

# Investigation of unconfined compressive strength for biopolymer treated clay

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## ABSTRACT

In this study, six typical biopolymers (xanthan gum (XG), sodium alginate (SA), kappa gum (KG), locust bean gum (LBG), agar gum (AG) and gellan gum (GE)) are selected to investigate the mechanical strength of biopolymer treated clay with the consideration of different hydrated conditions, biopolymer concentration, curing time, wetting–drying, the combination of two different types of biopolymers and biopolymer–soil mixing method. From the results, it can be seen, under the same conditions, out of the six different biopolymers, SA-treated clay provided the highest unconfined compressive strength (UCS) (3.58–4.5 times of untreated clay). Moreover, an optimum reinforcement performance was found when biopolymer concentration was within the range of 1–2% with a curing time between 28 and 42 days. Furthermore, despite biopolymers being eco-friendly materials, with great potential under the biodegradation process, current research results demonstrated that XG treated clay can maintain UCS even after curing 378 days and undertaking 3 cycles of wetting–drying processes. In addition, the maximum UCS of XG combined KG treated soil can be observed in the ratio of 1:1. Hot-water dry mixing method can be adopted to obtain uniform XG, SA or KG-clay mixture further improving the soil strength, while AG, GE and LBG treated clay has a better strengthening efficiency by using hot-water wet mixing method.

## 1. Introduction

Civil infrastructures are commonly constructed on weak soils that require improvement to resist applied loads. Thus, various ground reinforcement methods have been proposed to increase the soil bearing capacity. However, traditional soil stabilization materials, e.g. cement, have caused environmental concerns, especially by considering reaching the UN's sustainable development goal [1–3]. Biopolymer, directly extracted from plants and utilized biogenic excrement with abundant in nature, has been identified as one of ecofriendly materials [4–5]. In recent years, it has gained increased academic interest to be used for ground reinforcement because it is capable of improving the mechanical properties of soils even under a low biopolymer to soil ratio, e.g. 5% [6–8]. In particular, the UCS of 0.5% biopolymer treated even yielded much higher compressive strength values than the 10% cement treatment [1].

It has been recognized that biopolymer can increase soil strength due to the formation of ionic/electrostatic or covalent bond, hydrogen bond, van der Waals forces in biopolymer–soil matrices [9–11]. The strength efficiency is mainly dependent on biopolymer types, soil types,

biopolymer contents, curing periods, thermal treatment and mixing methods [12–16]. Cabalar and Demir [5] revealed the increase of undrained shear strength with the increase of xanthan gum content, and xanthan gum had a greater efficacy on finer and more angular grains than coarser and more rounded grains. Cabalar and Canakci [6] found that the shear strength of xanthan gum treated sand increased as the biological material content increased beyond 1% and the impact of curing time was not significant. Khatami and O'Kelly [7] found the UCS of agar and starch treated sand ranging from 158 to 487 kPa, and the biopolymers effectively increased the cohesion intercept and stiffness of the treated sand through the results of triaxial shear tests. Rashid et al. [17,18] and Latifi et al. [12,19] reported a significant increase in compressive strength of clay treated with 1.5% xanthan gum by weight of dry soils and with a curing time as 28 days, while the UCS of XG treated clay tended to keep constant beyond 1.5% concentration and curing 28 days. Cabalar et al. [20] illustrated that the only marginal change of UCS of xanthan gum treated low-plasticity clay can be observed after curing 56 days with a 3% content. Cheng and Geng [21] investigated the effects of xanthan gum on soil strengthening, and it depended on type of soil, hydration level (e.g., moisture content),

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xanthan gum content, and mixing method. Bozyigit et al. [22] explored the strength properties of xanthan gum and guar gum treated kaolinite at different water contents. The UCS of biopolymer treated specimens increased in all biopolymer inclusion levels and water contents up to 90 days curing period, and the maximum strength increase was observed at 25% water content and 2% xanthan gum with 90 days curing. Cheng and Geng [23] illustrated the engineering properties of sodium alginate treated clay, and the maximum UCS of treated specimens is obtained at the SA concentration, curing time, mixing method and initial water content of 2%, 28 days, room temperature water-dry mixing and 50%–55%, respectively. Ni et al. [24–26] illustrated that the UCS of XG treated Shanghai clay was elevated with the increase of initial moisture content, and there existed an ideal initial moisture content leading to the maximum strengthening efficiency.

Throughout the literature review, it is lacking comprehensive investigations on the reinforcement effect of different biopolymer types treated clay and exploring the strength efficiency of biopolymer treated clay with long-term curing time and undertaking wetting–drying cycles. Meanwhile, the roles of preparing conditions (e.g., initial water content and mixing method) were neglected before. For example, the biopolymer-soil mixtures were mostly prepared at a fixed initial water content and room temperature [8,14,20,22]. To filling in the current research gaps, kaolinite is selected as a research object in this study to illustrate its mechanical behaviours after being treated by biopolymer through performing unconfined compression tests by comprehensive considering various factors, such as hydrated condition, biopolymer type (e.g., XG, SA, KG, LBG, AG and GE), biopolymer concentration (e.g., 0.5%–3%), biopolymer cross-linking (XG-KG with the ratio of 1:4, 3:2, 1:1, 2:3, 4:1), curing time (e.g., 0–70 days), durability (long-term curing and wetting–drying cycles) and mixing method (e.g., RDM, RWM, HDM, HWM).

## 2. Materials and method

### 2.1. Materials

#### 2.1.1. Soil

The kaolinite used in this experimental study is quarried from the Southwest of England with ultrafine particles ( $\text{SiO}_2$  47% and  $\text{Al}_2\text{O}_3$  38%). See Fig. 1(a) for particle size distribution. Its plastic limit (PL) and liquid limit (LL) values are 30.7% and 69.9%, respectively. Moreover, the uniformity coefficient ( $C_u$ ) and curvature coefficient ( $C_c$ ) of soil are 3.95 and 0.66, respectively. The soil can be classified as clay of high plasticity (CH) based on the Unified Soil Classification System (USCS). The specific gravity ( $G_s$ ) of the clay grains is 2.65 and Fig. 1(b) illustrates the grading curves of clay.

#### 2.1.2. Biopolymer

Six typical biopolymers, xanthan gum (XG, CAS No: 11138-66-2),

sodium alginate (SA, CAS No: 9005-38-3), locust bean gum (LBG, CAS No: 9000-40-2), agar gum (AG, CAS No: 9002-18-0), carrageenan kappa gum (KG, CAS No: 90000-07-1) and gellan gum (GE, CAS No: 71010-52-1), are used in the current study. Fig. 2 illustrates the biopolymers and their chemical structures. The description of each biopolymer can be illustrated as follows.

XG is an anionic and high molecular weight polysaccharide fermented from *Xanthomonas campestris* bacterium, and it has been widely used as a thickener due to its viscous hydrogel formation in the presence of water [28].

SA is the sodium salt form of alginic acid and gum mainly extracted from marine brown algae [29]. 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.

LBG is a galactomannan vegetable gum extracted from carob tree seeds [30]. LBG is soluble in the 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.

AG obtains from the cell walls of some species of red algae of the *Gelidium* *Gelidium* and *Gracilaria* or red seaweeds [31]. It is a hydrocolloid, forming a hard, brittle, transparent and neutral gel to provide rigid textures as a stabilizer.

KG is extracted from red algae called *kappaphycus alvarezii*. 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 [32].

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 [33]. The low acyl gellan gum producing firm, non-elastic, brittle gels are used in this study.

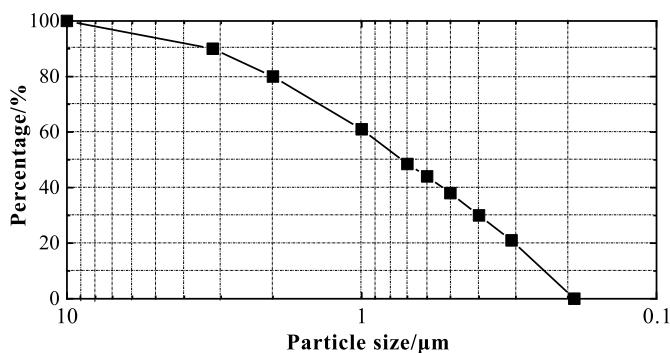
### 2.2. Sample preparation and testing apparatus

#### 2.2.1. Biopolymer-soil mixture preparation

There are four mixing methods to prepare soil samples, 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 soil will have been dried completely in an oven at 105 °C for 24 h and then cooled in sealed containers more 24 h. In dry mixing method, varying quantities of biopolymer particles are firstly poured into the dry soil with a thorough mixture. Subsequently, the soil-binder mixture is blended with a particular value of distilled water. For wet mixing, the biopolymer is firstly dissolved in distilled water. And then, the biopolymer solution is thoroughly mixed with soil. In the laboratory stage, the 100 °C distilled water can be adopted to further explore the thermal properties in the biopolymer treated clay and modify the application of biopolymer in practice. Therefore, hot water-dry/wet mixing is identical to room temperature water dry/wet mixing

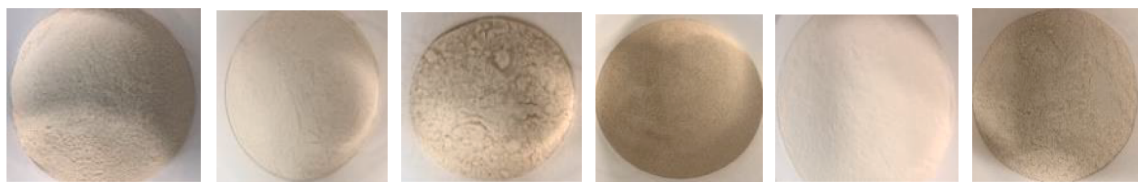


(a) Picture of kaolinite



(b) Grading curves

Fig. 1. Basic information of kaolinite.



(a) XG production (b) SA production (c) LBG production (d) AG production (e) KG production (f) GE production

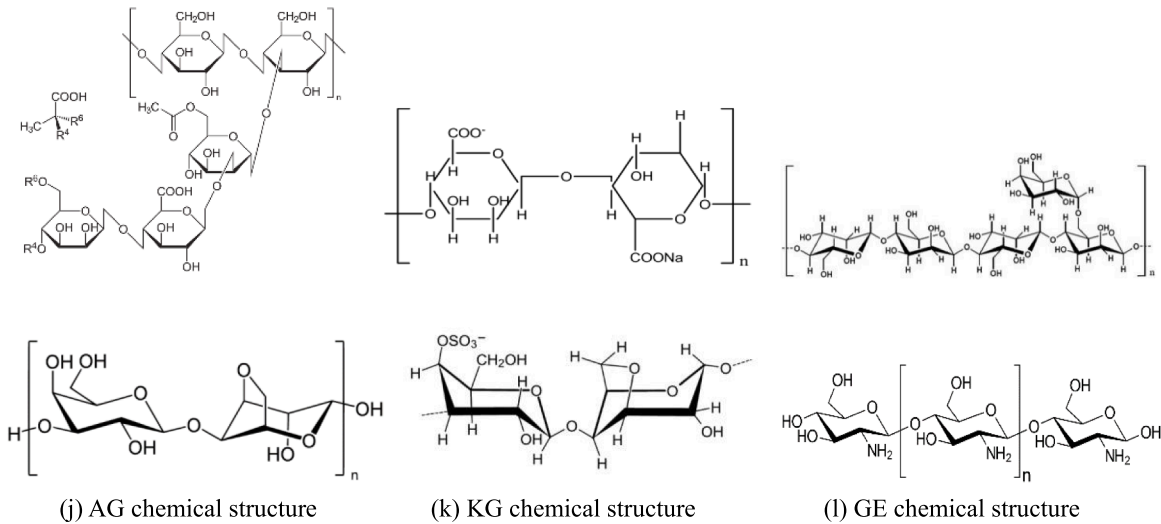


Fig. 2. Biopolymer production and chemical structures [27].

except for using the distilled water with 100 °C. For a reference group with untreated specimens, only distilled water at room temperature (RT) and 100 °C (HT) is added to the soil and keep the other conditions the same. The homogeneity distribution of the ultimate mixtures is guaranteed by hand mixing with palette knives.

For creating uniform unconfined compression strength (UCS) specimens, the uniform biopolymer-soil mixture is compacted into three-part cylinder moulds with a diameter of 50 mm and height of 100 mm. Eventually, the cylindrical specimens are extruded using a steel plunger. The biopolymer treated clay specimens are tested immediately to represent the hydrated condition, while specimens are cured for various days in room temperature conditions for the dehydrated condition. In terms of wetting–drying condition, the samples after curing 28 days are submerged in water until the moisture content of the samples reached the initial condition, and then the submerged specimens will be cured for another 28 days in room temperature conditions. One time of rewet condition and another 28 days drying represent one cycle of wetting–drying.

2.2.2. Test procedure

Unconfined compressive tests are performed by using Zwick/Roell Testing Machine device considering various factors, such as hydrated condition, biopolymer concentration (e.g., 0.5%, 1%, 2% and 3%), biopolymer type (e.g., XG, SA, LBG, AG, KG and GE), curing time (e.g., 0, 7, 14, 28, 35, 42, 49 and 70 days), durability (e.g., curing 378 days and rewetting–drying), the combination of two different types of biopolymers (e.g., XG–KG), and mixing method (e.g., RDM, RWM, HDM and HWM). The axial strain rate is controlled at 1.5%/min following ASTM D2166 [34] until the strength decreases 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. A series of unconfined compression tests are summarized in Table 1.

Table 1

Testing program of unconfined compression test.

Biopolymer type	Soil type	Concentration (%)	Initial water content (%)	Curing time (days)	Mixing method
XG, SA, LBG, AG, KG, GE	Clay	0, 1	45	0, 7, 14, 21, 28, 35, 42, 49, 70	RDM
XG, GE		2, 3	45	7, 14, 21, 28, 35, 42, 49, 70	RDM
SA		1, 2, 3	45	0, 5, 14, 21, 28, 35, 42, 49, 70	RDM
XG–KG (4:1, 3:2, 1:1, 2:3, 1:4)		1	45	7, 14, 21, 28, 35, 42, 49, 70	RDM
XG		1	45	28	RDM with 1, 2, 3 cycles of rewetting–drying
XG		0, 0.5, 1, 2	30, 35, 40, 45, 50	378	RDM
XG, SA, LBG, AG, KG, GE		0, 1	45	7, 14, 28, 35, 49	RDM, RWM, HDM, HWM

3. Results and discussion

3.1. Effect of hydrated condition on UCS

The stress–strain behaviours of each biopolymer treated clay at immediately stage and after curing 28 days are shown in Fig. 3. At hydrated condition, the strain-hardening can be observed for all

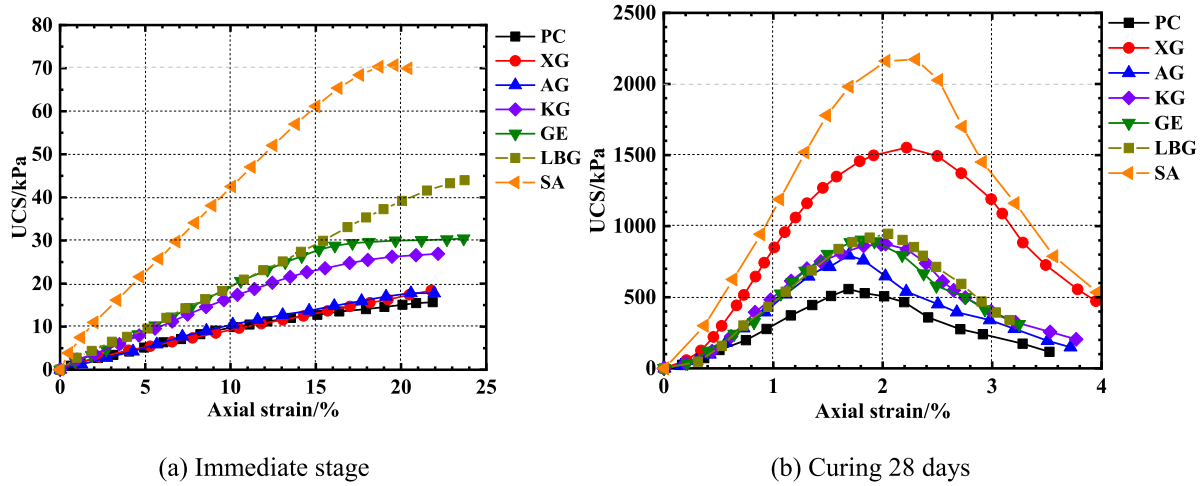


Fig. 3. Stress–strain curves of various biopolymers treated clay.

biopolymer treated clay hydrated condition because the maximum strength is obtained at over 20% strain and tends to keep stable beyond this level. Untreated clay shows a compressive strength as 15.7 kPa, while 1% SA, LBG, GE, KG, XG and AG enhances the soil strength up to 70.7 kPa, 44 kPa, 30.5 kPa, 26.9 kPa, 18.4 kPa and 17.8 kPa, respectively. Therefore, the highest strengthening biopolymer is SA with high elastic modulus values, while the strength and elastic modulus of LBG, GE and KG are slightly larger than that of untreated clay. In the current stage, the strengthening efficiency of biopolymer treated clay cannot be fully recognized because the biopolymer exists in the mixtures as gel solution [15].

At dehydrated conditions, the hydrogen and ionic bonds between clay particles and biopolymer chains can be formed to enhance soil strength and elastic modulus, which is significantly larger than that of hydrated conditions [20]. Moreover, strain-softening can be observed in the stress–strain curves of biopolymer treated clay after curing 28 days. In particular, the unconfined compressive strength of untreated clay is 557.6 kPa with the axial strain of 1.69%, while the unconfined compressive strength of 1% SA, LBG, GE, KG, XG and AG is 4.11, 2.78, 1.70, 1.62, 1.57 and 1.43 times of untreated clay, respectively, and the corresponding axial strain increases to 1.8%-2.3%.

### 3.2. Effect of biopolymer type on UCS

Fig. 4 illustrates the soil strengthening of various biopolymer treated clay at different curing time. SA and XG always shows higher strength than other biopolymers under the same curing time. Compared to

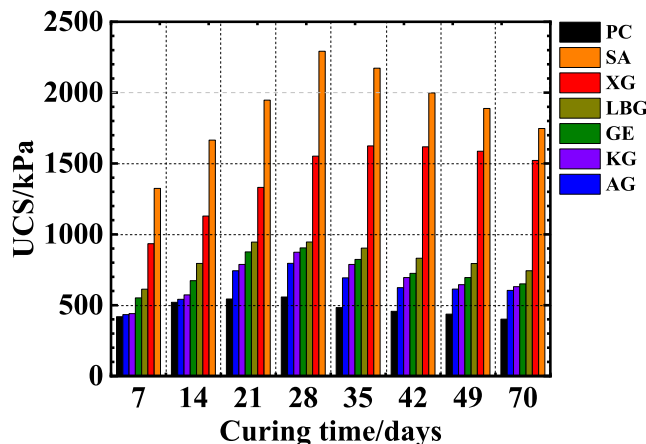


Fig. 4. UCS of 1% various biopolymers treated clay.

untreated clay, the UCS increment ratio of SA and XG treated clay is 216%-350% and 120%-280%, respectively, while small margin of UCS increment is observed for AG and KG treated clay, especially for curing less 14 days. After curing 21 days, LBG, GE, KG, and AG can be regarded as one group with similar soil strength efficiency, and the UCS increment ratio of biopolymer treated clay is in the range of 36%-87%.

It can be explained that SA is a linear polysaccharide derivative of alginic acid comprised of 1,4-β-d-mannuronic and α-l-guluronic acids, and XG is an extracellular polysaccharide gum consisting of glucose, mannose and glucuronic acid [16,18]. Therefore, both of them can bond clay particles directly through hydrogen bonding between the carboxyl (-COOH) and the hydroxyl (-OH) groups, and ionic bonding between electrically charged biopolymer molecule and fine particle surfaces [1,17]. Moreover, XG and SA have good solubility in room temperature water and the biopolymer gel can better fill in the soil void, while LBG, GE and AG are thermal-gelation biopolymer that cannot sufficiently exploit strengthening efficiency at room temperature water mixing condition in preparation stage [3]. It can thus be concluded that SA and XG are more suitable for forming biopolymer-clayey soil matrices.

### 3.3. Effect of biopolymer concentration on UCS

The UCS of various SA, XG and GE concentrations treated clay under different curing time and the corresponding water content are shown in Fig. 5. It is obvious that higher biopolymer concentration renders higher compressive strength values, while the UCS increment ratio decreases with the increase of biopolymer concentration regardless of biopolymer type. In particular, the UCS of GE treated clay even decreases from 551.8 kPa to 492.2 kPa with the concentration increasing from 1% to 3% under 7 curing days. It can be explained that the higher biopolymer concentration has good water retention causing the higher water content at the initial curing stage, while has a negative effect on the mechanical properties of soil [12]. Meanwhile, the soil-biopolymer bonds cannot be fully formed under curing a short time at higher biopolymer concentration.

After curing 14 days, compared to untreated clay, the UCS increment ratio of 1% SA, XG and GE treated clay is 181.6–350.3%, 117%-279% and 29%-66%, respectively. However, the UCS increment ratio of SA, XG and GE decreases to 35.9%-82.3%, 41.9%-112% and 6%-34%, respectively, with the concentration increasing from 2% to 3%. It can be found that the final water content of various biopolymer concentrations treated clay is similar with less than 2%. Therefore, the variation of the specimen's compressive strength of biopolymer treated clay at different concentrations in this stage is mainly attributed to the physical

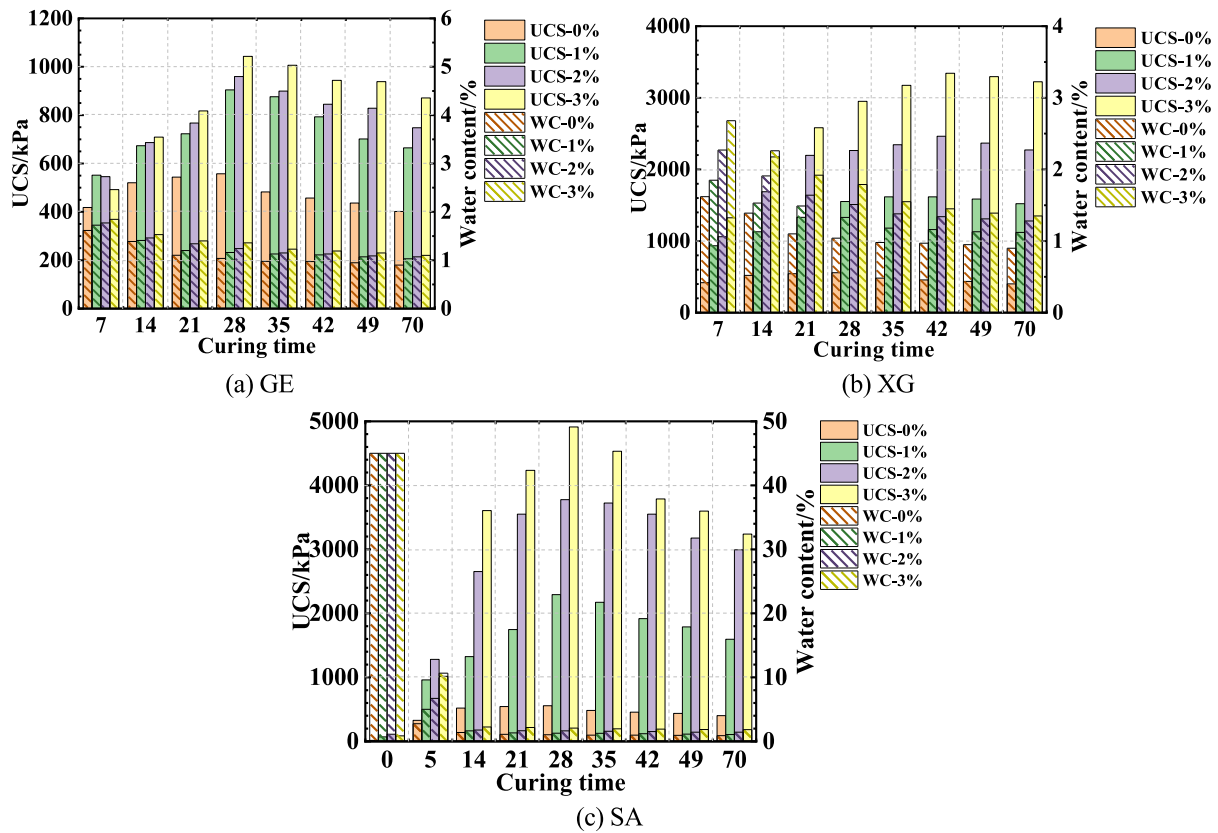


Fig. 5. UCS of various biopolymer concentrations treated clay.

association and chemical bonding (e.g., ionic bonding and hydrogen bonding) between biopolymer and soil particles [15]. Under higher concentration, failure might occur between organic coatings (biopolymer to biopolymer contacts) rather than the soil-to-soil contact during testing. Thus, there exists the optimum biopolymer concentration to obtain the better reinforcement effect, and it can be regarded as 1%–2% in this study.

3.4. Effect of curing time on UCS

As shown in Fig. 5, the maximum UCS of GE, SA and XG treated clay is observed at curing 28 days, 28 days and 42 days, respectively. In addition, the compressive strength of biopolymer-treated clay increases significantly with up to 14 days of drying reaching 65%–75% of the maximum value. However, the UCS of biopolymer treated clay shows a relatively low amount of strengthening decrement at long curing time, and it indicates an optimum curing time (e.g. 28 days) exits for an optimum strengthen result. The similar results were also illustrated in the previous researchers [12,17–20,35,36].

Fig. 6 illustrates the UCS and increment ratio of biopolymer treated clay under optimum curing time (OCT) and curing 70 days (70D). It is found that the UCS decrement ratio of 1%, 2% and 3% GE treated clay is 26.5%, 22.1% and 19.36%, respectively, with the curing time increasing from the ideal value to 70 days, while the corresponding values of SA treated clay is 23.79%, 20.76% and 18.46%, respectively. However, a slight UCS decrement of XG treated clay can be observed from 1723.98 kPa to 1521.2 kPa, from 2463.3 kPa to 2331.4 kPa, and from 3343.2 kPa to 3224.4 kPa at 1%, 2% and 3%, respectively. The corresponding decrement ratio is only 11.76%, 5.35% and 3.55%, respectively. Therefore, XG shows the lowest UCS decrement under long curing time. In addition, the higher biopolymer concentration can also contribute to a lower UCS decrement.

On the other hand, the UCS of untreated clay also decreases under

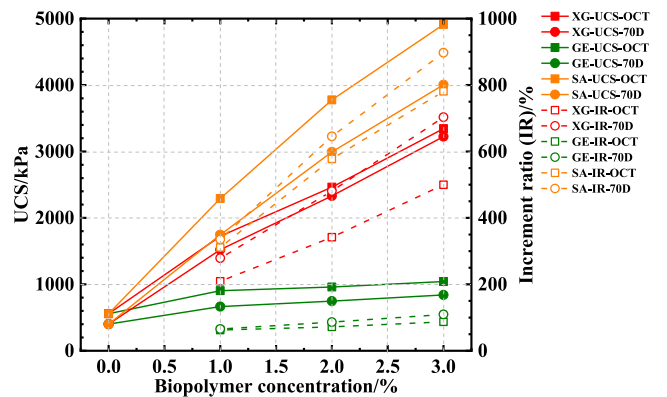


Fig. 6. UCS and its increment ratio of biopolymers treated clay with ideal conditions.

curing long time due to no internal bridge linking between clay particles. Therefore, compared to the UCS of untreated clay at the same curing time, the strength increment ratio of biopolymer treated clay under curing 70 days is even larger than that of ideal curing time. In particular, compared to the UCS of untreated clay at the same curing time, the UCS increment ratio of GE, XG and SA treated clay increases 3.5%–22%, 69.5%–200% and 24%–116%, respectively, with the curing time increasing from the optimum curing time to 70 days.

The reinforcement mechanism of biopolymer treated clay can be illustrated as shown in Fig. 7. At the initial condition (Fig. 7(b)), it forms uniformly dispersed and high viscosity biopolymer hydrogels immediately with a relatively flat and smooth surface structure. The viscosity of biopolymer solution contributes to the mechanical properties of biopolymer treated clay under hydrated conditions [37]. Under curing short time (e.g., less than 7 days), the fluid property still plays a

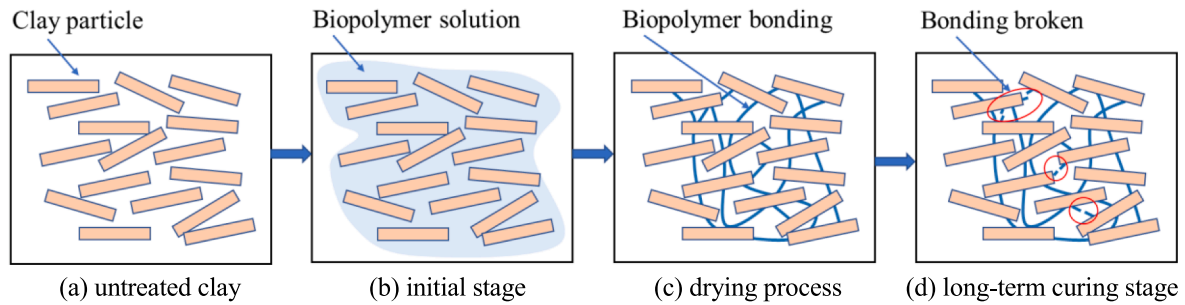


Fig. 7. Treatment process of XG treated clay [23].

prominent role compared to its adhesive bonding property of biopolymer hydrogel, and the biopolymer solution is a weak gel. It means biopolymer strengthening properties still cannot be fully recognized causing the weak gel is easily to be broken [38]. With the increase of curing time, it can be observed that the outer part of the sample is exposed to air-dry conditions showing crystallization and cement effect of biopolymer quickly (Fig. 7(c)). 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, hydroxyl (-OH) groups and carboxyl group (-COOH) 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 interparticle through biopolymer matrix formation among the clay particles [15]. Nevertheless, with the continuous water evaporation, the gel gradually spreads into the concentrated gel and then becomes a thin layer and shrank, especially for the outer surface of biopolymer treated specimens drying in a room temperature condition [56]. 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 Fig. 7(d) [23]. Thus, a part of the surface connections between the soil particles and biopolymer become brittle and it can be shown that the UCS of biopolymer treated clay slightly decreases at curing long time (e. g., >49 days).

3.5. Effect of durability on UCS

Fig. 8 shows the UCS of XG treated clay under different initial water contents and biopolymer concentrations at curing 378 days (solid column) and optimum time (dash column). It can be found that the XG still

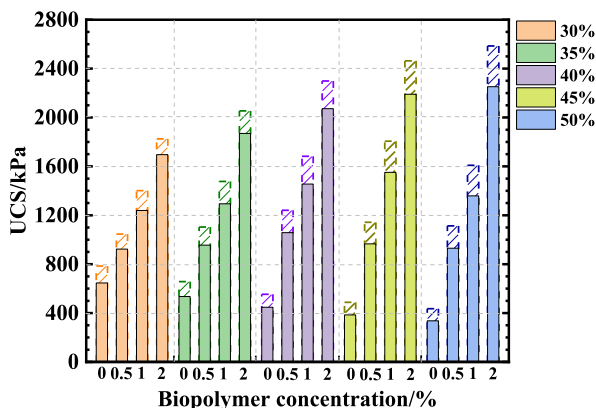


Fig. 8. UCS of XG treated clay with curing 378 days.

has a good durability in reinforcement and stabilization clay after a long curing time, which is consistent with previous findings [25,26]. In particular, the UCS of XG treated clay at the initial water content of 30%, 35%, 40%, 45% and 50% is 1.43–2.62, 1.78–3.49, 2.36–4.63, 2.51–5.69, 2.82–6.73 times of untreated clay, respectively. In addition, the most UCS decrement ratio of XG treated clay at curing 378 days is only 7–16.4% compared to the UCS at the ideal condition, while this value of untreated clay is 17.6–24.2%. Therefore, biopolymer can effectively keep the soil strength, and higher biopolymer concentration leads to a lower UCS decrement ratio. In addition, the strength efficiency of XG treated clay at curing 378 days increases with the increase of initial water content because the UCS of untreated clay significantly decreases at higher initial water content, while an appropriate increase in water content contributes to obtain the fully XG gel solution improving the performance of hydrogen and ionic bonding between biopolymer and fine particles [23]. Therefore, although the UCS decrement ratio at curing long-term may decrease compared to the maximum UCS value with the increase of initial water content, the UCS increment ratio of XG treated clay increases compared to the UCS of untreated clay.

Fig. 9 illustrates the UCS of 1% XG treated clay at an initial water content of 45% with various wetting–drying cycles. Biopolymer produced a more significant effect when 1% XG treated clay specimens were immersed in water after 28 days of air drying. Untreated clay specimens stated to dissolve immediately and became fully degraded after 2 h of submerged in water. However, XG treated clay retained their shape after the submergence reaching to the initial water content. The UCS of XG treated clay is 1397.4 kPa, 1285.9 kPa and 1197.7 kPa with the rewetting-drying cycles of 1, 2 and 3, respectively. Compared to the UCS of XG treated clay without wetting–drying at curing 28 days (1552 kPa), the decrement ratios were 9.96%, 17.15% and 22.83% under 1, 2 and 3 rewetting-drying cycles, 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 [10]. Importantly,

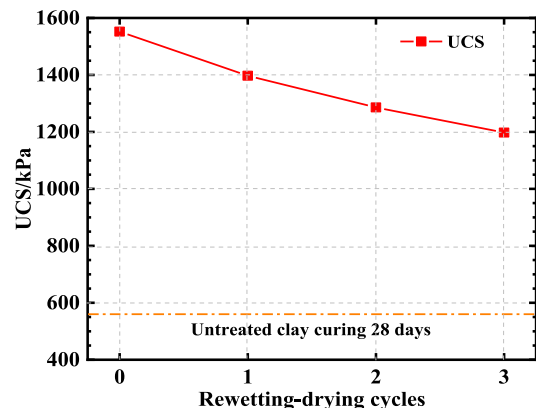


Fig. 9. UCS of various XG concentrations treated clay.

the UCS of XG treated clay after 1, 2 and 3 rewetting-drying cycles is still 2.51, 2.31 and 2.15 times of the highest UCS of untreated clay (curing 28 days), respectively. Therefore, the XG treated clay has excellent durability in undertaking rewetting-drying conditions.

3.6. Effect of biopolymer crossing-link on UCS

Fig. 10 illustrates the UCS of biopolymer treated clay by considering the combination of different biopolymers under various curing time. It can be found that there is a threshold ratio value (XG-KG 1:4) that the UCS of XG-KG treated clay is obviously larger than untreated clay beyond this ratio. With the ratio changing from 2:3 to 4:1, 3:2 and 1:1, the corresponding UCS almost linear increases, and the XG-KG at the ratio of 1:1 obtains the highest UCS value. Moreover, the UCS of XG-KG treated clay at the ratio of 1:1 is larger than that of pure XG treated clay at curing 7 days. 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. After curing 35 days, the USC of most ratios of XG-KG treated clay is larger than XG treated clay except for the ratio of 1:4. 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 28–35 days.

3.7. Effect of mixing method on UCS

Fig. 11 illustrates the UCS of XG and SA treated clay at four categories of mixing methods. It can be observed that dry mixing is more effective than wet mixing regardless of water temperature. Moreover, the UCS of XG/SA treated clay at RWM and HWM methods has a little difference, while the UCS of XG/SA treated at HDM mixing method is larger than that of RDM mixing method. Therefore, the HDM can be regarded as the most effective mixing method in the field application of XG/SA treated clay. The UCS increment ratio of XG/SA treated clay at the HDM method is 140–387% compared to untreated clay.

In terms of the above findings, it can be explained by the solubility and viscosity of biopolymer in water. 1.4% biopolymer content relative to water was the solubility point of biopolymer for complete dissolution, and higher biopolymer content in water is complicated due to the increased viscosity of the biopolymer solution [15]. In this study, a value of 1% biopolymer relative to the quantity of soil causes about 2.2% of biopolymer to water significantly higher than the solubility point. Thus, it is not easy to generate a uniform biopolymer solution by mixing biopolymer into the water, while dry mixing provides a well-distributed biopolymer 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 the increase of temperature [30], and 1% XG and SA can be fully dissolved in hot water (100 °C) to form the uniform biopolymer solutions in the HWM method. However, the UCS of biopolymer treated soil could be

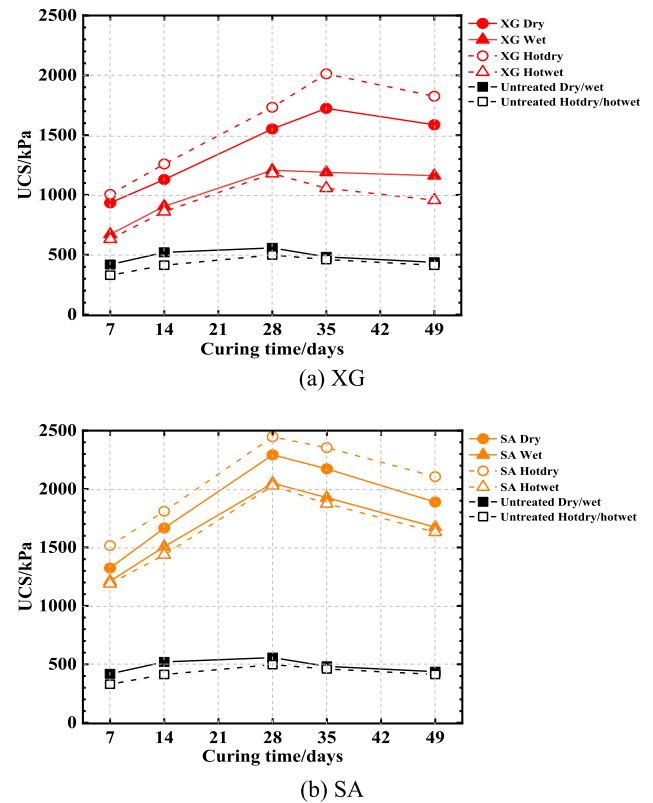


Fig. 11. UCS of XG and SA treated clay with different mixing methods.

obtained the maximum value at curing 60 °C. Moreover, excessively high temperatures 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 [1,8]. Therefore, under the contradictory roles of the water temperature, the UCS of XG and SA treated clay with the HWM mixing method is similar to that of the RWM mixing method. In terms of the HDM method, pouring hot water (100 °C) into the biopolymer-soil mixture can quickly reduce the water temperature in the mixture to the optimum temperature. Therefore, it can not only increase the solubility of biopolymer in water but provide the suitable temperature condition to interact more effectively and make stronger bonds between biopolymer and clay particles.

As shown in Fig. 12, the highest UCS of AG/GE treated clay is obtained at the HWM method following the RDM method, and the UCS of AG/GE treated clay with the HDM method is the smallest. Especially, the UCS of AG treated clay with the HDM method is even smaller than that of untreated clay. Therefore, the room-temperature water is more suitable in AG/GE treated clay specimens with dry mixing method, while the wet mixing method can effectively improve the strength behaviours of AG/GE treated clay by using hot water. It can be explained that there is challenging to generate the uniform biopolymer solution with the wet mixing method in room temperature water, while dry mixing can provide a relative well-distributed AG/GE gels in the soil to increase the viscosity of biopolymer-soil matrices. On the other hand, the solution of AG/GE increases with the increase of water temperature and the melt temperature of AG/GE temperature is about 85–95 °C [31,33]. Therefore, the HWM method can promote the solubility of AG/GE in hot water, and the uniformly clay-biopolymer matrices can significantly increase the strength behaviours. On the other hand, hot water molecules can easily bound with clay particles rather than biopolymer chains in the HDM method. Thus, the biopolymer cannot play the role of increasing UCS under this condition, and the clay combined with more hot water molecules can reduce the UCS causing the smallest UCS of

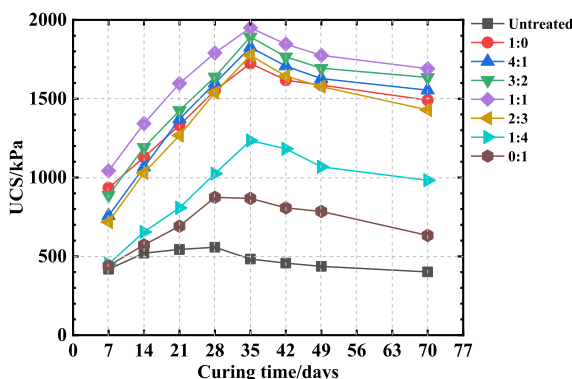
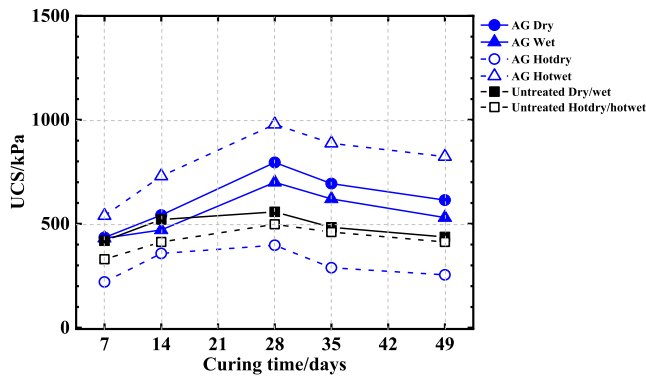
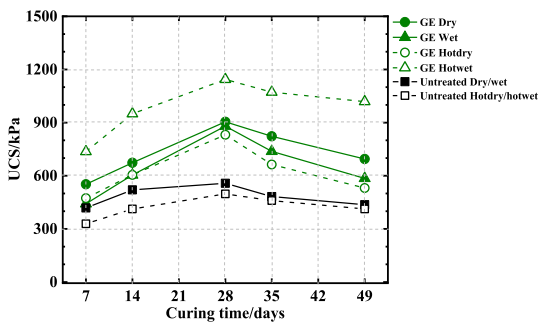


Fig. 10. UCS of XG-KG treated clay.

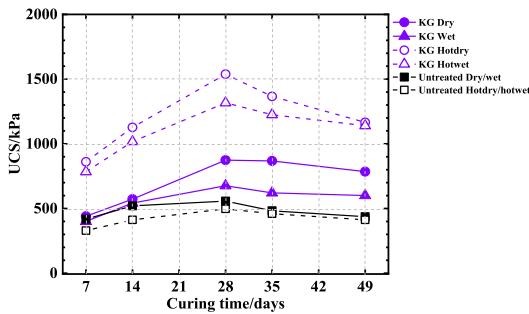


(a) AG



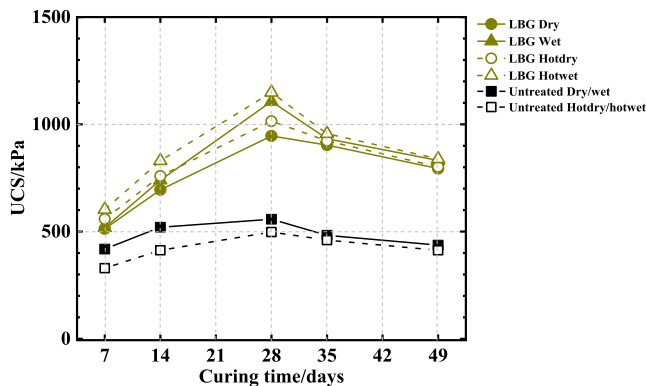
(b) GE

Fig. 12. UCS of AG and GE treated clay with different mixing methods.



(a) KG

10



(b) LBG

Fig. 13. UCS of KG and LBG treated clay with different mixing methods.

biopolymer treated clay in the HDM method.

Fig. 13 shows the UCS of KG treated clay by using hot water in mixing stage is higher than that of using room-temperature water. Moreover, the dry mixing method providing uniform clay-KG mixtures is more efficient in reinforcing clay than the wet mixing method. Therefore, the HDM method of KG treated clay can obtain the highest UCS following the HWM method, and the smallest UCS of KG treated clay is observed in the RWM method. It can be explained that the solubility of KG increases with the increase of water temperature, and the melt temperature of KG is about 70 °C. In the HWM method, the excessively high temperature can decrease and disturb the strength evolution of biopolymer to interrupt its strengthening function. However, the bonds of clay-KG matrices in the HWM method is still more significant than that of the RDM method. In terms of the HDM method, pouring hot water (100 °C) into the biopolymer-soil mixture can quickly reduce the water temperature in the mixture to the optimum mixing temperature.

Fig. 13(b) illustrates that the using hot water in mixing stage is more suitable for LBG treated clay. Moreover, the UCS of LBG treated with wet mixing method is also higher than that of the dry mixing method. It can be explained that the melting point of LBG is more than 90 °C causing it slightly soluble in room-temperature water. Meanwhile, the solubility of LBG in wet mixing is relevant larger than that of drying mixing [32]. Therefore, the maximum UCS of LBG treated clay can be observed in the HWM method following the RWM, HDM and RDM methods. Overall, the optimum mixing method of biopolymer treated clay depends on biopolymer solubility, thermal gelation properties and the melt temperature of the biopolymer.

#### 4. Conclusion

The influence of hydration condition, biopolymer properties, curing time, rewetting-drying and mixing method on the mechanical strength of biopolymer treated kaolinite is experimentally studied by performing unconfined compressive tests. The main conclusions can be drawn as follows.

- 1) The stress-strain curve of biopolymer treated clay can be observed as strain-hardening in hydrated conditions. The highest strengthening biopolymer is sodium alginate (SA) regardless of hydrated or dehydrated conditions that the UCS of SA treated kaolinite is 3.58–4.5 times of untreated kaolinite.
- 2) The UCS of biopolymer treated clay increases at dehydrated conditions with the increase of biopolymer concentration, and higher biopolymer concentration has good strength retention ability with the lower UCS decrement at curing long time. There exists the optimum biopolymer of 1–2% and curing time of 28–42 days to obtain a better reinforcement effect on treated clay.
- 3) XG has good durability to reinforce clay even curing long-term (378 days) and undertaking wetting-drying cycles that the UCS of 1% treated kaolinite can even reach 6.75 times of untreated clay at the same condition, and the UCS of 1% XG treated clay after 1, 2 and 3 rewetting-drying cycles is still 2.51, 2.31 and 2.15 times of untreated clay, respectively.
- 4) After considering the combination of different biopolymers, the XG-KG treated clay obtains the maximum UCS at the ratio of 1:1. The maximum UCS of XG, SA and KG treated clay is observed in the HDM method, while the optimum mixing method of AG, GE and LBG (thermal gelation biopolymers) treated clay is obtained in the HWM method.

#### CRediT authorship contribution statement

**Zhanbo Cheng:** Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Validation, Writing – original draft. **Xueyu Geng:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Resources, Writing – review &



editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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