increased with the increase of BC_c and the UCS increment ratio decreased in the BC_c range of 1-3% regardless of curing time. Specifically, the UCS of untreated S_1C_{4-1} was 222.4 kPa, 365.7 kPa, 330.4 kPa, 281 kPa, 249.3 kPa and 214.9 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. With the BC_c increasing to 1%, the UCS sharply increased to 1400.8 kPa, 1749 kPa, 1659.3 kPa, 1443.5 kPa, 1211.6 kPa and 1104.8 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively, which presented the UCS increment ratio of 529.9%, 378.3%, 402.2%, 413.7%, 386.0% and 414.1%, respectively. And then the UCS of 2% BC_c treated S_1C_{1-1} also significant increased to 2018.1 kPa, 2425.3 kPa, 2371.2 kPa, 2197 kPa, 2005.7 kPa and 1835.3 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to 1% BC_c, the UCS increment ratio was 44.1%, 38.7%, 42.9%, 52.2%, 65.5% and 66.1%, respectively. However, the UCS of 3% BC_c treated S_1C_{1-1} slightly increased to 2376.1 kPa, 2752.1 kPa, 2463.2 kPa, 2281.6 kPa, 2095 kPa and 1938.6 kPa, respectively. Compared to 2% BC_c, the UCS increment ratio was 17.7%, 13.5%, 3.9%, 3.9%, 4.5% and 5.6%, respectively.

Considering the ratio of biopolymer concentration to total soil weight, the UCS of XG treated S_1C_{1-1} increased firstly from 1% BC_{ts} to 2% BC_{ts} and then decreased from 2% BC_{ts} to 3% BC_{ts} regardless of curing time. Specifically, the UCS of 1% BC_{ts} treated S_1C_{1-1} was same with the 2% BC_c treated S_1C_{1-1}. Moreover, the UCS of 2% BC_{ts} treated S_1C_{1-1} was 2485.1 kPa, 3046.4 kPa, 2900.2 kPa, 2823.6 kPa, 2706.7 kPa and 2595.4 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to 1% BC_{ts} treated S_1C_{4-1}, the UCS increment ratio corresponded to 23.14%, 25.61%, 22.31%, 28.52%, 34.95% and 41.42%, respectively. However, the UCS of 3% BC_{ts} treated S_1C_{4-1} decreased to 2234.3 kPa, 2754.2 kPa, 2634.4 kPa, 2526 kPa, 2501.6 kPa and 2466.8 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Correspondingly, the UCS decrement ratio was -10.1%, -3.37%, -13.52%, -10.54%, -7.58% and -4.95%, respectively.

Overall, regardless of curing time, it can be concluded that the UCS of XG treated S_1C_{1-1} can be significantly improved even only adding small BC_{ts} (e.g., 0.5%), which was more about 3.78-5.3 times of untreated soil. And the 0.5% BC_{ts} treated S_1C_{4-1} corresponded to the highest UCS increment ratio. In addition, with the increase of BC_{ts}, the UCS of XG treated S_1C_{1-1} increased before 2% BC_{ts}. Furthermore, the UCS increment ratio also decreased with the increase of BC_{ts}, especially for curing 14 and 28 days. For a curing long time, the increment ratio significantly increased from 1.5% BC_{ts} to 2% BC_{ts}. Moreover, the UCS of XG treated S_1C_{4-1} can even decrease from 2% BC_{ts} to 3% BC_{ts} regardless of curing time. However, with the addition of XG, it can perform a good ability to huge increase the UCS of S_1C_{1-1}.

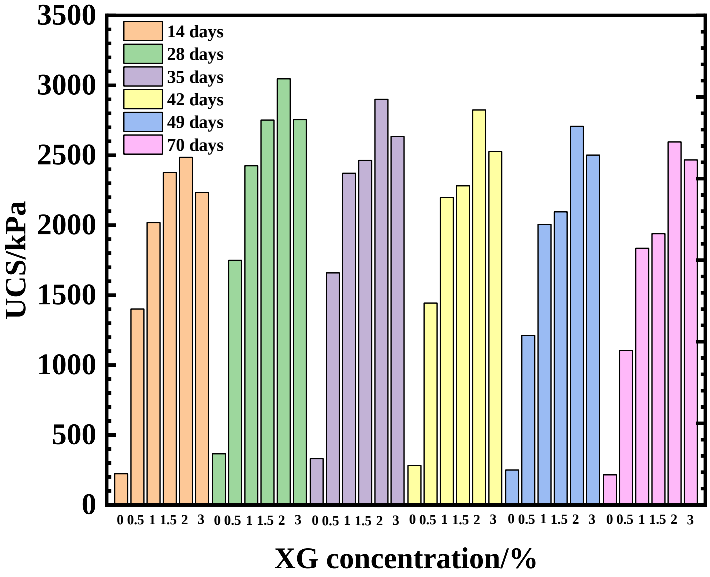


Figure 5.7 XG treated S_1C_{1-1}

Figure 5.8 illustrated the various XG concentrations treated the S1-clay mixture with the ratio of 1:4 (S_1C_{1-4}) at different curing time. The UCS of untreated S_1C_{1-4} was 349.6 kPa, 383.6 kPa, 363.3 kPa, 337.7 kPa, 317.9 kPa and 309.8 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Considering the ratio of biopolymer concentration to clay content, the results shown that the UCS of 1% BC_c treated S_1C_{1-4} sharply increased to 1299.9 kPa, 1780 kPa, 1683.3 kPa, 1514.8 kPa, 1456.4 kPa and 1381.1 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to untreated soil, the UCS increment ratio was 271.8%, 364.0%, 363.3%, 348.6%, 358.1% and 345.8%, respectively. With the BC_c increasing to 2%, the UCS was 1518.9 kPa, 2551.2 kPa, 2497.6 kPa, 2371.5 kPa, 2124.6 kPa and 2077.4 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to 1% BC_c, the UCS increment ratio corresponded to 16.85%, 43.33%, 48.38%, 56.56%, 45.88% and 50.42%, respectively. And then the UCS of 3% BC_c treated S_1C_{1-4} was 2525.7 kPa, 3617.7 kPa, 3397.7 kPa, 3148.4 kPa, 3105.8 kPa and 3063.8 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to 1% BC_c, the UCS increment ratio was 66.28%, 41.80%, 36.04%, 32.76%, 46.18% and 47.48%, respectively. It can be observed the UCS increment ratio decreased firstly from 1% BC_c to 2% BC_c and then increased from 2% BC_c to 3% BC_c. In addition, the highest UCS increment ratio can be obtained at 1% BC_c, which was more 2.72-3.64 times than untreated soil.

Considering the ratio of biopolymer concentration to total soil weight (BC_{ts}), the UCS of 1% BC_{ts} treated S_1C_{4-1} was 1491.1 kPa, 2337.7 kPa, 2134.7 kPa, 1951.4 kPa, 1879.7 kPa and 1610.1 kPa curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to untreated soil, the UCS increment ratio was 326.52 kPa, 509.41%, 487.59%, 477.85%, 491.29% and 419.72%, respectively. With the BC_{ts} increasing to 2%, the UCS was 1890.5 kPa, 2823.6 kPa, 2737.8 kPa, 2633.5 kPa, 2433.5 kPa and 2236.2 kPa, respectively. Compared to 1% BC_{ts}, the UCS was 26.79%, 20.79%, 28.25%, 34.95%, 29.46% and 38.89%, respectively. However, the UCS of 3% BC_{ts} decreased to 2324.4 kPa, 3056.9 kPa, 3030.2 kPa, 2928.3 kPa, 2751.4 kPa and 2586.9 kPa at curing 14, 28, 35, 42, 49 and 70 days, respectively. Compared to 2% BC_{ts}, the UCS decrement ratio was -7.97%, -15.50%, -10.82%, -6.99%, -11.41% and -15.57%, respectively.

Overall, it can be concluded that the UCS of XG treated S_1C_{1-4} increased firstly (BC_{ts} < 2.4%) and then decreased (BC_{ts} > 2.4%) with the increase of BC_{ts}. In addition, the highest UCS increment ratio was obtained at 0.8% BC_{ts}, and the value tended to decrease before 2% BC_{ts} followed by a slight increase until 2.4% BC_{ts}. However, with the BC_{ts} increasing to 3%, the UCS values were smaller than that of 2.4% BC_{ts}, and the increment ratio in this range was negative.

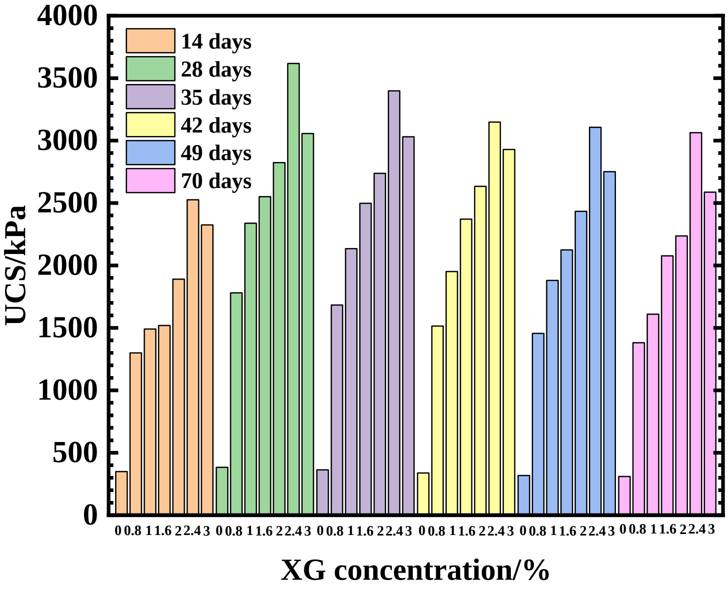


Figure 5.8 XG treated S_1C_{1-4}

5.3.3 Effect of soil type

Soil type played a vital role in the formation of biopolymer-soil matrices. For example, the biopolymer can connect clay particles through ionic and hydrogen bonds and link the sand particles through physical association and biopolymer chains. Moreover, biopolymer hydrogels are three-dimensional biopolymer networks in which individual hydrophilic biopolymer chains are connected, either by physical association or chemical bonds. In this part, the XG treated sand 1-clay and XG or SA treated sand 2-clay with a different mixing ratio (4:1, 1:1, and 1:4) and curing time were selected to illustrate the influence of soil type on the reinforcement effect of biopolymer treated soil.

Figure 5.9 illustrated the UCS of different XG concentrations (1%, 2% and 3%) treated different sand 1-clay mixture ratio (4:1 (S_1C_{4-1}), 1:1 (S_1C_{1-1}) and 1:4 (S_1C_{1-4})) at various curing time. The results have shown that the UCS of untreated soil about linear increased with the increase of clay content regardless of curing time because the strength of untreated soil normally depended on the internal friction angle and cohesion of soil. However, with the occurrence of biopolymer, the soil strength was sensitive to the formation of soil-biopolymer matrices influenced by physical association and chemical bonds (e.g., ionic bonds and hydrogen bonds). It can be observed that the highest UCS of 1% XG treated soil was obtained in the S_1C_{1-1} among all soil types regardless of curing time because of the good soil grade and the ionic/hydrogen bonds between XG chains and clay particles, and the physical association between XG and sand. At less curing time (e.g., 14 days), the 1% XG treated sand can be obtained the secondary high UCS value because the biopolymer treated sand had the poor water retention stability, causing this soil type to reach the maximum UCS quickly. However, with the increase in curing time, the soil type with the occurrence of clay tended to show the higher UCS because the biopolymer-soil matrices with strong bonds can be fully formed. In addition, the higher clay content needs more curing time to reach the maximum UCS and can still maintain its strength for a long time. Specifically, the UCS of 1% XG treated S_1C_{1-4} was more than that of pure sand from curing 28 days as the secondary high value. Moreover, the UCS of 1% XG treated pure clay was the smallest value at curing 14 and 28 days among these soil types. With the curing time increasing to 35 days, its UCS started to overcome the UCS of 1% XG treated S_1C_{4-1}, and the UCS difference between 1% XG treated pure clay, and 1% XG treated pure sand or S_1C_{1-4} decreased with the increase of curing time. For example, the UCS of 1% XG treated pure sand, S_1C_{1-4} and pure clay at curing 70 days was 1537.9 kPa, 1610.1 and 1521.2 kPa, respectively. The highest UCS of 1% XG treated soil was 78.75%, 56.27%, 65.89%, 58.29%, 71.05% and 71.70% at curing 14, 28, 35, 42, 49 and 70 days, respectively.

In terms of 2% XG treated different soil types, it can be shown that the UCS of XG treated sand was highest with less curing time (< 42 days) because of the poor water retention and the strong connection of biopolymer-soil matrices. Meanwhile, the secondary high UCS was observed at XG treated S_1C_{1-1} because of the good soil grade and the formation of ionic and hydrogen bonds formed between charged XG molecules and clay particles. However, with clay content, it tended to have good water retention. Therefore, the XG treated S_1C_{1-1} can keep higher UCS and reduce the decrement ratio at a longer curing time. The results have shown that the

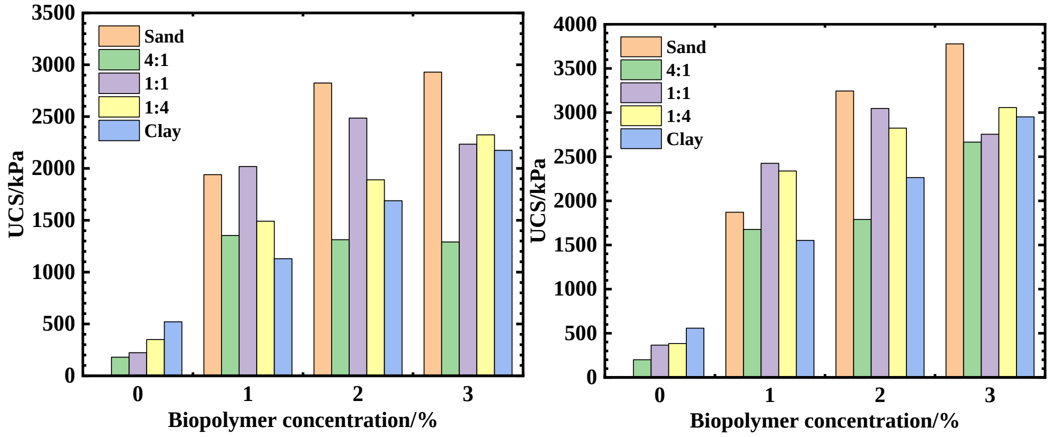
UCS of XG treated S_1C_{1-1} was higher than that of XG treated sand at curing 49 and 70 days. At the same time, although the UCS of XG treated S_1C_{1-4} was higher than that of XG treated pure clay at less curing time (< 49 days) because the former soil type had the different soil grades to generate the physical association and chemical bonds together, the UCS of XG treated pure clay (2271.4 kPa) also slightly overcame the UCS of XG treated S_1C_{1-4} (2236.2 kPa) at curing 70 days. In addition, the UCS of XG treated S_1C_{4-1} was the smallest among these soil types regardless of curing time because of the poor soil grade and the weak bonds between XG and soil particles. The highest UCS of 2% XG treated soil was 115.24%, 81.25%, 83.73%, 83.97%, 92.52% and 83.60% at curing 14, 28, 35, 42, 49 and 70 days, respectively.

Similarly, the UCS of 3% XG treated sand was the highest value among these soil types at less curing time (< 49 days). On the other hand, there were more biopolymer molecules connecting clay content to generate strong ionic and hydrogen bonds, with the XG concentration increasing to 3%. Therefore, the UCS of 3% XG treated S_1C_{1-4} was the secondary high value at less curing time (e.g., 14 and 28 days). And then, the UCS of 3% XG treated pure clay started to overcome the UCS of 3% XG treated S_1C_{1-4} after curing 35 days, while the UCS of 3% XG treated pure clay was even slightly larger than that of XG treated pure sand at curing 70 days becoming the highest value. Moreover, the UCS of 3% XG treated S_1C_{1-1} was always smaller than the UCS of XG treated pure sand, S_1C_{1-4}, and pure clay, while it was larger than the UCS of XG treated S_1C_{4-1} at the same curing time. The highest UCS of 3% XG treated soil was 126.90%, 41.76%, 37.81%, 63.91%, 79.70% and 68.54% at curing 14, 28, 35, 42, 49 and 70 days, respectively.

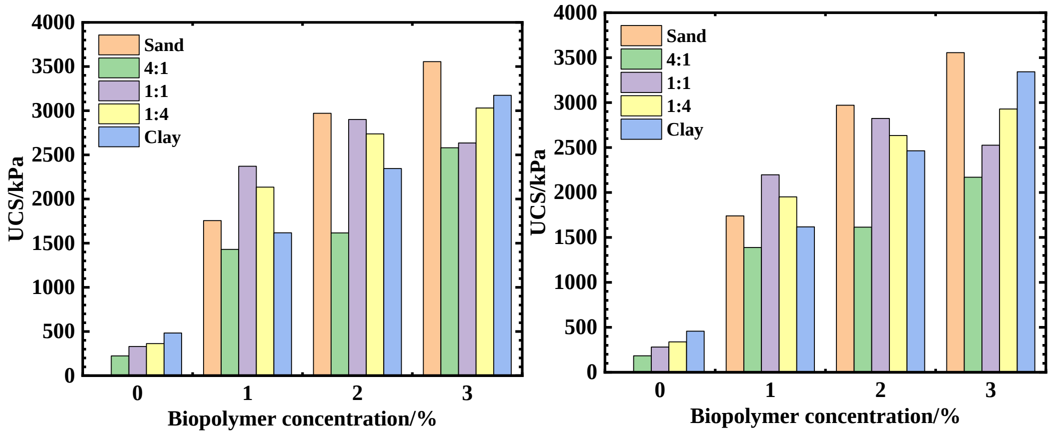
Overall, the strength of XG treated sand can keep at a high level regardless of curing time and biopolymer concentration, while its UCS decrement ratio was also more significant with the increase of curing time compared to other soil types. Moreover, the UCS of XG treated S_1C_{1-1} was relatively high at 1% and 2% XG concentrations, while the 3% XG treated S_1C_{1-4} at less curing time, and the 3% XG treated pure clay at long curing time were relative high. However, the XG treated S_1C_{4-1} performed a weak strength improvement compared to other soil types. Moreover, the increase ratio of the highest UCS of 1% XG treated soil to the lowest

UCS of 1% XG treated soil kept relatively stable in the range of about 56%-78% at different curing time, while the highest UCS of 3% treated soil and the lowest UCS of 3% treated soil had the significant change from 37% to 126% at different curing times. In addition, the soil types had a significant influence on the condition of 2% XG treated soil that the increment ratio of the obtained highest and lowest UCS was still at a high level from 81% to 115%.

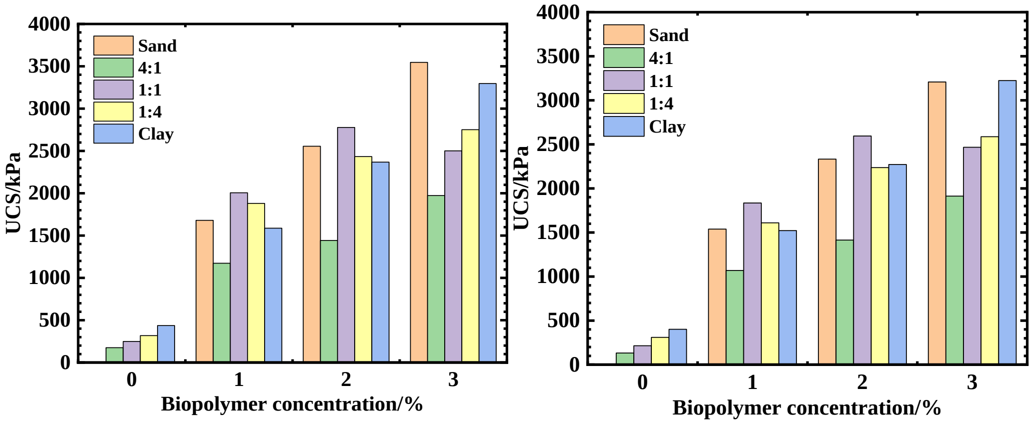
It can be concluded that the clay content played a vital role in reinforcing soil strength with the increase of biopolymer concentration, and the soil strength tended to be kept at higher clay content. Therefore, the influence of soil type on the strength of biopolymer treated soil should be comprehensively illustrated by considering biopolymer concentrations and curing time.



(a) 14 days (b) 28 days



(c) 35 days (d) 42 days



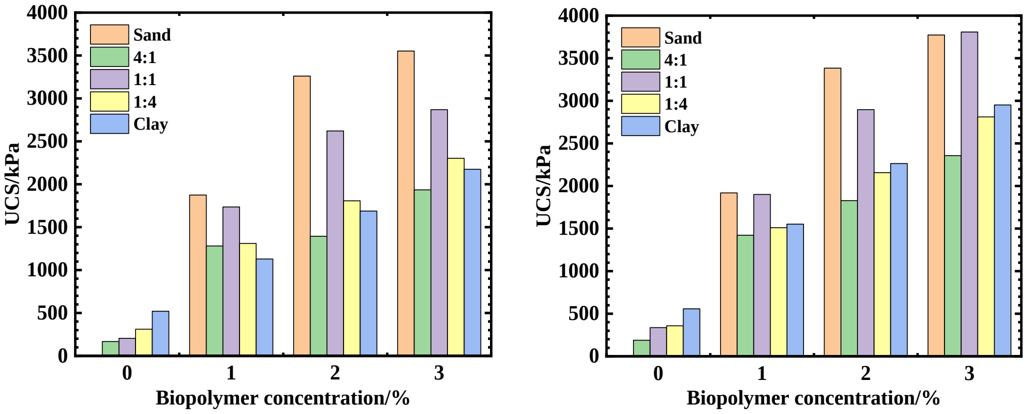
(e) 49 days (f) 70 days

Figure 5.9 XG treated different S1-clay ratio

Figure 5.10 illustrates the different XG concentrations treated in various soil types at curing 14 and 28 days. It is shown that the UCS of untreated soil increased with the increase of clay content, and the UCS of pure S2 can even be ignored, while the UCS of S2-clay with the ratio of 4:1 (S_2C_{4-1}), 1:1 (S_2C_{1-1}) and 1:4 (S_2C_{1-4}) was 167.5 kPa, 204.8 kPa and 311.2 kPa at curing 14 days, respectively. With the addition of XG, it can be observed that the UCS of XG treated sand was the highest, followed by XG treated S_2C_{1-1} and then the XG treated S_2C_{1-4} at curing 14 days regardless of XG concentration. In addition, the UCS of XG treated pure clay was lowest at 1% concentration, while the UCS of XG treated pure clay was higher than XG treated S_2C_{4-1} at 2% and 3% concentrations because the more XG concentration can form the strong chemical bonds in XG-clay matrices to improve the strength of pure clay effectively. Specifically, the UCS of 1% XG treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4}, and pure clay was 1875 kPa, 1280.7 kPa, 1735.7 kPa, 1310.3 kPa and 1129 kPa, respectively. And the UCS of 2% XG treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4} and pure clay was 3260.6 kPa, 1393.4 kPa, 2621.6 kPa, 1807.1 kPa and 1688.2 kPa, respectively. Moreover, the UCS of 3% XG treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4}, and pure clay was 3552.4 kPa, 1934 kPa, 2868.9 kPa, 2302.1 kPa and 2174.7 kPa, respectively. Therefore, the increment ratio of the highest UCS to the lowest UCS of 1%, 2% and 3% treated soil was 66.08%, 134.00% and 83.68% at curing 14 days, respectively.

At curing 28 days, as shown in Figure 5.10 (b), the UCS of untreated soil still increased with the increase of clay content and the UCS of S_2C_{4-1}, S_2C_{1-1} and S_2C_{1-4} were 189.4 kPa, 337.5 kPa and 358.8 kPa, respectively. With the occurrence of

XG, it can be shown that the XG treated sand still obtained the highest UCS and followed by XG treated S_2C_{1-1} at 1% and 2% concentrations, while the UCS of XG treated S_2C_{1-1} overcame the UCS of XG treated sand with the concentration increasing to 3%. In addition, the UCS of XG treated S_2C_{4-1} was the smallest among these soil types regardless of XG concentrations. Meanwhile, the UCS of XG treated pure clay was more significant than that of XG treated S_2C_{1-4} regardless of XG concentrations. It can be illustrated that the biopolymer treated soil need more curing time to perform the reinforcement effect at the occurrence of clay. Specifically, the UCS of 1% XG treated S2, S_2C_{4-1}, $S_2C_{1-1,}$ S_2C_{1-4}, and pure clay was 1918.7 kPa, 1422.1 kPa, 1900.6 kPa, 1510.3 kPa and 1552 kPa, respectively. Moreover, the UCS of 2% XG treated S2, S_2C_{4-1}, $S_2C_{1-1,}$ S_2C_{1-4} and pure clay was 3384 kPa, 1828.6 kPa, 2896 kPa, 2155.8 kPa and 2263.6 kPa, respectively. Moreover, the UCS of 3% XG treated S2, S_2C_{4-1}, $S_2C_{1-1,}$ S_2C_{1-4}, and pure clay was 3772.8 kPa, 2356.9 kPa, 3807.5 kPa, 2811.5 kPa, and 2951 kPa, respectively. Therefore, the increment ratio of the highest UCS to the lowest UCS of 1%, 2% and 3% XG treated soil was 34.92%, 85.06% and 61.55% at curing 28 days, respectively.



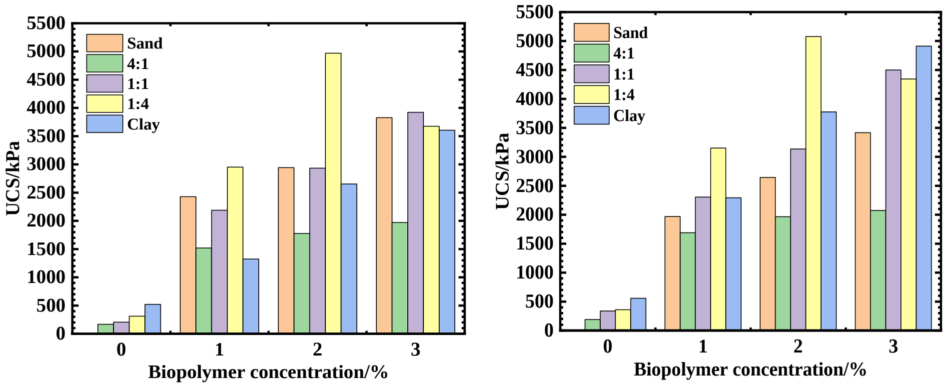
(a) 14 days (b) 28 days

Figure 5.10 XG treated different S2-clay ratio

Figure 5.11 illustrates the various SA concentrations treated with different S2-clay ratios of 4:1, 1:1 and 1:4 at curing 14 and 28 days. At curing 14 days, it can be observed that the UCS of SA treated S_2C_{1-4} was the highest value at 1% and 2% concentration, while the 3% SA treated S_2C_{1-1} obtained the highest UCS value. In addition, the UCS of SA treated sand was the secondary value regardless of SA concentration at curing 14 days. Meanwhile, the UCS of SA treated pure clay was the smallest value at 1% concentration, followed by SA treated S_2C_{4-1}, while the UCS of SA treated pure clay was significantly more extensive than that of SA treated S_2C_{4-1}. Specifically, at curing 14 days, the UCS of 1% SA treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4}, and pure clay was 2428.8 kPa, 1519.6 kPa, 2189.2 kPa, 2952.8 kPa and 1324.2 kPa, respectively. And the UCS of 2% SA treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4}, and pure clay was 2942.3 kPa, 1776.4 kPa, 2933.6 kPa, 4969.8 kPa and 2653.5 kPa, respectively. Moreover, the UCS of 3% SA treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4} and pure clay was 3828.5 kPa, 1970.6 kPa, 3923.1 kPa, 3675.8 kPa and 3605.2 kPa, respectively. It can be shown that the SA treated S2, S_2C_{1-1} and S2C$_{1-4}$ had a similar strength value at 1% concentration, which was significantly more extensive than that of SA treated S_2C_{4-1} and pure clay. However, the strength of SA treated S2C$_{1-4}$ was obviously more prominent than that of SA treated other soil types at 2% concentration, while the UCS of 2% SA treated S2, S_2C_{1-1}, and pure clay was about the same. At 3% concentration, the UCS of SA treated S2, S_2C_{1-1}, S2C$_{1-4}$, and pure clay was about the same at the high level, which was also significantly more extensive than that of SA treated S_2C_{4-1}. Therefore, the increment ratio of the highest UCS to the lowest UCS of 1%, 2%, and 3% SA treated soil was 122.99%, 179.77% and 99.08% at curing 14 days, respectively.

At curing 28 days, the highest UCS obtained in SA treated S2C$_{1-4}$ at 1% and 2% concentrations, while the UCS of SA treated pure clay was the highest at 3% concentration. In addition, the SA treated S_2C_{1-1} was the secondary high UCS value at 1% and 3% concentrations, while the secondary high UCS value at 2% concentration was obtained in SA treated pure clay. Moreover, the UCS of SA treated S2 was only larger than that of SA treated S_2C_{4-1} regardless of SA concentrations. Specifically, the UCS of 1% SA treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4} , and pure clay was 1969 kPa, 1688.9 kPa, 2305.9 kPa, 3150.7 kPa and 2292.4 kPa, respectively. Moreover, the UCS of 2% SA treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4}, and pure clay was 2644.8 kPa, 1965.8 kPa, 3136.2 kPa, 5077.3 kPa and 3776.9 kPa, respectively. It has shown that the UCS of 1% and 2% SA treated S_2C_{1-4} was significantly larger than other soil types. In addition, the UCS of 1% SA treated S_2C_{1-1} and pure clay was about the same, while the UCS at 2% SA concentration about linear decreased from pure clay, S_2C_{1-1}, S2 to S_2C_{4-1}. Moreover, the UCS of 3% SA treated S2, S_2C_{4-1}, S_2C_{1-1}, S_2C_{1-4}, and pure clay was 3417.6 kPa, 2073.6

kPa, 4500.2 kPa, 4343.8 kPa and 4911.5 kPa, respectively. It illustrated that the strength of 3% SA treated S_2C_{1-1}, S_2C_{1-4} and pure clay had little difference. Overall, the increment ratio of the highest UCS to the lowest UCS of 1%, 2%, and 3% SA treated soil was 86.55%, 158.28% and 136.86% at curing 14 days, respectively. It can also be illustrated that the SA had an obviously different reinforcement effect on the various soil types.



(a) 14 days

(b) 28 days

Figure 5.11 SA treated different S2-clay ratio

5.3.4 Effect of curing time

To illustrate the influence of curing time on the UCS of biopolymer treated sand/sand-clay mixture, the six biopolymers with 1%, 2% and 3% concentrations were selected to reinforce two sand types with curing 14 and 28 days. Moreover, taking the typical biopolymer, XG, as an example, the UCS of XG treated different S1-clay ratios with more curing time, and the UCS of XG/AG treated different S2-clay ratios with curing 14 and 28 days was also revealed.

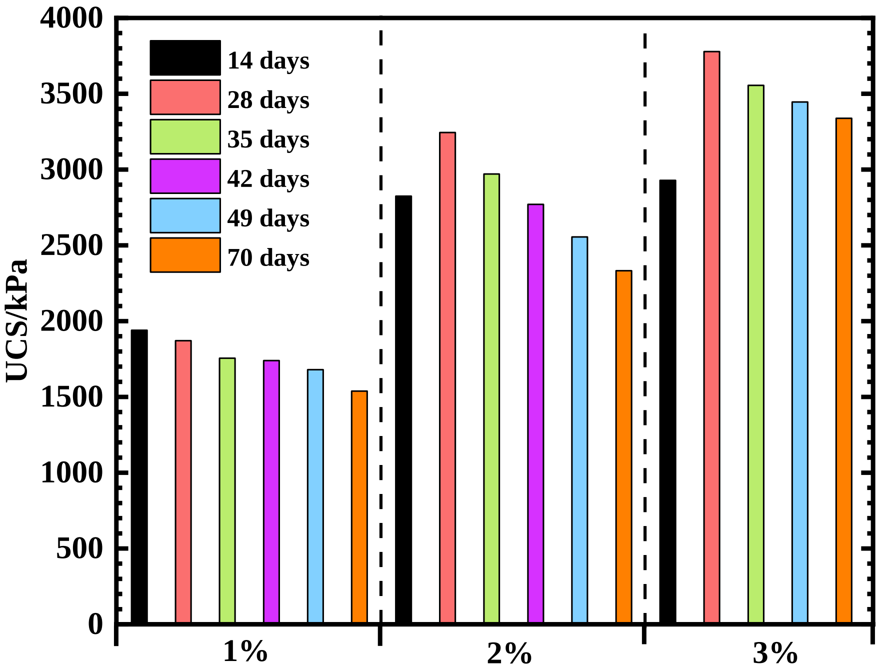
Figure 5.12 illustrated the UCS of 1%, 2%, and 3% XG treated S1, S_1C_{4-1}, S_1C_{1-1} and S_1C_{1-4} with curing more time. It illustrated that the maximum UCS of 1%, 2%, and 3% XG treated S1 was obtained at curing 14 days, 28 days and 28 days, respectively. And compared to the highest UCS value, the UCS decrement ratio of 1% XG treated S1 was -3.57%, -9.55%, -10.32%, -13.41% and -20.75% at curing 28, 35, 42, 49 and 70 days, respectively. In addition, the UCS of 2% and 3% XG treated S1 at curing 14 days reached 87.05% and 77.52% of the corresponding maximum UCS, respectively, which illustrated that the reinforcement effect of XG treated sand at less curing time decreased with the increase of biopolymer concentration. Moreover, compared the highest UCS value, the UCS decrease ratio of 2% XG treated S1 was -8.44%, -14.63%, -21.24% and -28.10% at curing 35, 42, 49 and 70 days, respectively, while the corresponding value of 3% treated S1 was -5.88%, -8.79%, -11.65% and -15.07%, respectively. It can be observed that although there was about 15%-28% UCS decrement at long curing time, the UCS of XG treated S1 was still significantly larger than that of untreated soil.

In terms of XG treated S_1C_{4-1}, the maximum UCS was obtained at curing 28 days, due to the occurrence of clay particles. It is shown that the UCS of XG treated S_1C_{4-1} at curing 14 days can reach the 79.90%, 80.67%, 73.30% and 48.43% at 0%, 1%, 2% and 3%, respectively, which also illustrated the higher biopolymer concentration normally had the good water retention causing the weak strength of soil at less curing time. However, the water content can reach the stable stage at curing 28 days and it can fully form a good connection between biopolymer chains and soil particles to perform the highest UCS value. Moreover, with the continuous increase of curing time, the biopolymer film tended to shrink, and the biopolymer also slightly degraded. Therefore, the UCS of XG treated soil decreased with the increase of curing time regardless of soil types and biopolymer concentrations. Specifically, the UCS decrement ratio of untreated S_1C_{4-1} was -10.74%, -18.14%, -21.79% and -41.13% at curing 35, 42, 49 and 70 days, respectively. At the same time, the UCS decrement ratio of 1% XG treated S_1C_{4-1} was -14.76%, -17.23%, -30.07% and -36.26%, respectively. And the corresponding value of 2% XG treated S_1C_{4-1} was -9.68%, -15.38%, -19.42% and -21.03%, respectively, while the UCS decrement ratio of 3% XG treated S_1C_{4-1} was -3.18%, -18.60%, -25.96% and -28.22%, respectively. It illustrated that the UCS decrement ratio of soil decreased due to the occurrence of biopolymer. At curing 70 days, the UCS of 1%, 2%, and 3% XG treated S_1C_{4-1} was 8.09, 10.70 and 14.48 times that of untreated S_1C_{4-1}.

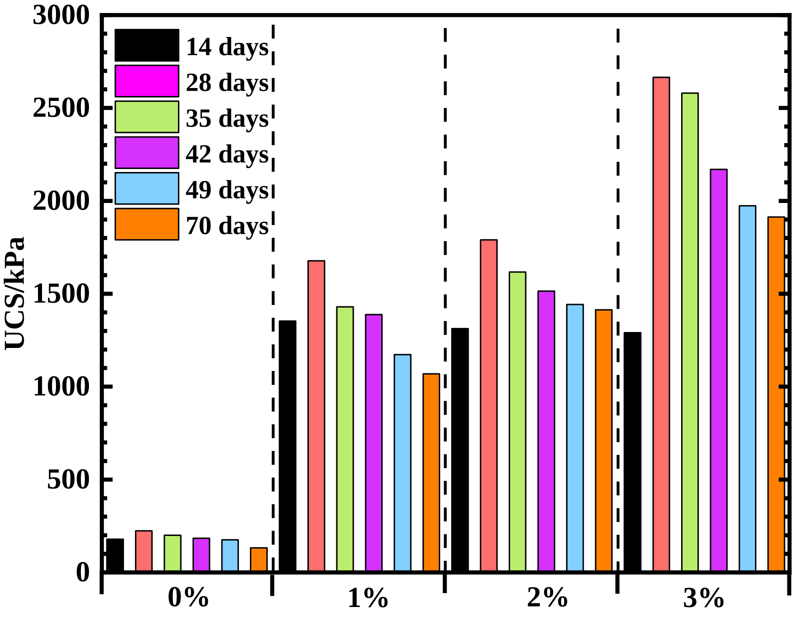
As shown in Figure 5.12 (c), the UCS of XG treated S_1C_{1-1} at curing 14 days obtained the 86.82%, 83.21%, 61.88% and 81.12% of the corresponding maximum UCS of 0%, 1%, 2% and 3%, respectively. It also shows that the treated soil tended to achieve a relatively little strength at the initial curing stage, especially for 2% XG treated S_1C_{1-1}, corresponding to the optimum soil type and biopolymer concentration. In addition, compared to other conditions to obtain the maximum UCS at curing 28 days, the 2% XG treated S_1C_{1-1} reached the maximum UCS at curing 35 days. With the increase in curing time, the UCS of treated soil also decreased. Specifically, the UCS decrement ratio of untreated S_1C_{1-1} was -9.65%, -23.16%, -31.83% and -41.24% at curing 35, 42, 49 and 70 days, respectively. Meanwhile, the UCS decrement ratio of 1% XG treated S_1C_{1-1} was -2.23%, -9.41%, -17.30% and -24.33%, respectively, while the corresponding value of 3% XG treated S_1C_{1-1} was -4.35%, -9.03%, -9.17% and -10.44%, respectively. Moreover, compared to the highest UCS value, the UCS decrement ratio of 2% XG treated S_1C_{1-1} was -7.31%, -8.85% and -21.37% at curing 42, 49 and 70 days, respectively. It can be illustrated that the UCS increment ratio decreased with the occurrence of XG, and the higher XG concentration can still better keep the strength even at the long curing time. At curing 70 days, the UCS of 1%, 2%, and 3% XG treated S_1C_{1-1} was 8.54, 11.15 and 11.48 times that of untreated S_1C_{1-1}.

Figure 5.12 (d) illustrated that the optimum curing time for obtaining the highest UCS of XG treated S_1C_{1-4} was 28 days regardless of biopolymer concentration. And then, the UCS slightly decreased with the continuous increase of curing time. It shown the UCS of XG treated S_1C_{1-4} at curing 14 days can reach the 91.14%, 58.45%, 66.95% and 76.04% of the corresponding maximum UCS at 0%, 1%, 2% and 3%, respectively. With the occurrence of biopolymer, the less curing time seemed to obtain the relatively weak strength. Compared to the maximum UCS value, the UCS loss ratio of untreated S_1C_{1-4} was -5.29%, -11.97%, -17.13% and -19.24% at curing 35, 42, 49 and 70 days, respectively, while the corresponding value of 1% XG treated S_1C_{1-4} was -2.10%, -7.04%, -16.72% and -18.57%, respectively. Meanwhile, the UCS loss ratio of 2% XG treated S_1C_{1-4} was -3.04%, -6.73%, -13.82% and -20.80% at curing 35, 42, 49 and 70 days, respectively, while the corresponding value of 3% XG treated S_1C_{1-4} was -0.87%, -4.21%, -9.99% and -15.38%, respectively. It can be observed that the UCS loss ratio decreased at a long curing time with the increase of clay content, and the UCS can still keep the high level even curing for a long time. At curing 70 days, the UCS of 1%, 2%, and 3% XG treated S_1C_{1-4} was 6.71, 7.22 and 8.35 times that of untreated S_1C_{1-4}.

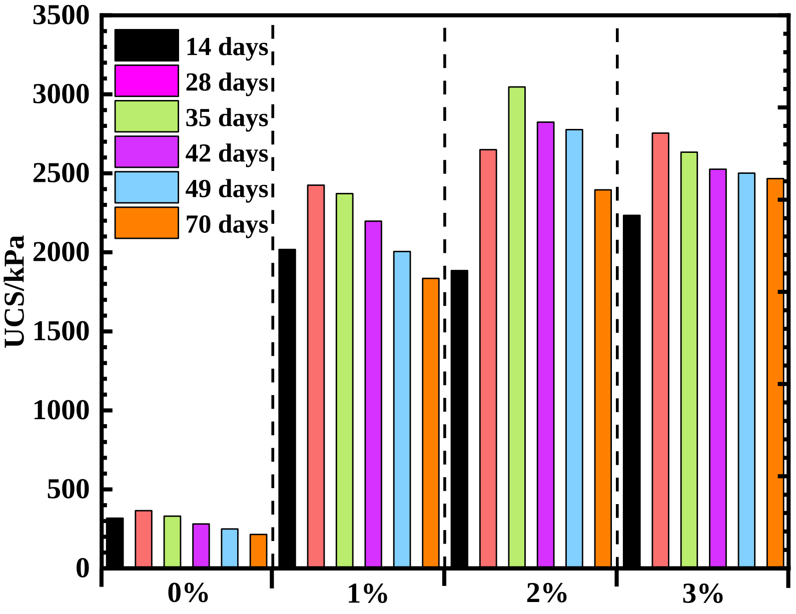
Overall, the biopolymer treated sand usually need less curing time to reach the maximum UCS, while the optimum curing time of most biopolymer treated sand-clay mixture was 28 days to reach the maximum UCS value due to the occurrence of clay particles. Generally, the UCS of biopolymer treated soil within the first 14 days curing can reach 70%-90% of the maximum UCS value. Overcoming the optimum curing time, the UCS of biopolymer treated soil decreased with the continuous increase of curing time. Meanwhile, the UCS loss ratio decreased with the occurrence of biopolymer and the increase of clay content. However, even after curing a long time (e.g., 70 days), the UCS of biopolymer treated soil was significantly more extensive than that of untreated soil (e.g., more 5.7-13.5 times).



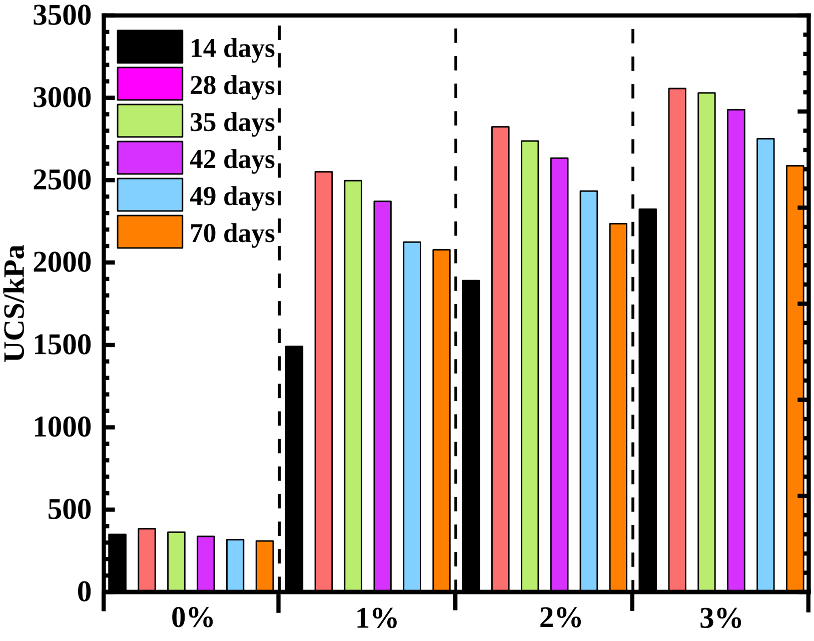
(a) S1



(b) S_1C_{4-1}



(c) $S_1C_{1\text{-}1}$



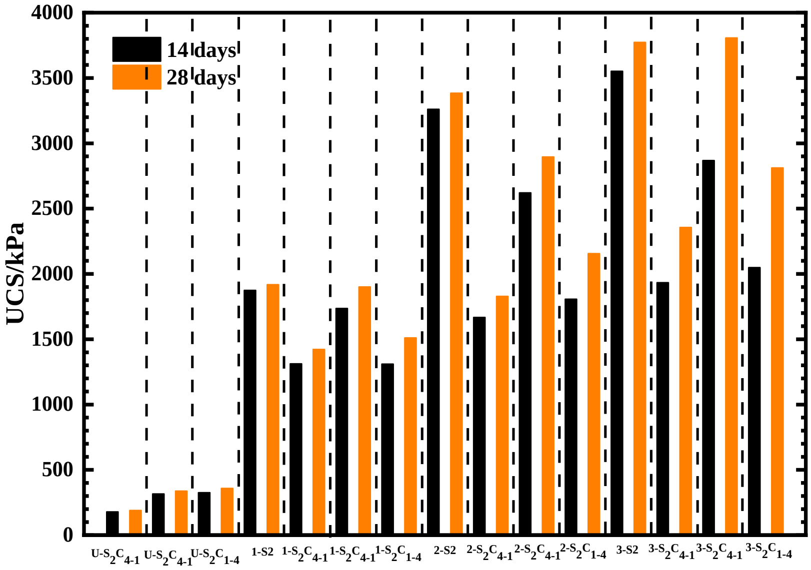
(d) $S_1C_{1\text{-}4}$

Figure 5.12 XG treated various soil types at different curing time

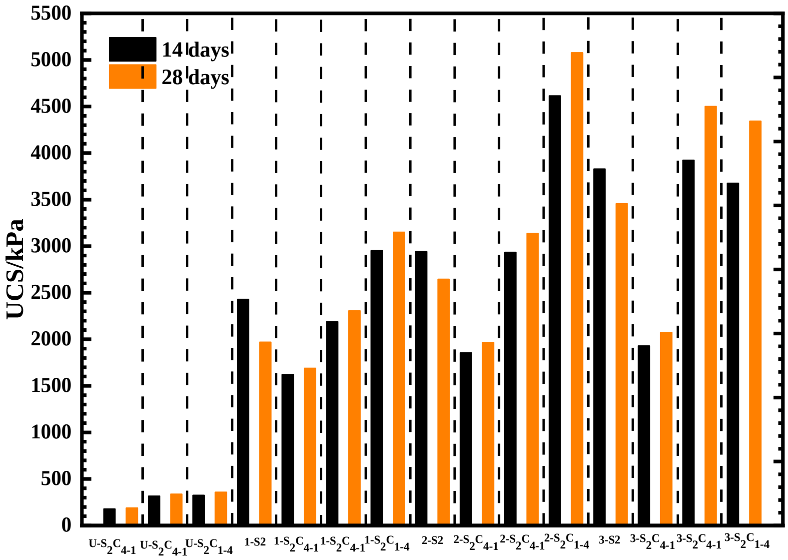
Figure 5.13 illustrated the UCS of XG and SA treated S2-clay mixture at curing 14 and 28 days. It is shown that the UCS of XG increased with the curing time increasing from 14 days to 28 days regardless of soil types. Specifically, at curing 14 days, the UCS of 1%, 2% and 3% XG treated sand can reach 97.72%, 96.35% and 94.16% of the UCS at curing 28 days, respectively, while the corresponding ratio was 94.43%, 92.26%, 91.21% and 82.06% in 0%, 1%, 2% and 3% XG treated $S_2C_{4\text{-}1}$, respectively. Meanwhile, the UCS of 0%, 1%, 2% and 3% XG treated $S_1C_{1\text{-}}$

$_1$ can reach 93.57%, 91.32%, 90.52% and 75.35% of the UCS at curing 28 days, respectively, while the corresponding ratio was 90.73%, 86.76%, 83.83%, 72.88% in 0%, 1%, 2% and 3% XG treated S_2C_{1-4}, respectively. It is shown that the ratio of the UCS of XG treated S2-clay mixture at curing 14 days to the UCS of XG treated S2-clay mixture at curing 28 days decreased with the increase of biopolymer content and clay content.

As shown in Figure 5.13 (b), the UCS of SA treated S2 at curing 14 days was larger than that of curing 28 days, and the decrement ratio was 18.93%, 10.11% and 9.73% at 1%, 2% and 3%, respectively, while illustrated the higher SA concentrations tended to keep the UCS for a long time. On the other hand, with the occurrence of clay particles, the UCS of SA treated S2-clay mixture increased with the curing time increasing from 14 to 28 days. Specifically, the increment ratio of the SA treated S_2C_{4-1} was 4.01%, 5.63% and 6.97% at 1%, 2% and 3%, respectively, while the increment ratio of 1%, 2% and 3% SA treated S_2C_{1-1} was 5.06%, 6.46% and 12.82%, respectively. In addition, the increment ratio of SA treated S_2C_{1-4} was 6.28%, 9.12% and 15.38% at 1%, 2% and 3% concentrations, respectively. It illustrated that the increment ratio increased with the increase of biopolymer concentration and clay content.



(a) XG



(b) SA

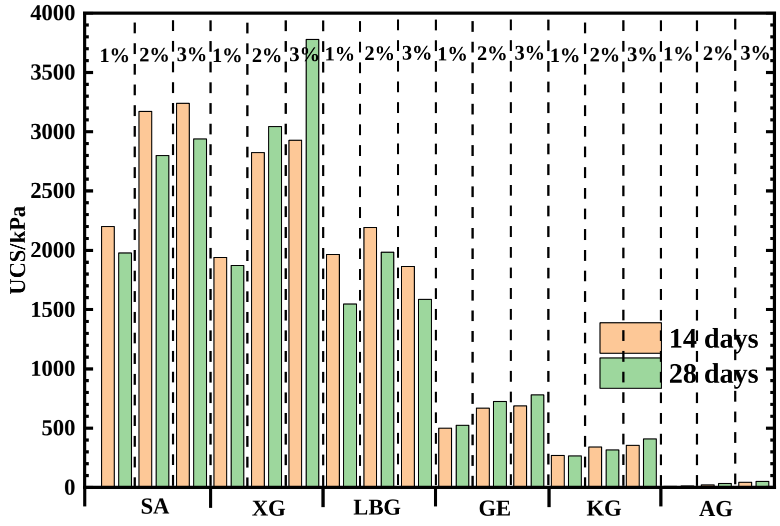
Figure 5.13 Biopolymer treated S2-clay ratio at different curing time

Figure 5.14 (a) shows that the SA and LBG treated S1 obtained the highest UCS value at curing 14 days regardless of biopolymer concentrations. Similarly, the UCS of 1% XG, 1% and 2% KG treated S1 at curing 14 days was larger than that of curing 28 days. However, with the increase of biopolymer concentration, the UCS of 2% and 3% XG, 3% KG treated also increased at a longer curing time. Meanwhile, the UCS of GE and AG treated S1 at curing 28 days was also larger than of curing 14 days regardless of biopolymer concentration. Specifically, with the curing time increasing to 28 days, the UCS decrement ratio of SA treated S1 was -10.12%, -11.73% and -9.29% at 1%, 2% and 3%, respectively. And the UCS decrement ratio of LBG treated S1 was -21.27%, -9.52% and -14.8% at 1%, 2% and 3%, respectively. In addition, the UCS decreased ratio of 1% XG, 1% and 2% KG treated S1 was only -3.57%, -0.86% and -7.32%, respectively. On the other hand, the UCS of most other conditions of biopolymer treated S1 at curing 14 days also reached 70%-90% of the UCS at curing 28 days.

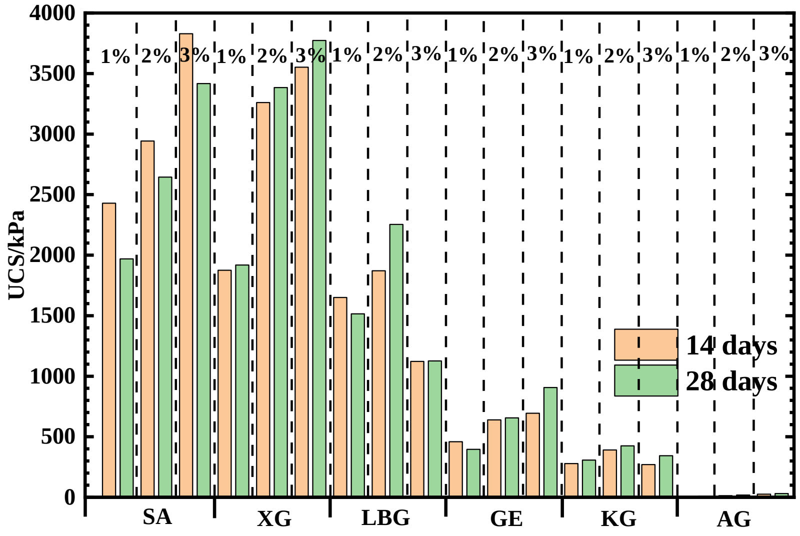
In terms of biopolymer treated S2, the SA treated S2 also obtained the highest UCS value at curing 14 days. The same result can be found in 1% LBG and GE treated S2. The UCS of biopolymer treated S2 increased with the curing time increasing to 28 days for other conditions. Specifically, the UCS decrement ratio of SA treated S2 was -18.93%, -10.11% and -10.73% at 1%, 2% and 3%, respectively. Moreover, the UCS decrement ratio of 1% LBG and GE treated S2 was -8.16%

and -13.59%, respectively. In addition, the UCS of other biopolymer treated S2 at curing 14 days can reach more than 70% of the UCS at curing 28 days, especially for XG treated S2, which can even reach 95% of the UCS at curing 28 days.

Overall, it illustrated that some biopolymers treated sand with high porosity typically tended to cost less curing time (e.g., 14 days) for obtaining the highest value compared to biopolymer treated clay, such as SA. Furthermore, with the increase in biopolymer concentration, there also needs more curing time to reach the highest UCS value.



(a) S1



(b) S2

Figure 5.14 Various biopolymer types treated sand

5.4 Summary

For meeting the current gaps on the mechanical behaviours of biopolymer treated sand-clay mixture, this chapter illustrates the unconfined compressive strength of biopolymer treated sand-clay mixture by considering biopolymer type (SA, XG, LBG, GE, KG and AG), biopolymer concentration (1%, 2% and 3%), curing time (14, 28, 35, 42, 49 and 70 days), soil type (paving joint sand (S1) and sharp sand (S2)) and mixture ratio (1:0, 4:1, 1:!, 1:4, 0:1). The main new findings can be illustrated as follows.

(1) The UCS of biopolymer treated sand is greatly vastly than untreated sand. The highest UCS of SA and XG treated sand is more than 3700 kPa at 3% concentration. At curing 14 days, SA is the best performance biopolymer to increase soil strength following with XG, LBG, GE, KG, and AG. At curing 28 days, the UCS of SA, LBG and XG treated sand is almost same at 1% concentration, while the UCS of XG treated sand is obviously higher than that of SA and LBG treated sand at 2% and 3% concentrations. In addition, the UCS of the above three biopolymers treated sand is significantly larger than that of GE, KG and AG treated sand. Overall, the SA and XG can be regarded as highest efficient biopolymers for reinforcing sand, while AG has a poor performance in increasing the soil strength.

(2) The UCS increment ratio of most biopolymer treated sand decreases with the increase of biopolymer concentration except for KG, and the UCS of biopolymer treated sand at 3% concentration can only have the margin increase, even lower than the UCS of biopolymer treated sand at 2% concentration (e.g., LBG). Therefore, the optimum biopolymer concentration can be regarded as 2% to obtain the best reinforcement effect on sand. In terms of biopolymer treated sand-clay mixture, only a tiny biopolymer concentration can significantly increase the UCS of soil. For example, the UCS of 0.2% XG (BC_{ts}) treated S_1C_{4-1} can even reach 4.9 times of untreated soil. In addition, the UCS of biopolymer treated sand-clay mixture increases firtly and then decreases with the increase of BC_c, while the UCS increment ratio of biopolymer sand-clay mixture is variable with the increase of BC_{ts}.

(3) In terms of XG treated S1-clay mixture, the highest UCS is obtained in the XG treated S_1C_{1-1} regardless of curing time at 1% concentration, while the smallest UCS can be observed in pure clay or S_1C_{4-1} depending on curing time. The

difference between 1% XG treated pure sand, S_1C_{1-4} and pure clay is limited under curing long time (e.g., 70 days). At 2% XG concentration, the highest UCS is observed in pure sand followed by S_1C_{1-1}, S_1C_{1-4} and pure clay curing for less than 42 days. Subsequently, the UCS of XG treated S_1C_{1-1} overcomes the UCS of XG treated pure sand, after curing 49 days, and the UCS of XG treated pure clay is also slightly larger than that of XG treated S_1C_{1-4} with curing 70 days. At 3% XG concentration, the highest UCS is obtained in pure sand at less curing time (e.g., 14 days), followed by S_1C_{1-4}, S_1C_{1-1} and pure clay. However, with the increase in curing time, the strength of XG treated soil with more clay content can significantly increase and even keep stable for a long curing time. Therefore, the UCS of XG treated pure clay starts to overcome the UCS of XG treated S_1C_{1-1} at curing 28 days and then is more significant than that of XG treated S_1C_{1-4} from curing 35 days, while it even overcomes the UCS of XG treated pure sand at curing 70 days. At the same time, the smallest UCS is observed in XG treated S_1C_{4-1}. It can be concluded that the clay content plays a vital role in soil strength, especially for high biopolymer concentration.

(4) In term of biopolymer treated S2-clay mixture, at curing 14 days, XG treated S2 can be observed with the highest UCS following by XG treated S_2C_{1-1} and S_2C_{1-4} regardless of biopolymer concentration. On the other hand, the maximum UCS of SA treated soil can be observed in S_2C_{1-4} at 1% and 2% concentrations and S_2C_{1-1} at 3% concentrations. At curing 28 days, XG treated S2 also has the maximum UCS at 1% and 2% concentration, while the UCS of XG treated S_2C_{1-1} is slightly larger than that of XG treated S2 at 3% concentration. Moreover, the highest UCS of SA treated soil is obtained in S_2C_{1-4} at 1% and 2% concentrations and pure clay at 3% concentration. Moreover, the UCS of SA treated S_2C_{1-1} can maintain a high level regardless of biopolymer concentration, which is also larger than that of SA treated S2. Under this condition, the smallest UCS value can be illustrated in the biopolymer (XG/SA) treated S_2C_{4-1}.

(5) Normally, the maximum UCS of untreated sand or biopolymer treated sand at low concentration is obtained under curing 14 days. With the increase of clay content and biopolymer concentration, the optimum curing time increases, while the UCS of biopolymer treated soil at first curing 14 days can reach 66%-90% of

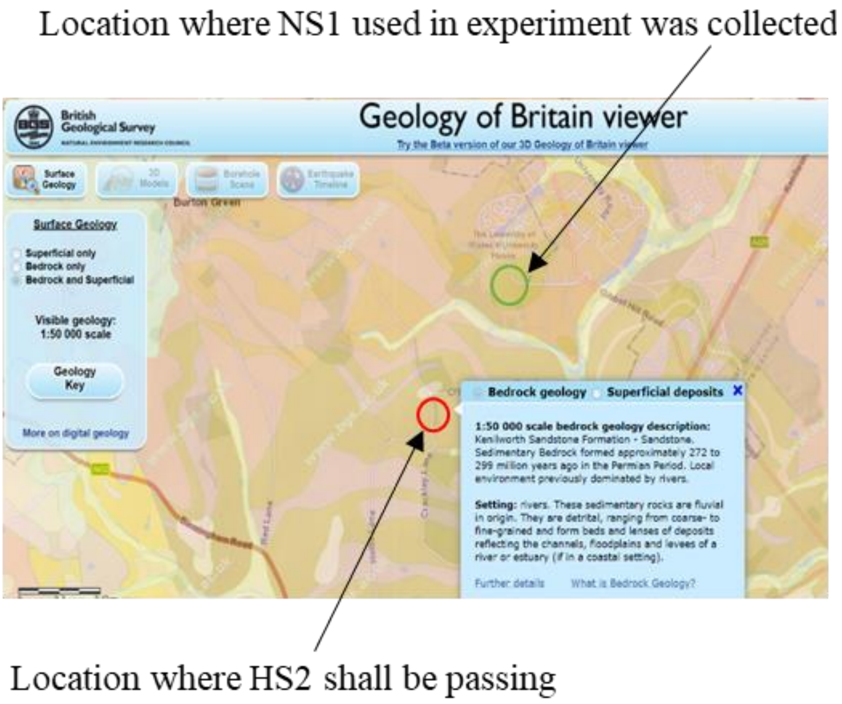
the maximum UCS. However, the UCS of biopolymer treated sand/sand-clay mixture slightly decreases (e.g., the decrement ratio of 15%-28%) with the continuous increase of curing time and the decrement ratio decreases with the increase of biopolymer concentration and clay content. Under this condition, the UCS of biopolymer soil is also significantly more extensive than that of untreated soil (e.g., more 5.7-13.5 times).

Chapter 6 Mechanical Properties of Biopolymer Treated Natural Soil

6.1 Materials and Method

6.1.1 Natural soil

Topsoil is often reused from the location of road and railway embankments. Hence, the soil is collected from two University of Warwick campuses (main campus and Gibbet hill campus, named natural soil 1 (NS1) and natural soil 2 (NS2), respectively, in this study. The location is chosen after the consultation of BGS maps which shows the geology and soil type of this location to be similar to that of the proposed location of High Speed 2 (HS2) as shown in Figure 6.1. Once transported back to the laboratory, excess grass, worms and rocks are removed. It is so that this will not interface with the test results. The commercial topsoil used in this study is obtained from a construction material company (Central Construction Services Ltd), named natural soil 3 (NS3) in this study. And the soil is sieved twice to eliminate large stones and any roots residuals before use for sample preparation.



Location where NS1 used in experiment was collected

1:50 000 scale bedrock geology description: Kenilworth Sandstone Formation - Sandstone. Sedimentary Bedrock formed approximately 272 to 299 million years ago in the Permian Period. Local environment previously dominated by rivers.

Setting: rivers. These sedimentary rocks are fluvial in origin. They are detrital, ranging from coarse- to fine-grained and form beds and lenses of deposits reflecting the channels, floodplains and levees of a river or estuary (if in a coastal setting).

Location where HS2 shall be passing

(a) Geology Map of HS2 Area in relation to campus (BGS, 2022)

(b) HS2 route passing near campus (HS2, 2022)

Figure 6.1 Natural soil 1 map information

Before any samples are generated or testing is completed, the soil collected is subjected to several standard tests to classify it. The particle distribution curves of three natural soil types are present in Figure 6.2. Moreover, Table 6.1 summarises the specific physical parameters of natural soils. The basic soil size parameters of NS1 are D_{50} = 0.255 mm, C_u = 0.976 and C_c = 1.886, respectively, which belongs to poor gradation. In addition, the plastic limit (PL) and liquid limit (LL) are 19.8% and 26%, respectively. Furthermore, the specific gravity of NS1 is 2.06. The soil can be classified as low plasticity clay based on USCS. In addition, the D_{50}, C_u and C_c of NS3 are 0.401mm, 3.347 and 1.402, respectively, and it can be classified as poorly graded sand (SP) based on ASTM D2487-17 (2017). On the other hand, the D_{50}, C_u and C_c of NS3 are 0.404 mm, 2.107 and 1.081, respectively, which belongs to poor gradation. In addition, it can be classified as silty sand (SM) based on ASTM D2487-17 (2017).

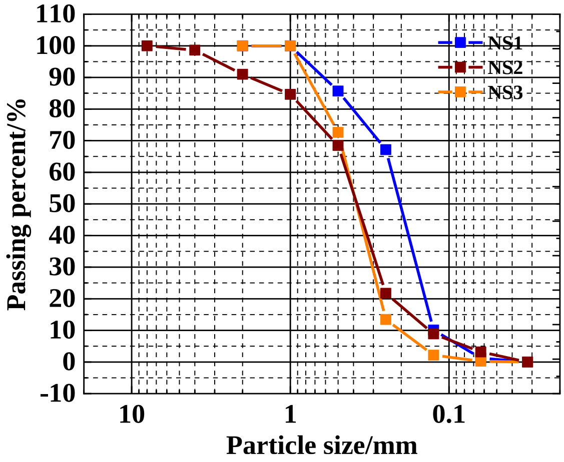


Figure 6.2 Gradation curve of natural soil

Table 6.1 Basic physical parameters of natural soil

Soil properties	Value		
Soil type	NS1	NS2	NS3
D_{10}/mm	0.149	0.136	0.212
D_{30}/mm	0.202	0.294	0.320
D_{50}/mm	0.255	0.401	0.404
D_{60}/mm	0.281	0.455	0.447
C_c/mm	1.886	1.402	1.081
C_u/mm	0.976	3.347	2.107
Liquid limit/%	23.1	14.5	21.4
Plastic limit/%	19.8	9.1	15.6
Plasticity index	6.2	5.4	5.8
Soil type (UCUS)	CL	SP	SM
Density (kg/m^3)	1905.8	1980.96	1912.33

6.1.2 Biopolymer

Different biopolymers (e.g., XG, LBG, AG, GE, KG and SA) are selected to treat three natural soils. The details of these biopolymers can be found in section 3.1.2.

6.2 Sample preparation and experimental programme

The untreated soil and biopolymer treated soil with a certain initial water content are uniformly mixed using the room temperature water-dry mixing method and then compacted in a clear cylinder mould with 50*100 mm in diameter and height, respectively, in three layers. The details of sample preparation can be found in section 3.1.3. To evaluate the engineering properties of the soil-biopolymer mixture, unconfined compressive tests are performed on untreated natural soils/biopolymer treated natural soils. Table 6.2 listed the program details for the experimental test of untreated/biopolymer treated natural soils.

Table 6.2 Experimental program summary of natural soils

Soil	Biopolymer	Concentration/%	Curing time/days	Initial water content/%
NS1	XG	0, 0.5, 1, 2, 3	4, 21, 28, 70, 90	15

NS2	Untreated	0	14, 28, 35, 42, 49, 56, 63, 70, 365	15
	XG	1, 2, 3	14, 28, 35, 42, 49, 56, 63, 70, 365	25
	SA	1, 2, 3		30
	SA	1		25, 27, 30, 33
	SA	2		30, 32.5, 35
	XG, LBG, SA, AG, GE, KG	1	14, 28, 49, 70	22-30
NS3	Untreated	0	14, 28	20
	AG, LBG, XG, KG, SA	1, 2, 3	14, 28	22.5-35

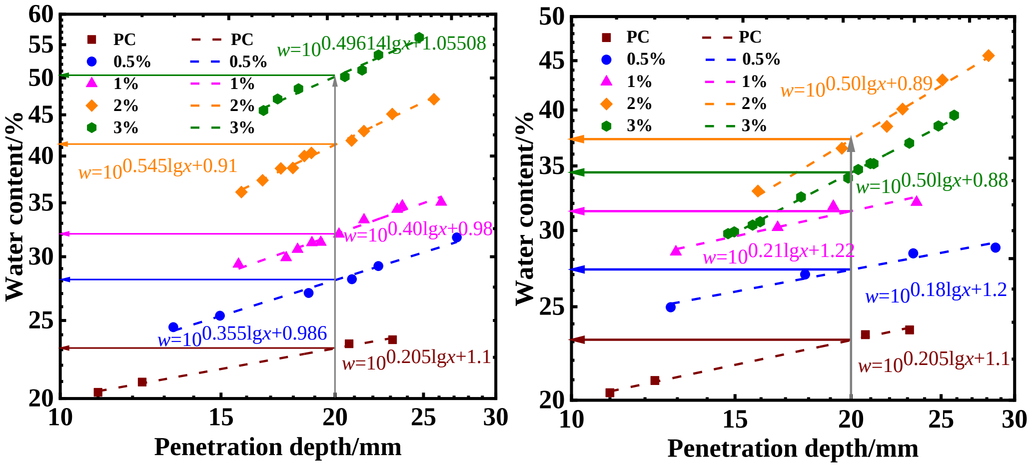
6.3 Test results

6.3.1 Physical and mechanical properties of biopolymer treated NS1

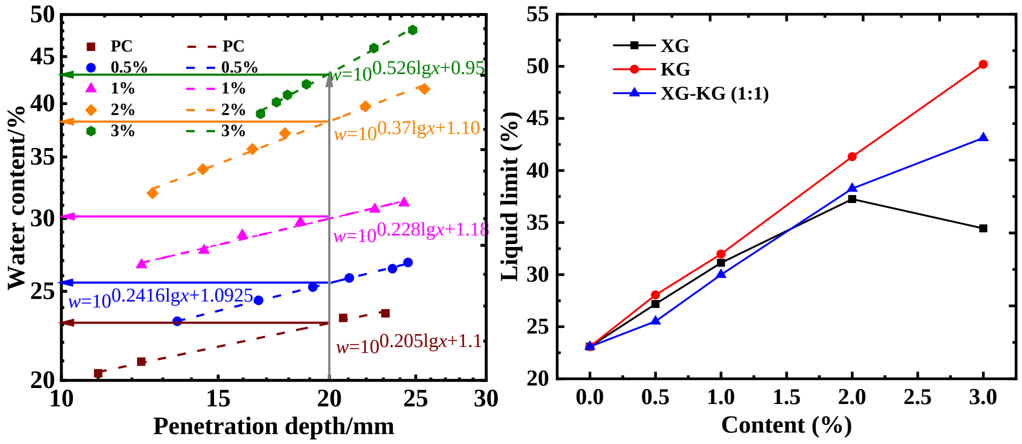
6.3.1.1 Fall cone test results

The log-log plots of cone penetration versus water content for the biopolymer treated NS1 are shown in Figure 6.3. The corresponding fitting curves of each condition are drawn to obtain the liquid limit. It shows that the cone penetration of KG and XG-KG treated NS1 decreases with the increased biopolymer concentration for given water content, and the same results can be observed in XG treated NS1 with less than 2% concentration. It indicates that the inclusion of more biopolymers makes the kaolinite stronger.

As shown in Figure 6.3 (d), the liquid limit of KG treated NS1 is higher than that of XG and XG-KG treated NS1 regardless of biopolymer concentration. Moreover, it approximately linear increases to 50.2% at 3% concentration. In addition, the liquid limit of XG treated NS1 increases to 37.3% at 2% concentration and then decreases to 34.4% at 3% concentration. Combined with the performance of both biopolymers treated NS1 together, the liquid limit of XG-KG with the ratio of 1:1 almost linear increases to 38.3% firstly and then continues to increase to 43.1% slightly. On the other hand, the XG treated NS1 has a higher liquid limit than that of XG-KG with less than 1% concentration, while the liquid limit of XG-KG treated NS1 starts to overcome the pure XG treated NS1 from 2 % concentration.



(a) Kappa gum treated natural soil (b) Xanthan gum treated natural soil



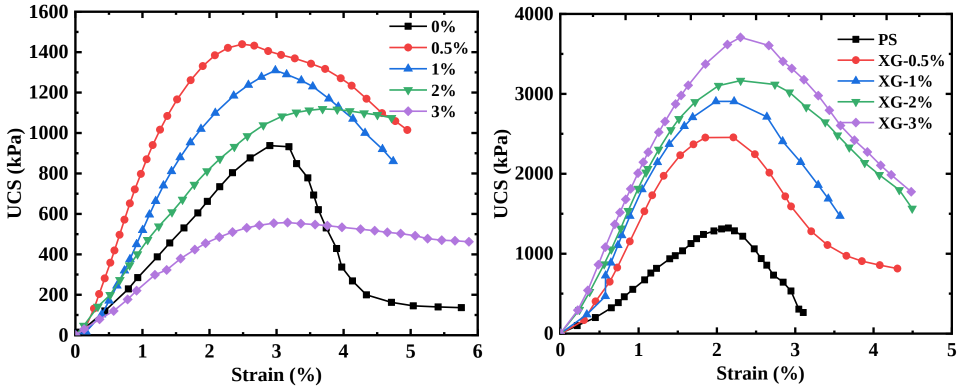
(c) XG-KG mixture treated NS1 (d) Liquid limit results

Figure 6.3 Fall cone tests of biopolymer treated NS1

6.3.1.2 Unconfined compressive strength results

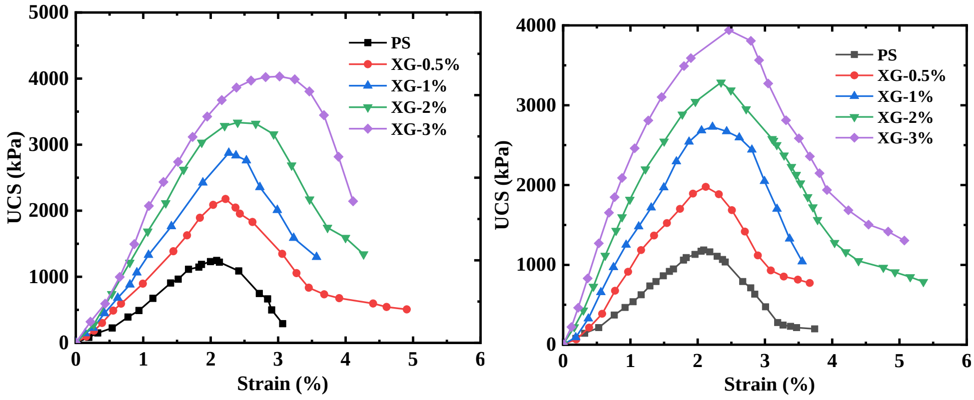
Figure 6.4 illustrates the stress-strain curves of various XG treated NS1 at different curing time. The strain-softening behaviour can be observed in untreated soil and XG treated soil with low concentration (e.g., < 1%) at the initial curing stage. In addition, the strain obtaining the maximum strength in biopolymer treated soil is obviously larger than that of untreated soil, and it increases with the increase of biopolymer concentration. On the other hand, the stress-strain curves of XG treated soil with high concentration (e.g., > 2%) present the strain-hardening behaviour. It can be explained that the water evaporation of untreated soil and low XG concentration treated soil is relatively high to form the strong biopolymer-soil matrices or soil-soil matrices. Moreover, the higher XG concentration still keeps higher water content in biopolymer-soil matrices. Therefore, the UCS of 0.5% XG treated soil is highest in this condition, while the UCS of 3% XG treated soil is even lower than that of untreated soil. Specifically, the UCS of XG treated soil is 937.69 kPa, 1439.48 kPa, 1310 kPa, 1119.21 kPa, 557.41 kPa at 0%, 0.5%, 1%, 2% and 3%, respectively, at curing 4 days. Compared to untreated soil, the increment ratio of XG treated NS1 is 53.51%, 39.71%, 19.36% and -40.56% at 0.5%, 1%, 2% and 3%, respectively.

With the continuous drying, all stress-strain curves represent the strain-softening behaviours, and the strain obtaining the maximum strength increases with the increase of biopolymer concentration. Moreover, the XG presents obvious soil strengthing and stabilization at a long curing time, especially for higher concentrations. For example, the UCS of 3% XG treated soil at curing 21 days is 6.65 times that of curing 4 days. In addition, the optimum curing time of untreated soil and low XG concentration treated soil is 21 days to obtain the highest UCS, and the corresponding optimum curing time of higher XG treated soil is 28 days. However, with the continuous increase of curing time, the UCS of untreated/XG treated soil has slightly decreased (e.g., the decrement ratio is 5.75%-25.68%), while the UCS of XG treated soil is still significantly higher than that of untreated soil. To be specific, the UCS of XG treated NS1 is 1320.2 kPa, 2455.39 kPa, 2905.98 kPa, 3165.52 kPa and 3706.9 kPa at 0%, 0.5%, 1%, 2% and 3% with curing 21 days, respectively. Compared to untreated soil, the increment ratio of XG treated soil is 85.99%, 120.12%, 139.78% and 180.78% at 0.5%, 1%, 2% and 3%, respectively. In addition, the UCS of XG treated NS1 is 1245.9 kPa, 2176.74 kPa, 2875.35 kPa, 3335.24 kPa and 4032.46 kPa at 0%, 0.5%, 1%, 2% and 3% with curing 28 days, respectively. And the UCS of 0.5%, 1%, 2% and 3% XG treated soil is about 1.75, 2.31, 2.68 and 3.24 times of untreated soil. With the curing time increasing to 49 days, the UCS of XG treated soil is 1186.3 kPa, 1977.87 kPa, 2728.4 kPa, 3285.58 kPa and 3940.35 kPa at 0%, 0.5%, 1%, 2% and 3%, respectively. The corresponding UCS increment ratio is 66.73%, 129.99%, 176.96% and 232.15%, respectively, compared to untreated soil. However, the UCS of XG treated soil slightly decreases to 1139.2 kPa, 1724.76 kPa, 2650.7 kPa, 3143.63 kPa and 3700.09 kPa at 0%, 0.5%, 1%, 2% and 3% with curing 28 days, respectively, with the curing time increasing to 70 days. Under this condition, the UCS of 0.5%, 1%, 2% and 3% XG treated soil is still 1.51, 2.33, 2.76 and 3.25 times that of untreated soil. Overall, the UCS of 0.5%, 1%, 2% and 3% XG treated soil is more 1.50, 2.20, 2.39 and 2.80 times than untreated soil regardless of curing time. Meanwhile, the biopolymer can perform good soil strengthening and stabilization behaviours with small XG concentration, while the effective strength increment tends to decrease under the same increment of XG concentration. For example, the UCS increment ratio is 130.79%, 15.99 and 20.90% with each 1% XG concentration increment at curing 28 days. Therefore, it also occurs the optimum biopolymer concentration to perform the optimum soil strengthing and stabilization behaviours.



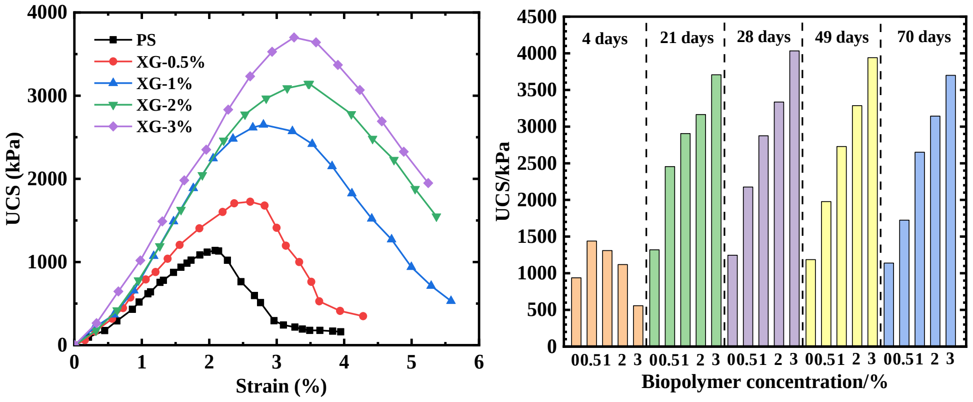
(a) 4 days

(b) 21 days



(c) dry 28 days

(d) dry 49 days



(e) dry 70 days (f) UCS results

Figure 6.4 Stress-strain curves and UCS of XG treated NS1

6.3.2 Unconfined compressive strength of biopolymer treated NS2

Figures 6.5 and 6.6 illustrate the strength of various SA and XG concentrations treated NS2 at different curing time. It shows that the optimum curing time is 28 days to obtain the maximum strength regardless of biopolymer type and concentrations. Moreover, the strength decreases with the continuous increase of curing time, while the soil stabilization can still be observed even with curing 1-year days. In addition, the strength of biopolymer treated NS2 increases with the increase of biopolymer concentration. However, the strength increment behaviour depends on the biopolymer type. Specifically, compared to untreated soil, the strength of SA treated soil only slightly increases with the concentration increasing to 1%, and the 2% SA treated soil also has a limited UCS increment. In addition, the UCS of SA treated NS2 linear increases with the increase of biopolymer concentration in the range of 0-2%, while the UCS of 3% SA treated NS2 has a significant increase, which is more 1.7 times than that of untreated soil at the same curing time. On the other hand, the UCS of XG treated NS2 obviously increases with the concentration increasing to 1%. Furthermore, with the continuous increase of XG concentration, the UCS increment of XG treated NS2 is still high. Moreover, the UCS of XG treated NS2 is significantly larger than that of SA treated NS2 at the same curing time and biopolymer concentration.

To be specific, as shown in Figure 6.5, with curing 14 days, 28 days, 35 days, 42 days, 49 days, 56 days, 63 days, 70 days and 365 days, the UCS of untreated NS2 is 847.7 kPa, 908.1 kPa, 866.3 kPa, 796.2 kPa, 764.2 kPa, 733.4 kPa, 685.4 kPa, 663.6 kPa and 644.1 kPa, respectively. Compared to untreated soil and at the same curing time, the UCS of 1% SA treated NS2 is 855.3 kPa, 1011.3 kPa, 975.5 kPa, 917.3 kPa, 865.8 kPa, 849.5 kPa, 829.3 kPa, 798.6 kPa and 779 kPa, respectively, which the corresponding UCS increment ratio is 0.90%, 11.36%, 12.61%, 15.21%, 13.29%, 15.83%, 21.00%, 20.34% and 20.94%, respectively. Moreover, the UCS of 2% SA treated NS2 is 974.9 kPa, 1181.3 kPa, 1099 kPa, 1077.9 kPa, 1023.1 kPa, 993.8 kPa, 964.5 kPa, 948.8 kPa and 928.3 kPa, respectively, which the corresponding UCS increment ratio is 15.01%, 30.08%, 26.86%, 35.38%, 33.88%, 35.51%, 40.72%, 42.98% and 44.12%, respectively. In addition, the UCS of 3% SA treated NS2 is 1863.04 kPa, 2328 kPa, 2249.2 kPa, 2156.3 kPa, 1999 kPa, 1987.6 kPa, 1859.5 kPa, 1855.6 kPa and 1842 kPa, respectively, which the corresponding UCS increment ratio is 119.78%, 156.36%, 159.63%, 170.82%, 161.58%, 171.01%, 171.30%, 179.63% and 185.98%, respectively. Overall, compared to untreated soil, the UCS increment ratio of 1%, 2% and 3% SA treated soil is about 15%, 30% and 170% with the formation of strong biopolymer-soil matrices.

On the other hand, the UCS of SA treated NS2 at curing 14 days can reach 93.35%, 84.57%, 82.53% and 80.03% of the maximum UCS at 0%, 1%, 2% and 3%. It can be explained that the biopolymer treated soil still keeps a higher water content than untreated soil and the reaching ratio decreases with the increase of biopolymer concentration. However, more than 80% maximum strength can be reached in the first 14 curing days, and the strength can be fully performed until reaching the final water content condition. With the continuous increase of curing time, the biopolymer film is shrunk to reduce the connection of the biopolymer chain and soil particles. Therefore, the UCS decrement ratio of SA treated NS2 at curing 1-year days is about 29.07%, 22.97%, 21.42% and 20.88%, respectively, and the higher biopolymer can relieve the decrease of soil strength to keep the high value even at curing long-term. In addition, the strength decrement ratio of biopolymer treated soil tends to keep stable, and it can be expected that the UCS of biopolymer treated soil only has slightly decreased even after curing more time. Meanwhile, with each 1% SA concentration increment, the UCS increment ratio is smaller than 21% in the SA concentration less than 2%. However, compared to the UCS of 2% SA, the strength obviously increases that the corresponding increment ratio is more than 90% regardless of curing time.

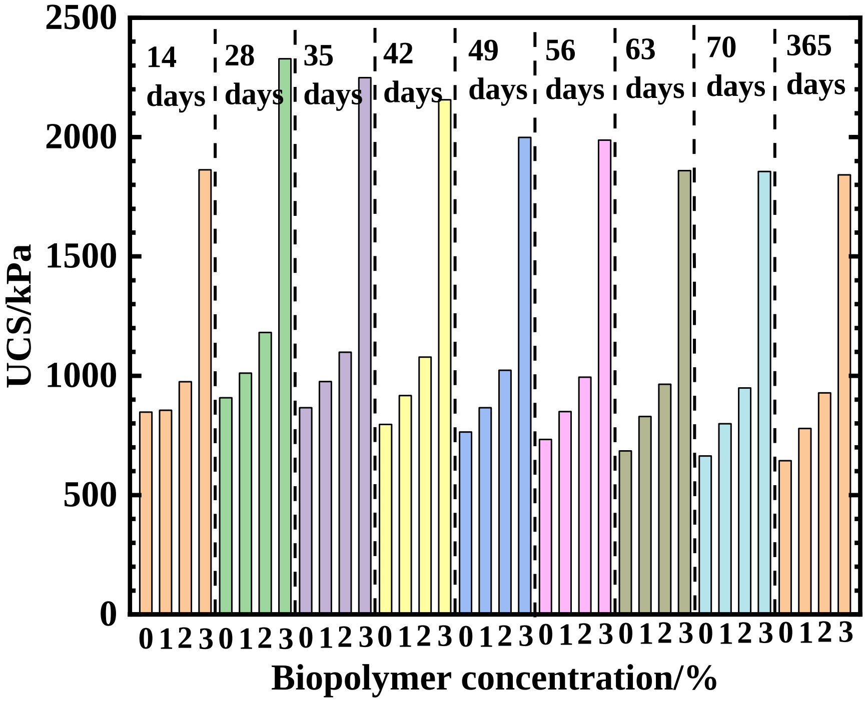


Figure 6.5 UCS of SA treated NS2

As shown in Figure 6.6, with curing 14 days, 28 days, 35 days, 42 days, 49 days, 56 days, 63 days, 70 days and 365 days, the UCS of 1% XG treated NS2 is 1220.9 kPa, 1727.2 kPa, 1407 kPa, 1353.6 kPa, 1247.1 kPa, 1160 kPa, 1064.3 kPa, 1029 kPa and 981.4 kPa, respectively, which the corresponding UCS increment ratio is 40.02%, 90.2%, 62.41%, 70.01%, 63.19%, 58.17%, 55.28%, 55.06% and 52.37%, respectively. And the UCS of 2% XG treated NS2 is 2222.4 kPa, 2506.6 kPa, 2407.3 kPa, 2354.5 kPa, 2248.5 kPa, 2045.1 kPa, 1954 kPa, 1832.6 kPa and 1790.3 kPa, respectively, which the corresponding strength increment ratio is 162.17%, 176.03%, 177.88%, 195.72%, 194.23%, 178.85%, 185.09%, 176.16% and 177.95%, respectively. With the XG concentration increasing to 3%, the UCS is 3175.3 kPa, 3487.6 kPa, 3329.8 kPa, 3157.4 kPa, 2818 kPa, 2727.1 kPa, 2648.4 kPa, 2535.1 kPa and 2420.1 kPa, respectively, which the corresponding UCS increment ratio is 274.58%, 284.06%, 284.37%, 296.56%, 268.75%, 271.84%, 286.4%, 282.02% and 275.73%, respectively.

At the first curing 14 days, the UCS of XG treated NS2 can reach 93.35%, 90.95%, 88.66% and 85.88% of the maximum strength value at 0%, 1%, 2%, 3%, respectively. It shows that the reaching ratio decreases with the increase of XG concentration because the higher XG concentration can relieve the water evaporation in the initial stage. Moreover, the water content can reach a stable condition (e.g., normally lower than 2%) after curing 28 days to obtain the maximum strength. In addition, the strength can decrease the ratio of 29.07%, 29.28%, 28.58% and 28.03% at 0%, 1%, 2%, 3%, respectively, even curing 1-year days. It illustrates that the UCS of XG treated soil also has a limited decrease at curing long-term and the strength decrement tends to be ignored. Moreover, the strength of XG treated soil is still significantly higher than untreated soil. Meanwhile, with each 1% XG concentration, the UCS increment ratio decreased from about 90%, 50% to 35% in the XG concentration range from 0% to 3%. Therefore, it can be expected that there may be the optimum XG concentration to strengthen and stabilize the NS2.

Overall, it should also note that the untreated soil samples are prepared with the initial water content of 15%, which is significantly smaller than that of biopolymer treated soil. On the one hand, untreated soil samples with high water content cannot be made because the soil becomes a fluid state. On the other hand, the strength of untreated soil decreases with the increase of optimum water content. Therefore, it can be predicted that the strength of biopolymer treated soil is of great larger than that of untreated soil under the same condition (e.g., initial water content and curing time).

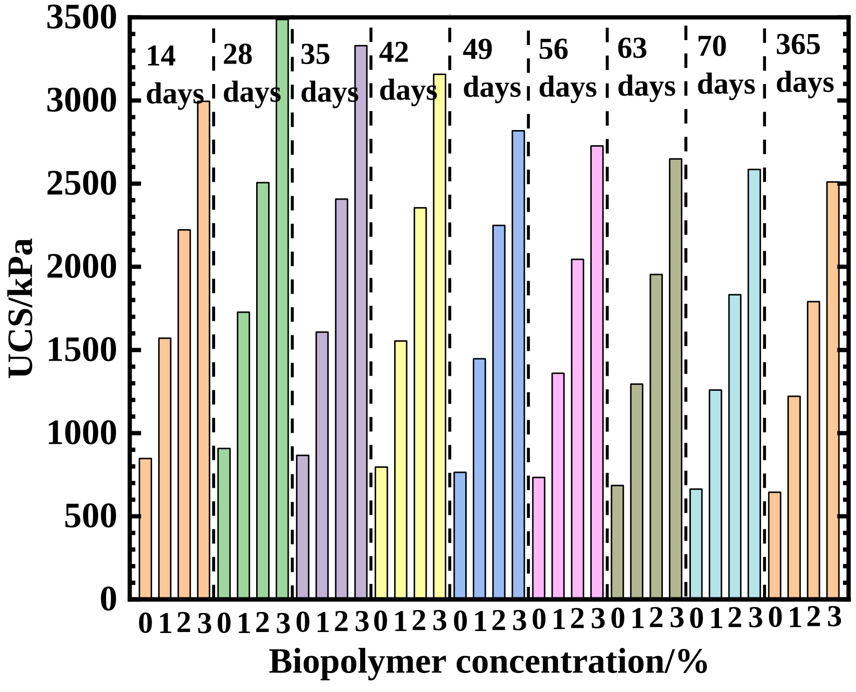


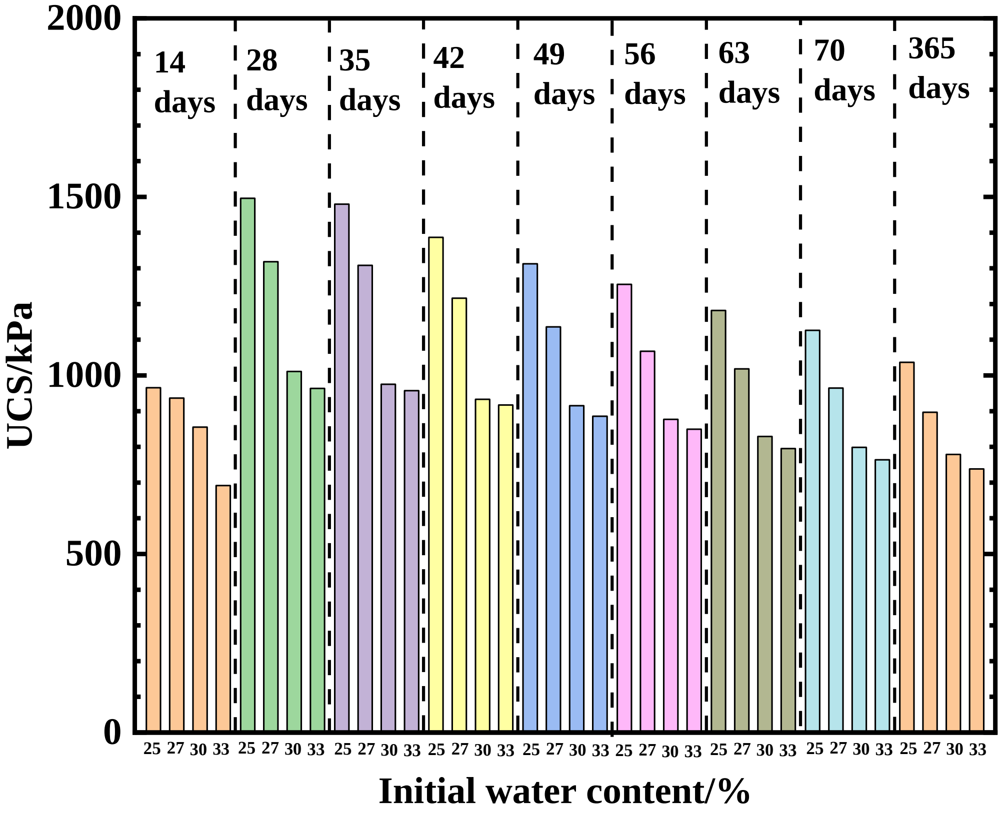
Figure 6.6 UCS of XG treated NS2

For exploring the influence of initial water content on the strength of biopolymer treated soil, the UCS of 1% and 2% SA treated NS2 with different initial water content at various curing time is shown in Figure 6.7. Regardless of curing time, the UCS of 1% SA treated NS2 decreases with the increase of initial water content from 25% to 33%, while the UCS of 2% SA increases with the initial water content increased from 30% to 35%. Therefore, the optimum initial water content of 1% and 2% SA treated NS2 in the preparing stage can be regarded as 25% and 35%, respectively. It can be explained that the high SA concentration needs absorb more water molecules to generate the uniformly biopolymer-soil matrices. In addition, the maximum UCS is obtained at curing 28 days, and then the strength decreases with the continuous increase of curing time regardless of initial water content and SA concentrations.

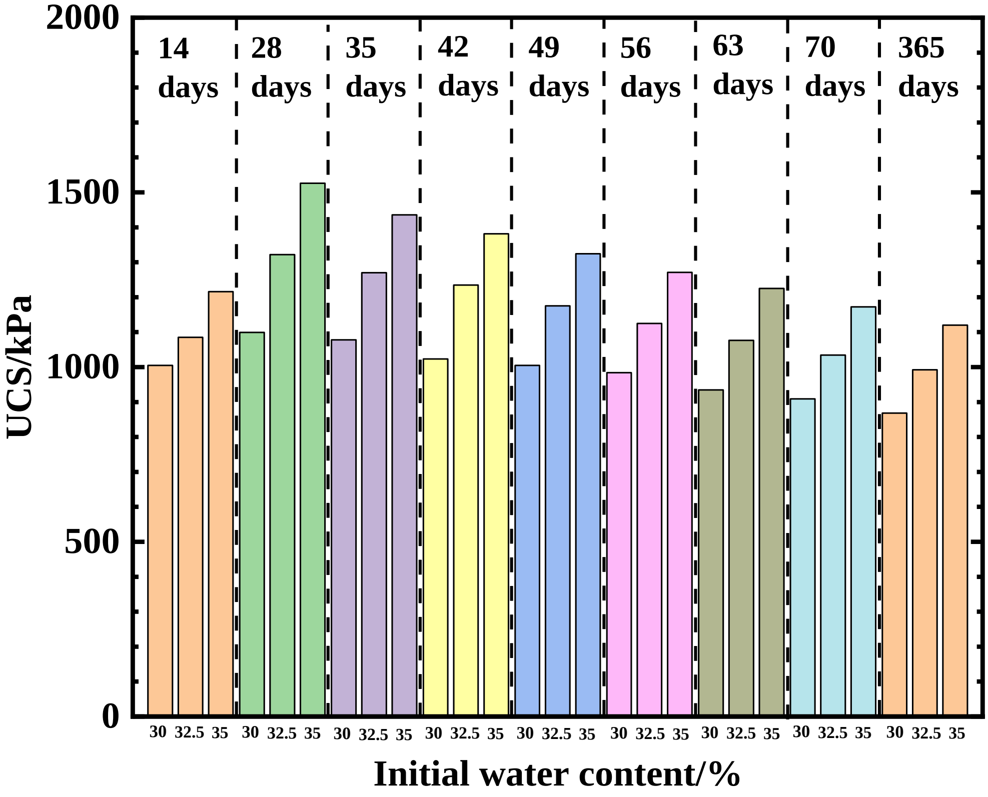
Specifically, the UCS of 1% SA treated NS2 at initial water content 25% is 965.5 kPa, 1496.2 kPa, 1479.6 kPa, 1386.5 kPa, 1312.7 kPa, 1255.2 kPa, 1181.9 kPa, 1126.4 kPa and 1036.8 kPa with curing 14, 28, 35, 42, 49, 56, 63, 70 and 365 days, respectively. And with the initial water content increasing to 27%, the UCS of 1% SA treated NS2 is 936.7 kPa, 1318.3 kPa, 1308.4 kPa, 1216.3 kPa, 1136.2 kPa, 1067.7 kPa, 1018.2 kPa, 964.9 kPa and 897.1 kPa with curing 14, 28, 35, 42, 49, 56, 63, 70 and 365 days, respectively. In addition, the UCS of 1% SA treated NS2 at initial water content 30% is 855.3 kPa, 1011.3 kPa, 975.5 kPa, 933.2 kPa, 915.3 kPa, 877.1 kPa, 829.3 kPa, 798.6 kPa and 779 kPa with curing 14, 28, 35, 42, 49, 56, 63, 70 and 365 days, respectively. Moreover, the UCS of 1% SA treated NS2 at initial water content 33% is 691.6 kPa, 963.9 kPa, 957.4 kPa, 917.3 kPa, 885.8 kPa, 849.5 kPa, 795.3 kPa, 763.7 kPa and 738.2 kPa with curing 14, 28, 35, 42, 49, 56, 63, 70 and 365 days, respectively. It shows that the UCS of 1% SA treated at initial water content 25% and 27% is significantly larger than other two conditions, especially for short curing time. Compared to the lowest UCS, the increment ratio of the highest UCS is 39.60%, 55.22%, 54.54%, 51.15%, 48.19%, 47.76%, 48.61%, 47.49% and 40.45% with curing 14, 28, 35, 42, 49, 56, 63, 70 and 365 days, respectively.

As shown in Figure 6.7 (b), with the curing14, 28, 35, 42, 49, 56, 63, 70 and 365 days, the UCS of 2% SA treated NS2 at the initial water content 30% is 1004.9

kPa, 1099 kPa, 1077.9 kPa, 1023.1 kPa, 1004.9 kPa, 983.8 kPa, 934.5 kPa, 908.8 kPa and 868.3 kPa, respectively, and the UCS of 2% SA treated NS2 at the initial water content 32.5% is 1085.1 kPa, 1322 kPa, 1270.1 kPa, 1234.9 kPa, 1175.1 kPa, 1125.1 kPa, 1076.7 kPa, 1034.6 kPa and 992.1 kPa, respectively. With the initial water content increasing to 35%, the UCS increases to 1216.1 kPa, 1526.3 kPa, 1435.7 kPa, 1381.3 kPa, 1324.2 kPa, 1271.1 kPa, 1224.9 kPa, 1172.1 kPa and 1120.1 kPa, respectively, which corresponds the increment ratio of 21.02%, 38.88%, 33.19%, 35.01%, 31.77%, 29.20%, 31.08%, 28.97% and 29.00%, respectively, compared to the lowest strength at the same curing time. In addition, it shows that the strength of SA treated NS2 almost linear increases with the increase of initial water content. In addition, it should also be noted that it is difficult to continuous increase the initial water content in the 2% SA treated NS2 due to the biopolymer-soil matrices becoming fluid states when the initial water content overcomes 35% in the preparing stage.



(a) 1%



(b) 2%

Figure 6.7 UCS of SA treated NS2 with different initial water contents

Figure 6.8 illustrates the UCS of 1% different biopolymer types treated NS2 with curing various time. It shows that the XG can obtain the best performance on increasing soil strength following SA and LBG, which is more significant than other biopolymers treated soil and untreated soil regardless of curing time. In addition, the UCS of AG and GE treated NS2 is almost the same at the same curing time, which is slightly larger than that of KG treated NS2. It can be explained that the viscosity of XG, LBG and SA solution significantly increases. Meanwhile, strong ionic and hydrate bonds can be formed to increase the soil strength. On the other hand, the dry density of biopolymer treated soil is more diminutive than untreated soil causing a decrease in soil strength because there is a positive correlation between soil strength and the dry density of soil. And the formation of KG-NS2 bonds cannot overcome the negative effect caused by the decrease in soil's dry density. Therefore, the UCS of KG treated soil is smaller than that of untreated soil regardless of curing time. Meanwhile, the biopolymer-soil matrices can normally keep stable even at curing long time, while the connection of soil-soil particles is easily broken in the curing long time. Thus, although the UCS of

AG and GE treated NS2 is lower than that of untreated soil at curing 14 and 28 days, the UCS of AG and GE is slightly larger than that of untreated soil at curing long time (e.g., > 70 days).

Specifically, the UCS of XG, LBG, SA, AG, GE and KG treated NS2 at curing 14 days is 1570.9 kPa, 886.5 kPa, 965.5 kPa, 706.4 kPa, 700.7 kPa and 694.059 kPa, respectively. With the curing time increasing to 28 days, the UCS of XG, LBG, SA, AG, GE and KG treated NS2 increases to 1727.2 kPa, 1285.9 kPa, 1496.2 kPa, 846.5 kPa, 832.5 kPa and 753 kPa, respectively. And then, the UCS of XG, LBG, SA, AG, GE and KG treated NS2 decreases to 1447.1 kPa, 1069.2 kPa, 1312.7 kPa, 830.5 kPa, 824.3 kPa and 685.5 kPa at curing 49 days, respectively. Subsequently, the UCS of XG, LBG, SA, AG, GE and KG treated NS2 slightly decreases to 1259 kPa, 996.3 kPa, 1126.4 kPa, 732.6 kPa, 720.9 kPa and 658.5 kPa at curing 70 days, respectively. It shows that the maximum UCS of biopolymer treated NS2 is obtained in curing 28 days regardless of biopolymer types, and then the strength has slightly decreased with the continuous increase of curing time. Meanwhile, the UCS of XG, LBG, SA, AG, GE treated NS2 is about 2.1, 1.5, 1.8, 1.1 and 1.1 times that of KG treated soil (corresponding to the lowest strength of biopolymer treated soil), respectively.

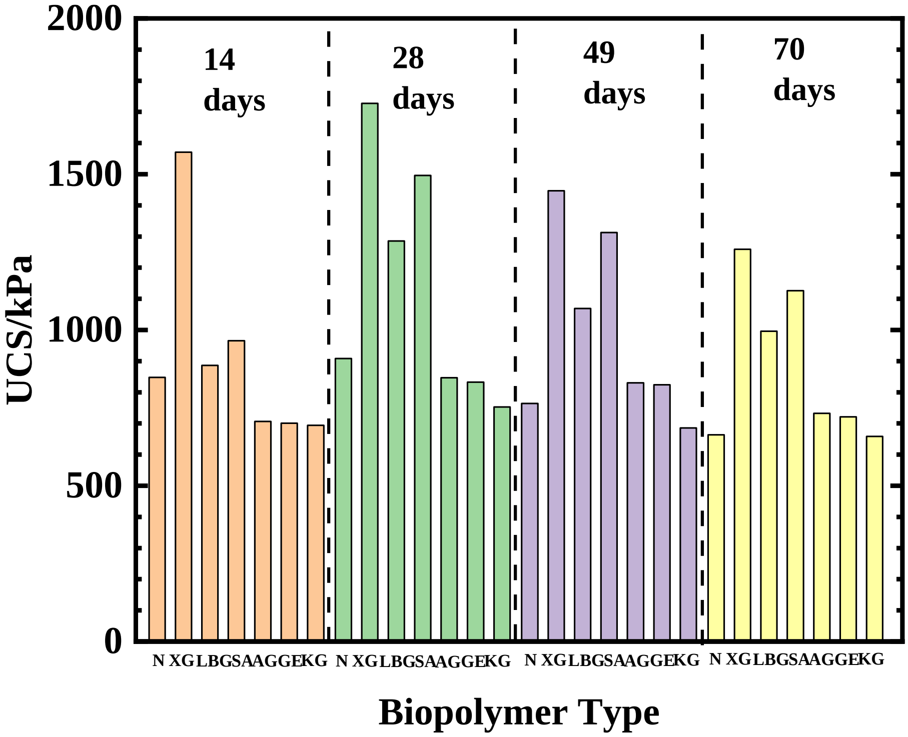


Figure 6.8 UCS of different biopolymers treated NS2

6.3.3 Unconfined compressive strength of biopolymer treated NS3

Figure 6.9 illustrates the UCS of various biopolymers (e.g., XG, SA, LBG, KG and AG) treated NS3 with the concentrations of 1%, 2% and 3% at curing 14 and 28 days. It shows that the highest UCS is obtained in XG treated NS3 regardless of curing time and biopolymer concentrations. And then, the 1% and 3% SA treated NS3 is larger than the same LBG concentration treated NS3, while the condition is reversed in 2% concentration regardless of curing time. Moreover, the same results can also be found in the KG and AG treated NS3. The UCS of 1% and 3% KG treated NS3 is more significant than that of AG treated NS3, and the condition is reversed in 2% concentration regardless of curing time. Overall, the XG, SA and LBG have a better performance on increasing soil strength, especially for XG even at low concentration (e.g., 1%), while the AG has a weak performance on the reinforcing soil and the KG treated soil is only slightly larger than that of untreated soil at low concentration. The UCS of XG treated NS3 is about 2-2.6 times that of SA or LBG treated soil regardless of biopolymer concentration, while the UCS of XG treated NS3 is about 3-6 times that of KG and AG treated NS3 and the corresponding ratio increases with the increase of biopolymer concentration and curing time.

Specifically, the UCS of untreated NS3 is 376.8 kPa and 416.7 kPa at curing 14 and 28 days, respectively. With curing 14 days, the UCS of 1% XG, SA, LBG, KG and AG treated NS3 is 1223.1 kPa, 490.4 kPa, 480.4 kPa, 450.8 kPa and 348.1 kPa, respectively, and the UCS of each biopolymer treated NS3 is 1555.3 kPa, 706.3 kPa, 811.2 kPa, 393.3 kPa and 362.9 kPa with the biopolymer increasing to 2%, respectively. In addition, the UCS of 3% XG, SA, LBG, KG and AG treated NS3 is 1738 kPa, 910.4 kPa, 866.1 kPa, 349.6 kPa and 301.9 kPa at curing the same time, respectively. On the other hand, with the curing time increasing to 28 days, the UCS of 1% XG, SA, LBG, KG and AG treated NS3 is 1402.2 kPa, 585.1 kPa, 531.8 kPa, 439.1 kPa and 350.6 kPa, respectively, and the UCS of 2% each biopolymer treated NS3 is 1768.6 kPa, 766.8 kPa, 870.5 kPa, 373.7 kPa and 421.2 kPa, respectively. Meanwhile, with the biopolymer concentration increasing to 3%, the UCS of XG, SA, LBG, KG and AG treated NS3 is 1924.8 kPa, 967.9 kPa, 911.3 kPa, 328.5 kPa and 314.4 kPa, respectively.

It shows the UCS of XG, SA, LBG and AG increases with the increase of curing time from 14 to 28 days regardless of biopolymer concentration, while the UCS of biopolymer treated soil at curing 14 days can reach 83.8%-99.3% of the obtaining UCS with curing 28 days. On the other hand, the maximum UCS of KG is obtained in curing 14 days, and there is a slight decrease with the ratio of about 2.6%-6.0% at curing 28 days. With each 1% concentration increment from 0% to 3%, the UCS increment ratio of XG treated NS3 is about 230%, 27% and 10%, respectively, regardless of curing time. Meanwhile, the UCS increment ratio of SA treated NS3 is about 40%, 40% and 27%, respectively, while the UCS increment ratio of LBG treated NS3 is about 27%, 65% and 5%, respectively. It can be found that the UCS of XG, SA and LBG treated NS3 continuously increases, while the UCS increment ratio of XG and SA treated NS3 decreases (e.g., especially for XG) with the increase of biopolymer concentration, and the UCS increment ratio of LBG treated NS3 has a significant increase from 1% to 2%. Therefore, the UCS of 2% LBG treated NS3 is even larger than that of SA treated NS3.

On the other hand, with each 1% concentration increment, the UCS increment ratio of KG treated NS3 is about 10%, -13% and -12%, respectively, and the UCS increment ratio of AG treated NS3 is about -10%, 10% and -20%, respectively. Therefore, the maximum UCS of KG and AG treated NS3 is obtained in 1% and 2%, respectively. Overall, there is the optimum biopolymer concentration to reinforce NS3, which corresponds the 1%, 2%, 2%, 1% and 2% for XG, SA, LBG, KG and AG, respectively.

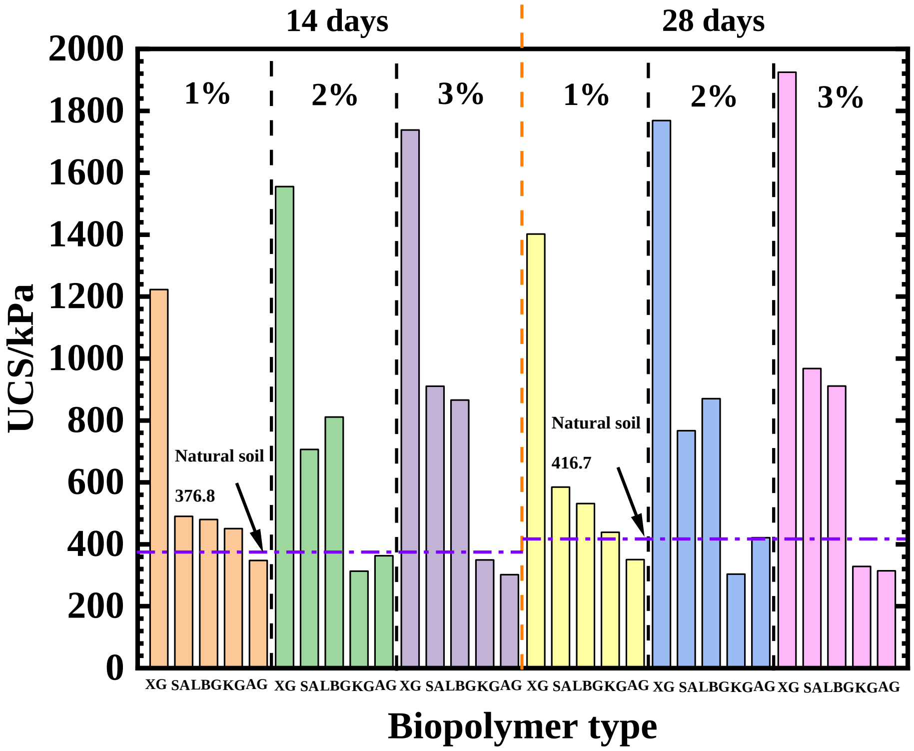


Figure 6.9 UCS of various biopolymers treated NS3

6.4 Summary

It is necessary to explore the reinforcement effect of biopolymer treated natural soil before field application. For meeting the current gaps on the mechanical behaviours of biopolymer treated natural soil, this chapter illustrates the unconfined compressive strength of biopolymer treated three locations of natural soil by considering biopolymer type (SA, XG, LBG, GE, KG and AG), biopolymer concentration (1%, 2% and 3%), initial water content (25-35%) and curing time (14, 28, 35, 42, 49, 56, 63, 70 and 365 days). The innovation conclusions can be summerized as follows.

(1) With the biopolymer concentration increasing from 0% to 3%, the liquid limit of KG and XG-KG with the ratio of 1:1 treated NS1 increases to 50.2% and 43.1%, respectively, while the liquid limit of XG treated NS1 increases to 37.3% at 2% concentration and then decreases to 34.4% at 3% concentration. In addition, the strain-softening behaviours can be observed in low XG concentration treated NS1 after curing less time (e.g., 4 days), while the high XG concentration treated NS1 still has strain-hardening behaviours. Moreover, the optimum curing time of untreated NS1 and XG treated NS1 is 21 and 28 days, respectively. Meanwhile,

the UCS increment ratio tends to decrease with each 1% XG increment and there exists the optimum XG concentration (1%) to reinforce NS1.

(2) The UCS of SA and XG treated NS2 after curing 14 days can reach more than 80% of maximum UCS (at cuirng 28 days). Even after curing 1-year, the UCS decrement ratio of SA and XG treated soil is only about 20% and 29%, respectively, which is still significantly larger than that of untreated soil. Meanwhile, the decrement ratio decreases with the increase of biopolymer concentration. Moreover, the optimum biopolymer concentration of SA and XG treated NS2 is about 3% and 2%, respectively. In addition, the optimum initial water content of 1% and 2% SA treated NS2 in the preparing stage can be regarded as 25% and 35%, respectively. Through comparing the UCS of six typical biopolymers treated NS2, it can be found that the best performance on increasing soil strength is XG following SA and LBG, which is obviously larger than other biopolymers treated soil and untreated soil regardless of curing time.

(3) The optimum curing time of biopolymer treated NS3 is still 28 days, except for KG (14 days). Meanwhile, XG, SA and LBG still have the better performance on increasing soil strength than KG and AG. Especially, the UCS increment ratio of 1%, 2% and 3% XG treated NS3 is more than 220%, 310% and 360% of untreated soil. In addition, the optimum concentration of XG, SA, LBG, KG and AG treated NS3 can be regarded as 2%, 2%, 2%, 1% and 2%, respectively.

Chapter 7 Conclusions and Future Work

7.1 Research conclusions

This study aims to investigate soil stabilize and strengthening by using biopolymer through 643 basic physical tests of biopolymer treated clay, 2739 unconfined compression tests of biopolymer treated soil and 369 triaxial shear tests of biopolymer treated clay. Specifically, the basic physical properties of XG treated clay (e.g., maximum dry density, optimum water content and water evaporation ratio) are illustrated by considering XG concentration and curing time. In addition, the Atterberg limits, undrained shear strength and shear viscosity of biopolymer treated clay are revealed by considering biopolymer type and concentration (Chapter 3). Moreover, the mechanical properties of biopolymer treated clay are comprehensively illustrated by considering biopolymer type, biopolymer concentration, initial moisture content, curing time, durability, biopolymer cross-linking and mixing method through unconfined compression tests and triaxial shear tests (Chapter 4). Meanwhile, the UCS of biopolymer treated clay-sand mixture and natural soil is also domenstrated by considering biopolymer type, biopolymer concentration, soil type and curing time (Chapter 5 and Chapter 6). On the other hand, the feasibility analysis of biopolymer treated soil is performed on the aspects of reinforcement mechanism and economic indexes (Chapter 4), and the possible implementation of biopolymer in field application is also proposed on the basis of the current research results (Chapter 3 and Chapter 4). The main conclusions of the current research are drawn as follows.

(1) The optimum water content of biopolymer treated clay increases with the increase of biopolymer concentration. The maximum dry density of biopolymer treated clay has a slight increase at very low concentration (e.g., 0.2%) and then decreases with the increase of biopolymer concentration. Moreover, the plastic limit of biopolymer treated clay also increases with the increase of biopolymer concentration. In terms of the liquid limit of biopolymer treated clay, it can be divided into three conditions. The liquid limit of KG, SA and GE treated clay decreases firstly at low concentration and then increases with the increase of biopolymer concentration. The liquid limit of XG, LBG and GG treated clay

obtains the peak value at 0.5%, 1% and 1%, respectively, and then tends to keep constant after 3% concentration. Meanwhile, the liquid limit of AG and CH treated clay tends to keep constant. Most biopolymers treated clay can be classified as high plasticity silt. Based on the big data on fall cone test results, the *m* value of 0.323 can be used to estimate the liquid limit of biopolymer treated clay by one fall cone test with cone penetration falling between 15 and 25 mm. In addition, the empirical equations of $S_{\mathrm{u}}=508.3\exp(-5.54w/\mathrm{LL})$ and $\mu=375.8\exp(-1.2w/LL)$ are proposed to predict the undrained shear strength and shear viscosity of biopolymer treated clay, respectively. On the other hand, the water evaporation rate of biopolymer decreases, while the biopolymer concentration and water retention capacity can be observed as a positive correlation. The ultimate water content of biopolymer treated clay has a limited difference under below 3% after curing 28 days.

(2) The UCS of biopolymer treated clay is significantly larger than that of untreated clay. Moreover, there exists the optimum biopolymer concentration (e.g., 1%-2%) to strengthen clay and then the UCS of biopolymer treated clay tends to keep stable or even decrease with the continuous increase of biopolymer concentration. The highest UCS of biopolymer treated clay can be obtained in SA following XG. Meanwhile, LBG, GE, KG and AG have a similar strengthening efficiency after curing 28 days that the UCS increment ratio of these four biopolymers treated clay is less than 90%. In addition, there is also the optimum initial water content in preparing the biopolymer treated clay samples to achieve a better reinforcement effect. Specifically, the optimum initial water content of 0.5%, 1%, 2% and 3% XG treated clay is 40%, 45%, 50% and 60%, respectively, which is 1.3, 1.46, 1.67 and 2 times of the optimum water content of untreated clay (30%). Compared to untreated clay, the XG concentration (C_{XG}) and the UCS increment ratio (IR_{UCS}) regardless of curing time can be expressed as $IR_{\mathrm{UCS}} = 100\ C_{\mathrm{XG}}$. On the other hand, the optimum initial water content of SA treated clay is in the range of 50%-55%. Most biopolymers treated clay obtains the maximum strength at curing 28 days, while the optimum curing time of XG treated clay tends to increase with the increase of XG biopolymer. Even under curing 54 weeks, the UCS decrement ratio of biopolymer treated clay is in the range of 7%-26% compared to the maximum value

that the UCS of biopolymer treated clay is 1.43-7.83 times that of untreated clay. Moreover, the samples of untreated clay are easily broken under the rewetting-drying, while the UCS of XG treated clay is still obviously larger than that of the highest UCS of untreated clay, which was 2.51, 2.31 and 2.15 times with the rewetting-drying cycles of 1, 2 and 3, respectively.

(3) The UCS of XG-AG and XG-LBG treated clay increases with the increase of XG content. Furthermore, there is the threshold ratio value with the XG-AG or XG-LBG ratio of 1:4 that the UCS significantly increases beyond this ratio. And the UCS of XG-AG/LBG with the ratio of 4:1 is even slightly larger than that of pure XG treated clay. On the other hand, the maximum UCS of XG-KG treated clay is obtained in the ratio of 1:1, and the UCS of XG-KG treated clay is gradually larger than that of pure XG treated clay. In terms of considering the mixing method, the XG/SA treated clay with dry mixing is more effective than wet mixing to increase strength. Moreover, the optimum mixing method in the preparing stage of XG/SA treated clay is to adopt HDM and then RDM, which is significantly larger than that of biopolymer treated clay mixing with RWM and HWM. Moreover, the highest UCS of AG/GE treated clay is obtained in HWM followed by RDM, while the AG/GE treated clay with the HDM obtains the smallest UCS. Meanwhile, the highest UCS of KG treated clay and LBG treated clay obtains in HDM and HWM, respectively. Considering the cross-link of XG-AG, the highest UCS can be achieved in RDM and HWM at low and high XG-AG ratios, respectively.

(4) Biopolymer can significantly increase the soil shear strength under hydraulic conditions, and the cohesion of biopolymer treated clay is obviously larger than that of untreated clay, while the internal friction angle has little change. SA, AG, GE and GG treated clay are the most effective biopolymer to increase soil cohesion, following KG, GL and CA. Subsequently, the LBG, XG and SU can be regarded as the third level to increase soil cohesion, while the cohesion of CH and WT treated has limited increase compared to untreated clay. Moreover, the cohesion of biopolymer treated clay increases with the increase of biopolymer concentration. At the same time, the internal friction angle varies because there are contradictory effects with aggregating soil particles to change particle size distribution for increasing the internal friction of soil particles and the viscous biopolymer gel reducing the surface roughness to

decrease the internal friction of soil particle. At this stage, the thickened biopolymer gels begin to coagulate around the soil particles under the electrical interaction and the hydrogen bonding between the biopolymer chains and the diffuse double layer of clay minerals. After dehydration, the condensed film-like biopolymer gels enhance the inter-particle, and there is the optimum curing time to obtain the maximum shear strength of biopolymer treated clay. Meanwhile, the cohesion and internal friction angle of biopolymer treated clay increases compared to untreated clay. However, the biopolymer gel gradually spreads into the concentrated gel and becomes a thin layer under long curing time. During this process, the mobility of biopolymer gradually decreased to zero, causing the thin film of biopolymer to break easily with a slight decrease of strength. In terms of economic analysis, the present high cost of biopolymers restricts their application in geotechnical engineering compared to other current soil improvement materials (e.g., cement, lime). However, some biopolymers (e.g., XG, GG, AG and SA) are competitive considering environmental impact.

(5) The UCS of untreated sand is ignored due to the cohesionless of soil particles, and the biopolymer can significantly increase sand strength. For example, the UCS of 3% SA and XG treated sand reaches more than 3700 kPa at curing 28 days. At curing 14 days, the best performance biopolymer on increasing sand strength can be observed in SA following XG, LBG, GE, KG and AG. With the curing time increasing to 28 days, the UCS of SA, LBG and XG treated sand is almost the same at 1% concentration, while the UCS of XG treated sand is obviously larger than that of SA and LBG treated sand at high biopolymer concentration following GE, KG and AG. Thus, the SA and XG can be regarded as efficient biopolymers for increasing sand strength. On the other hand, the UCS increment ratio of most biopolymer treated sand decreases with the increase of biopolymer concentration except for KG. Typically, the UCS of 3% biopolymer concentration treated sand has a limited increase, even less than that of 2% biopolymer concentration treated sand. Moreover, the optimum biopolymer concentration to reinforce soil strength can be regarded as 2%.

(6) The minimal XG concentration (e.g., 0.2%) can significantly increase the strength of the sand-clay mixture. Furthermore, the behaviours of UCS increment ratio of biopolymer treated clay-sand mixture with the increase of biopolymer

concentration depend on the ratio of clay-sand. In addition, the 1% XG treated S_1C_{1-1} can obtain the highest UCS regardless of curing time, and the smallest UCS is obtained in pure clay or S_1C_{4-1} depending on curing time. Normally, the UCS of XG treated clay-sand mixture needs more curing time to reach the maximum strength and tends to keep stable with the increase of clay content. At 2% XG concentration, the highest UCS is observed in S1 following S_1C_{1-1}, S_1C_{1-4} and pure clay at curing less than 42 days. And then, the UCS of XG treated S_1C_{1-1} is more significant than that of XG treated pure sand, while the UCS of XG treated pure clay can overcome the UCS of XG treated S_1C_{1-4} at curing long time. At 3% XG concentration, the highest UCS can be obtained in pure sand following S_1C_{1-4}, S_1C_{1-1} and pure clay at curing less time. With the increase of curing time, the UCS of XG treated pure clay subsequently overcomes the UCS of XG treated S_1C_{1-1}, S_1C_{1-4} and pure sand. Meanwhile, the smallest UCS can be observed in XG treated S_1C_{4-1} at 2% and 3% concentrations. The clay content plays a vital role in the strength of the biopolymer treated sand-clay mixture. In terms of S2-clay mixture, with curing 14 days, the XG treated S2 can be observed as the highest UCS following XG treated S_2C_{1-1} and S_2C_{1-4}, while the highest UCS of SA treated soil is obtained in S_2C_{1-4} or S_2C_{1-1} depending on SA concentration. On the other hand, the UCS of XG treated S_2C_{1-1} is slightly larger than that of XG treated S2 at 3% concentration becoming the highest value at curing 28 days. Meanwhile, the highest of SA treated soil is obtained in S_2C_{1-4} or pure clay. Moreover, the UCS of XG/SA treated S_2C_{4-1} can be observed as the smallest value. The optimum curing time of untreated sand and biopolymer treated sand at low concentration is 14 days, while the maximum UCS of biopolymer treated sand at high concentration is 28 days. Moreover, with the increase of biopolymer concentration and clay content, the UCS decrement ratio of the biopolymer treated clay-sand mixture decreases after curing for a long time. However, the UCS of biopolymer treated soil can be still 5.7-13.5 times that of untreated soil.

(7) The optimum curing time to reach the maximum strength of most biopolymers treated natural soils is 28 days in this study. The UCS of 0.5%, 1%, 2% and 3% XG treated NS1 is more 2.08, 3.02, 3.39 and 3.97 times than that of untreated soil regardless of curing time. In addition, the UCS increment ratio tends to decrease with each 1% XG increment and there exists the optimum XG concentration (1%) to reinforce NS1. Although there is about 20% and 29% UCS decrement ratio of

SA and XG treated NS2, respectively, after curing 1-year days, the UCS of biopolymer treated is still more significant than that of untreated NS2. Moreover, the UCS decrement ratio decreases with the increase of biopolymer concentration under curing long time. Meanwhile, the optimum biopolymer concentration of SA and XG treated NS2 to obtain better reinforcement can be regarded as 3% and 2%, respectively. In addition, the optimum initial water content of 1% and 2% SA treated NS2 in the preparing stage is 25% and 35%, respectively. Moreover, the performance on increasing NS2 strength is XG following SA and LBG, which is obviously larger than other biopolymers (e.g., AG, GE and KG) treated soil and untreated soil. On the other hand, the highest UCS of biopolymer treated NS3 is obtained in XG following SA and LBG, which is more significant than that of KG or AG treated NS3. Especially, the UCS increment ratio of 1%, 2% and 3% XG treated NS3 is more than 220%, 310% and 360% of untreated soil. In addition, the optimum concentration of XG, SA, LBG, KG and AG to reinforce NS3 can be regarded as 1%, 2%, 2%, 1% and 2%, respectively.

7.2 Future work

It can be seen that biopolymer treated soil can increase strength and change the soil consistency. Thus, it can be used to construct temporary support facilities and hydraulic barriers in geotechnical practices. Moreover, there is high viscosity after mixing with water and soil grains, and it can also be utilised as grout material in compaction grouting or deep cement mixing method. However, there are still some issues that should be considered and researched in future studies.

(1) Currently, thousands of experimental tests have been conducted to obtain loads of data forming a database about the physical and mechanical properties of biopolymer treated soil. However, more advanced constitutive models of soil (e.g., critical state model and modified cam clay model) should be further modified, established and adopted to analyze and explain the current experimental results. On the other hand, more triaixal shear tests of biopolymer treated clay-sand mixture or natural soil should be further performed by considering various conditions (e.g., consolidated undrained and consoliated drained) for better modifying and adopting the advanced soil mechanics model in turn.

(2) More experimental tests should be performed in the further research to investigate the hydraulic properties of biopolymer treated soil (e.g., permeability and coefficient of consolidation), the void characteristics of biopolymer treated soil (e.g., volume change). In addition, the coupling effect of multi-influence factors (e.g., temperature, seepage, chemical and stress) should be further considered in the experimental tests and analyzed by using optimizing methods.

(3) More SEM images should be further obtained to reveal the micro-scale mechanism of biopolymer treated soil. Moreover, the numerical simulation (e.g., FEM, DEM or coupled both them) should also be performed to further explain the fundamental mechanism at particle level. And then, the bridge between micro-scaled mechanism of biopolymer treated soils and the macro-scaled mechanical behaviours is also my future research direction.

(4) The durability of biopolymers is still an important issue due to biodegradable and hydro sensitive behaviours. Therefore, the long-term behaviours of biopolymer treated soil have to be verified to define its serviceability, especially for considering cyclic loading and climate change (e.g., rewetting-drying). To be practically and economically applicable for in situ geotechnical engineering purposes, the development of suitable equipment and the workability of biopolymer is required to be accessed for desired construction performance and reliability.

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