Compressive Strength of Foam Concrete with Coal Mining Waste

Esegbushota Josephine Foghi[1], Thanh Vo[2], and Mohammad Rezania[3]

Abstract

Coal mining wastes (CMW) consist of fragments of rocks and coal seams which are brought to the surface during coal extraction. As CMW do not constitute any part of a coal product, they have often been left insufficiently treated in storage facilities, causing significant economic and environmental costs to society worldwide. Processing CMW into an ingredient of foam concrete is a promising solution, however the behavior of this construction product is not well understood. This paper reports on experimental investigations of the compressive strength of foam concrete samples made with a coal mining waste from Poland. Experimental results show that the compressive strength exhibits an increase with the increase in curing duration and an increase in CMW replacement percentage from 10 to 20%.

Author Keywords: Coal mining waste · Foam concrete · Compressive strength · Foaming agent · Foam characterisation

[1]Warwick University, Coventry CV4 7AL, UK
Email: Esegbushota.foghi@warwick.ac.uk

1 Introduction

Coal mining waste (CMW), a by-product of the mining and production of coal accounts for about 15% of coal production, which varies from 10 to 15% with the change in geological and mining conditions [1]. The majority of CMW has been dumped as cone- shaped heaps and tips, with the potential to cause environmental problems and become a constraint to economic development. The main effect of CMW on the environment is dust pollution, air pollution from self-ignition, ground water contamination, visual impact, and potential slope failure of coal tips [2, 3]. One way to lessen the environmental effect of CMW is their reuse as construction material, mostly in concrete; the most widely used construction material [4]. Furthermore, the reuse of CMW in concrete provides a potential solution to the short supply problem of natural aggregates [5].

However, the low strength and high carbon content of CMW compared to natural aggregates, as well as the poor interfacial bonding with concrete matrix [6, 7], limits the utilization of CMW as aggregate in high-performance concrete [8]. Nevertheless, this limitation can be accounted for in foam concrete, a lightweight cellular material mostly used for non- and semi-structural applications, where strength is not a prime consideration. In recent years, foam concrete has gained significant importance in construction. In recent years, foam concrete has gained significant importance in construction industry due to its unique properties such as low density, high flowability, controlled low strength, and excellent thermal, fire and acoustic insulation; thus, it is used in a wide range of applications such as house foundations and fire protection, utilizing its high thermal insulation capacity, for geotechnical highway, bridge abutment and backfill [9, 10].

The mechanical properties of foam concrete have been regarded as the most significant characteristic. Amongst which, the compressive strength has been widely investigated.

However, there is a limited number of studies on CMW reuse in foamed concrete. The objective of this study is to investigate the feasibility of using CMW as a replacement of river sand in the production of foamed concrete. This paper mainly discusses the influence of CMW content on the compressive strength of foamed concrete.

2 Materials

Waste and by-products of diverse sources have been used in foam concrete as either a partial or total replacement of cement and fine aggregate, to reduce energy consumption and CO_2 emission related to cement production, conserve natural resources and protect the environment. Wastes with a certain degree of pozzolanic reactivity and adequate fineness such as fly ash and bottom ash, as well as those with high amorphous silica content e.g., rice husk ash, seashell, waste glass and silica fume, have been used as supplementary cementitious material [11–15]. On the other hand, waste available in larger sizes and with low pozzolanic reactivity such as mining waste, construction and demolition waste is primarily used as a replacement for fine aggregate. The waste material investigated in this study is a CMW, used as a partial replacement for natural sand.

The porous structure of foam concrete is attained by introducing aqueous foam into cement paste or mortar. Foams are created using different types of foaming agents (FA), e.g., protein-based foaming agents, synthetic foaming agents. In this study, a protein- based foaming agent is used. Protein-based foaming agents can produce small isolated spherical air bubbles resulting in strong and closely spaced stable cellular structure as well as produces foam concrete with high compressive strength [12, 15]. Foaming agents are typically used in conjunction with other organic and inorganic additives to control various mix properties. However, only 5 foam concrete ingredients are used in this study (Fig. 1) to better focus on the raw ingredients themselves. In addition, the foam was created in the laboratory according to a calibrated procedure to ensure consistent properties when poured into the fresh mixture.

2.1 Geomaterials (Binder, Fillers)

The geomaterials used to make the foam concrete in this study comprise a CMW geo- material, a cement (CEM II/A-LL 32.5 R supplied by Hanson, UK) and a silica sand (55% SiO_2 as determined from X-ray fluorescence). The grain size distribution (GSD) of the sand used in the foam concrete mix is shown in Fig. 2. The CMW is an aggregate sourced from Bogdanka coal mine in Poland. It was taken from a jig separator at the mine, crushed into smaller particles inside a cylindrical chamber of 145 mm diameter using a 1000 kN actuator (Servocon Systems Ltd, UK), sorted into different sizes; and those particles finer than 2.36 mm were selected to make foam concrete (as partial replacement for the sand).

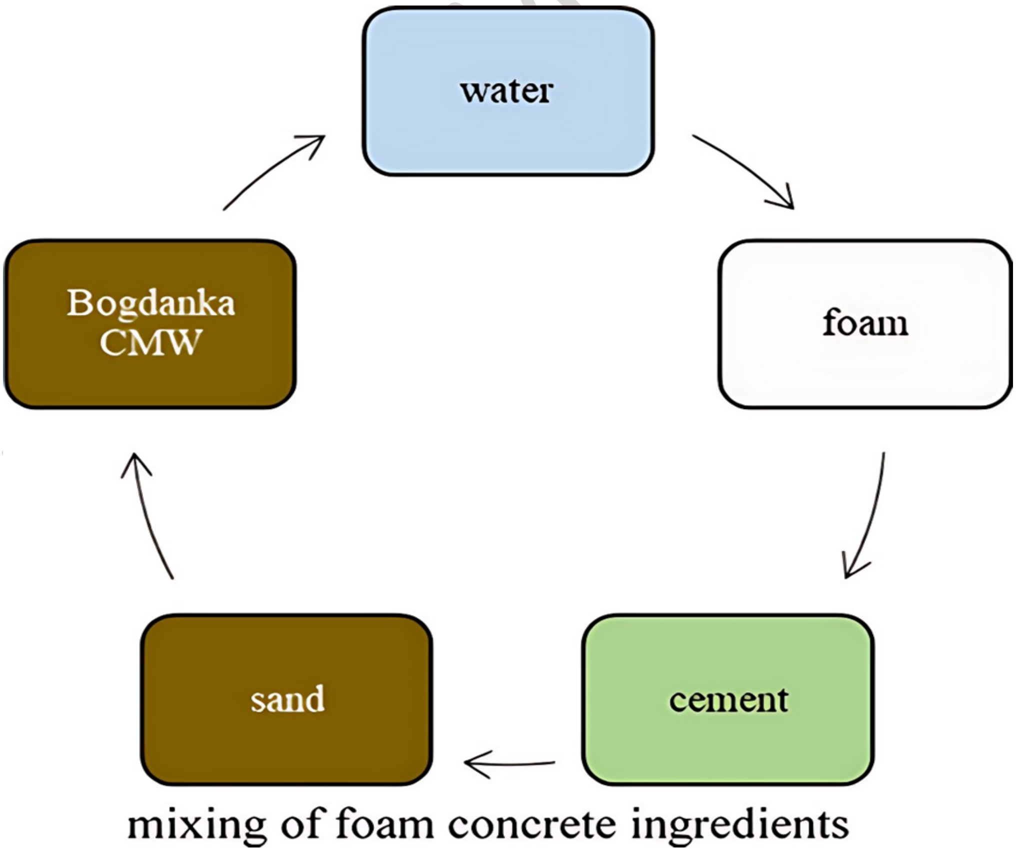


Fig. 1. Ingredients to make foam concrete.

Figure 2 shows the GSD of this CMW used in the foam concrete paste preparation. The maximum particle size of this CMW was selected to be 2.36 mm to achieve similarity with the particle size of the sand for a uniform blend. The specific gravity (G_s) and particle density of the geomaterials used to make the foam concrete are listed in Table 1.

Table 1. Index properties of the geomaterials

	Bogdanka CMW	Cement	Sand
*G*s	2.56	3.15	2.62
Particle density	1.87	3.37	2.27

2.2 Foaming Agent

The structure of foam and its distribution in a setting paste are indicative of properties achieved of the hardened foam concrete [16]. Different foam production methods have been reported in the literature, including chemical foaming, air entrainment, and mixing with aqueous precursor foam (also referred to as the pre-forming method) [10, 17]. The pre-forming method is adopted in this study as it was reported to have a lower foaming agent requirement and results in a close relationship between the amount of foaming agent used and the air content of the mix [10]. It was also found that this method facilitates larger and more accurate foam entry compared to the mixed foaming method [18]. A protein-based foaming agent (Propump 26 supplied by Propump Engineering Ltd, UK) was used in this study. It possesses a density of 1.12 (g/mL) and pH of 6.5–7.5.

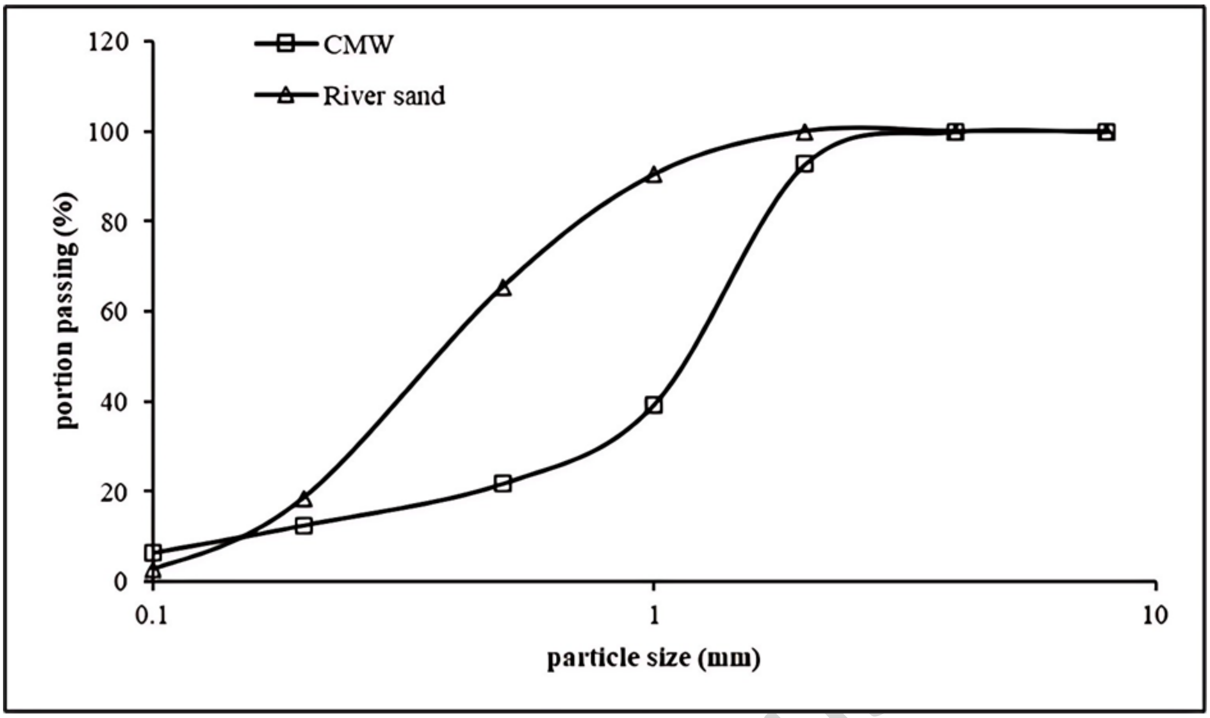


Fig. 2. Grain size distributions of Bogdanka CMW from Poland and of a sand used in the foam concrete mix.

3 Equipments Setups and Test Procedures

3.1 A Foam Generation Device

A foam generation device was custom-built in the laboratory using standard laboratory components. It permits air between 0 and 450 kPa to be introduced into an enclosed cylinder (of 1,338 cm^3 in volume) and turbulently mixed with a targeted amount of diluted foaming agent. The mixing of the two phases generates foam.

3.2 Foam Characterisation

Measurements of foaming capacity and stability have been conducted previously [16] to assess how a foaming agent entrains air in concrete. In this study, the effectiveness of the foam [17] used is assessed by examining the density and stability of foam produced at different foam generation pressures (150, 200, 250, 300, 350, 400 and 450 kPa) and foaming agent (FA) concentrations (m_{FA}/m_w = 2%, 4%, 6%, 8% and 10% where m_{FA} and m_w denote the mass of foaming agent and the mass of water, respectively).

Immediately after foam production, the foam density was measured by filling a pre- weighed standard container of known volume with the foam and weighing it. The foam stability was evaluated by measuring the mass of liquid that drains from the bottom of the foam at 5, 10, 30, 60, 120, 180, 240, 360, and 720 min.

3.3 Unconfined Compression Test

The unconfined compression tests (UCTs) were conducted on a 100 kN capacity Uni- versal testing machine. During the loading stage, the loading rate was kept constant as 0.2 mm/min, and the stress-strain curves of the foamed concrete specimens were recorded automatically.

3.4 Specimen Preparation

Cement paste and foam were prepared separately to produce a foam concrete sample. To obtain the cement paste, selected geomaterials (sand and/or Bogdanka CMW) were oven-dried at 105 °C, cooled down to laboratory temperature then combined with cement in a mixer for half a minute. Then, the required quantity of water was added, and mixed further for approximately 4 min. To obtain the foam, the protein-based FA was diluted to a concentration ratio (i.e., m_{FA}/m_w) of 8% inside the foam generator. Then, compressed air at 350 kPa was introduced into the generator to turbulently mix with the surfactant solution to produce the targeted foam. Subsequently, the required amounts of foam and cement paste were blended and slowly stirred for up to 1 min to obtain a homogeneous state. To cast a foam concrete specimen, the mixture was slowly poured into cubic molds (100 x 100 x 100 mm^3) and demolded after 48 h. After demolding, they were wrapped with kitchen film and cured in a standard curing room with a temperature of 25 °C 10 °C, till test date.

4 Results

A testing program was conducted to investigate the compressive strength of foam concrete samples made with Bogdanka CMW. The testing program comprised 2 different plastic densities of 800 and 1000 kg/m^3, and CMW replacement values of 10 to 20%. A control specimen with 0% CMW was prepared for comparison. The specimens were denoted as FC8-0, FC8-10, FC8-20, and FC10-0, FC10-10, FC10-20, representing the density and CMW replacement percentages respectively. The mix proportions of the studied foamed concrete are summarized in Table 2.

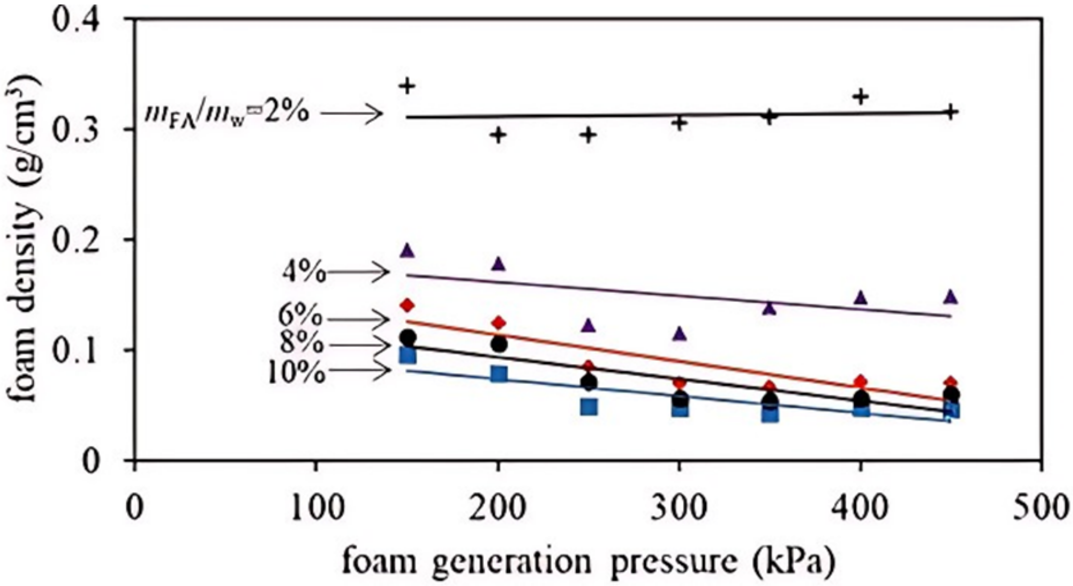
Table 2. Mix proportions of test samples

Label	Mass of constituent materials for 1m3 of foamed concrete				
	Cement (kg)	Sand (kg)	CMW (kg)	Water (kg)	Foam (kg)
FC8_0	333.33	333.33	0	133.33	31.77
FC8_10	333.33	300	33.33	133.33	31.77
FC8_20	333.33	266.66	66.67	133.33	31.77
FC10_0	416.67	416.67	0	166.67	27.22
FC10_10	416.67	375.0	41.67	166.67	27.22
FC10_20	416.67	333.34	83.33	166.67	27.22

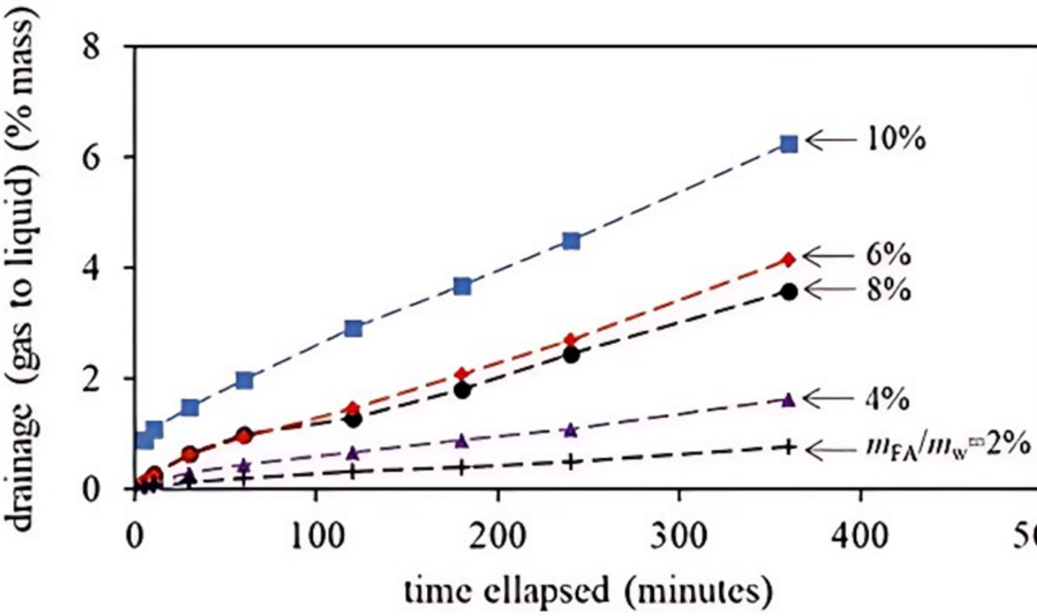
4.1 Foam Characterisation Result

The effects of FA concentration and foam generation pressure on the foam density are shown in Fig. 3a. For a foam generation pressure between 150 kPa and 450 kPa, it is shown that an increased FA concentration corresponds to a decreased foam density. Figure 3a also shows that the foam generation pressures have minor impact on the foam density. As the targeted foam density is 50 ± 5 kg/m^3 in this study, a FA concentration of 8% and a foam generation pressure of 350 kPa were adopted to create foam for the concrete mix.

Figure 3b shows the drainage of foams (% mass changed from gas phase to liquid phase) created at different FA concentrations and at a foam generation pressure of 350 kPa. An increase in FA concentration corresponds to an increase in the drainage i.e., the foam created at a higher FA concentration is less stable. However, for the selected FA concentration in this study (m_{FA}/m_w = 8%), after 6 h (360 min), only less than 5% of foam mass has changed from a gas to a liquid phase.



(a) foam density versus foam generation pressure



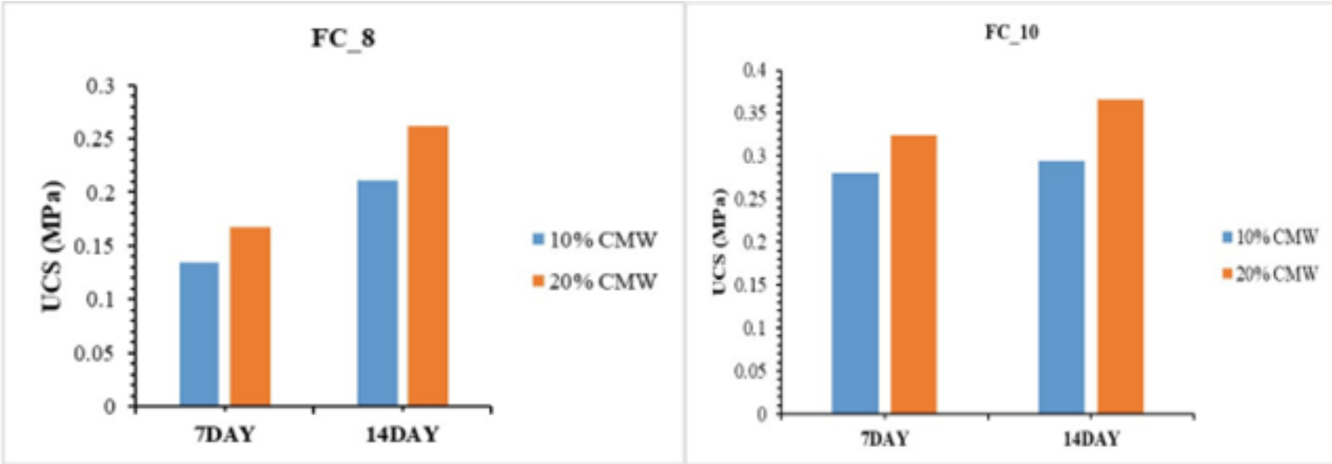
(b) foam drainage versus time elapsed (at foam generation pressure of 350 kPa)

Fig. 3. Impacts of air pressure and surfactant concentration on foam density.

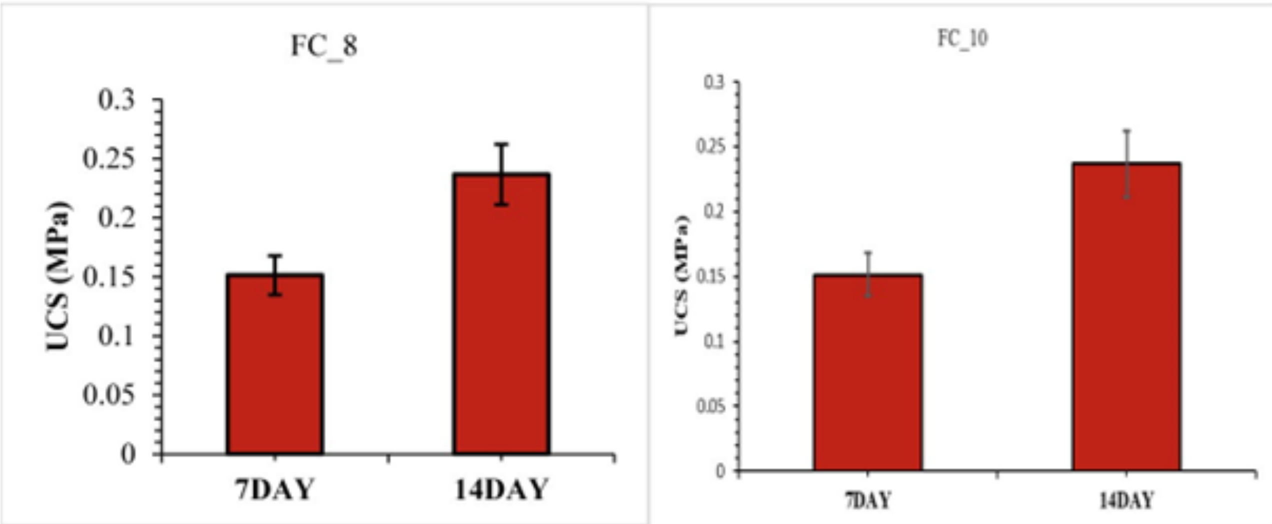
4.1 Uniaxial Compressive Strength Test Result

Effect of CMW on Compressive Strength of Specimens

Compressive strength values of the foamed concrete with different percentage of CMW are shown in Fig. 4a. While Fig. 4b shows the standard deviation. The bar graphs present the compressive strength exhibits an increase with the increase in curing duration and increase in CMW replacement percentage from 10 to 20%. However, the compressive strength of foamed concrete with CMW had lower values compared to the control foamed concrete (0% CMW).



a. Compressive strength of CMW-Foam concrete.



b. Standard deviation of compressive strength of CMW-Foam concrete.

Fig. 4. a. Compressive strength of CMW-Foam concrete. b. Standard deviation of compressive strength of CMW-Foam concrete.

5 Conclusion

In this study, the compressive strength of foamed concrete with different replacement percentages of natural aggregate with CMW was investigated. Results showed an increase in the compressive strength of foamed concrete with increase in CMW content from 10% to 20%.

References

1. Haibin L, Zhenling L (2014) Recycling utilization patterns of coal mining waste in China. Resour Conserv Recycl 56:113–127
2. Bian Z, Dong J, Lei S, Leng H, Mu S, Wang H (2008) The impact of disposal and treatment of coal mining wastes on environment and farmland. Environ Geol 58(3):625–634. https:// doi.org/10.1007/s00254-008-1537-0
3. Vo TL et al (2022) Coal mining wastes valorization as raw geomaterials in construction: a review with new perspectives. J Clean Prod 336
4. GCCA (2022) About Cement & Concrete. https://gccassociation.org/our-story-cement-and- concrete/. Accessed 24 Oct 2022
5. Torres A, Brandt J, Learand K, Liu J (2017) A looming tragedy of the sand commons: increasing sand extraction, trade, and consumption pose global sustainability challenges. Science 357(6355):970–971
6. Zhou M, Dou Y, Zhang Y, Zhang Y, Zhang B (2019) Effects of the variety and content of coal gangue coarse aggregate on the mechanical properties of concrete. Constr Build Mater 220:386–395
7. Ma XW, Liu JH, Shi CJ (2019) A review on the use of LWA as an internal curing agent of high-performance cement-based materials. Constr Build Mater 218:385–393
8. Zhu Y (2021) Valorization of calcined coal gangue as coarse aggregate in concrete. Cem Concr Compos 121
9. Zhang Z, Provis JL, Reid A, Wang H (2014) Geopolymer foam concrete: An emerging material for sustainable construction. Constr Build Mater 56:113–127

10. Ramamurthy K, Nambiar EKK, Ranjani GIS (2009) A classification of studies on properties of foam concrete. Cem Concr Compos 31:388–396

11. Shams T, Schober G, Heinz D, Seifert S (2022) Rice husk ash as a silica source for the production of autoclaved aerated concrete - a chance to save energy and primary resources. J Build Eng 57

12. Gencel O (2022) Lightweight foam concrete containing expanded perlite and glass sand: physico-mechanical, durability, and insulation properties. Constr Build Mater 320

13. Zhang Y, Chen D, Liang Y (2020) Study on engineering properties of foam concrete containing waste seashell. Constr Build Mater 260

14. Kashani A, Ngo TD, Hajimohammadi A (2019) Effect of recycled glass fines on mechanical and durability properties of concrete foam in comparison with traditional cementitious fines. Cem Concr Compos 99:120–129

15. Khan QS, Neaz Sheikhb M, McCarthy TJ, Robati M, Allen M (2019) Experimental investigation on foam concrete without and with recycled glass powder: A sustainable solution for future construction. Constr Build Mater 201:369–379

16. Kunhanandan Nambiar EK, Ramamurthy K (2007) Air-void characterisation of foam concrete. Cem Concr Res 37:221–230

17. Raj A, Sathyan D, Mini KM (2019) Physical and functional characteristics of foam concrete: a review. Constr Build Mater 221:787–799

18. Adams T, Vollpracht A, Haufe J, Hildebrand L, Brell-Cokcan S (2019) Ultra-lightweight foamed concrete for an automated facade application. Mag Concr Res 71:424–436