AN ECO-FRIENDLY WASTE BRICK POWDER BASED GEOPOLYMER GROUT FOR GEOTECHNICAL APPLICATIONS

Ahmed Ali AGHA[1], Altuğ SAYGILI[2]

ABSTRACT

The stabilization of soft and weak soils commonly involves the utilization of ordinary Portland cement (OPC) and lime. The conventional production methods of these stabilizers are characterized by high energy consumption and significant CO_2 emissions. Geopolymer, distinguished by its superior strength, cost-effectiveness, reduced energy requirements, and minimal CO_2 emissions in the synthesis phase, presents a viable and promising substitute for OPC in soil stabilization applications. The primary objective of this research endeavor was to enhance the mechanical and fresh properties of alkali-activated materials by incorporating a substantial quantity of waste red clay brick powder (WBP) as the primary raw material source. The composition of the waste brick powder (WBP) in the experimental mixture consisted of varying proportions, specifically accounting for 100%, 85%, 70%, and 55% of the total weight of the initial materials. The effects of the replacement of GGBS by the WBP-based geopolymer (at the dosages of 0, 15, 30 and 45%) on the compressive strength, fresh properties and durability were investigated. An alkali activator solution comprising sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was employed. Alkali-activated grout specimens were meticulously prepared and subjected to curing for durations of 7, 28, and 90 days. Various tests were conducted to assess the properties of the samples, including workability assessments through mini slump tests, setting time measurements and evaluation of compressive strength. The results from the experimentation indicate that the freshly prepared mixtures exhibited notable workability, as evidenced by the measured slump flow values of 130 mm and 115 mm for the CG-15S-85B and CG-30S-70B compositions, respectively. Additionally, the hardened grout samples demonstrated a high level of compressive strength, with results indicating values of less than 13 MPa. The results showed that the utilization of geopolymer-based grout offered numerous benefits in terms of mechanical strength, durability, and fresh stability. The findings of this investigation provide additional evidence supporting the significant viability of incorporating recycled WBP in the fabrication of grout with superior mechanical strength.

Keywords: Geopolymer; waste brick powder; Fresh properties; Compressive strength; Durability.

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GEOTEKNİK UYGULAMALAR İÇİN ATIK TUĞLA TOZU ESASLI GEOPOLİMER BAZLI HARÇ TASARIMI

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ÖZET

Sorunlu zeminlerin stabilizasyonunda genellikle çimento ve kirecin kullanımı yaygın olarak literatürde görülebilmektedir. Bu stabilizatörlerin geleneksel üretim yöntemleri, yüksek enerji tüketimi ve önemli CO_2 emisyonlarına sebep olmaktadır. Yüksek performansı, maliyet etkinliği, azaltılmış enerji gereksinimleri ve sentez aşamasında minimum CO_2 emisyonları ile öne çıkan geopolimerler, zemin iyileştirme uygulamalarında çimento vb. malzemelerin yerine geçen bir alternatif olarak son yıllardaki çalışmalarda öne çıkmaktadır. Bu çalışmanın temel amacı, birincil hammadde kaynağı olarak önemli miktarda atık kırmızı kil tuğla tozu (WBP) ekleyerek alkaliyle aktifleştirilen malzemelerin mekanik ve taze harç özelliklerini geliştirmektir. Deneysel karışımlardaki atık tuğla tozunun oranları, özellikle başlangıç malzemelerinin toplam ağırlığının %100'ünü, %85'ini, %70'ini ve %55'ini oluşturan değişen oranlarda olacak şekilde çalışılmıştır. GGBS'nin WBP bazlı geopolimerle değiştirilmesinin (%0, 15, 30 ve 45 dozajlarında) basınç dayanımı, taze harç özellikleri ve dayanıklılık üzerindeki etkileri araştırılmıştır. Sodyum silikat (Na_2SiO_3) ve sodyum hidroksit (NaOH) içeren bir alkali aktivatör çözeltisi çalışmalarda kullanılmıştır. Alkali ile aktifleştirilen karışım numuneleri titizlikle hazırlanmış ve 7, 28 ve 90 günlük kürlere tabi tutulmuştur. Numunelerin özelliklerini değerlendirmek için mini slump testleri aracılığıyla işlenebilirlik değerlendirmeleri, priz süresi ölçümleri ve basınç dayanımının değerlendirilmesi dahil olmak üzere çeşitli testler yapılmıştır. Deneylerden elde edilen sonuçlar, taze hazırlanmış karışımların, CG-15S-85B ve CG-30S-70B bileşimleri için sırasıyla 130 mm ve 115 mm'lik ölçülen çökme yayılma değerleriyle dikkate değer işlenebilirlik sergilediğini göstermiştir. Kürlenmiş harç numuneleri yüksek seviyede basınç dayanımı sergilemiş ve sonuçlar 13 MPa mertebelerine ulaşmıştır. Elde edilen sonuçlar, geopolimer esaslı harç kullanımının mekanik mukavemet, dayanıklılık ve taze harç stabilite özellikleri açısından çok sayıda fayda sunduğunu göstermiştir. Bu araştırmanın bulguları, üstün mekanik mukavemete sahip harç imalatında geri dönüştürülmüş tuğla tozu kullanılmasının önemli ölçüde uygulanabilirliğini destekleyen kanıtlar sunmaktadır.

Anahtar Kelimeler: Geopolimer, Atık Tuğla Tozu, Taze Harç Özellikleri, Serbest Basınç Dayanımı, Dayanıklılık.

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Introduction

The construction and demolition (C&D) industry is a significant contributor to waste generation, with the majority of this waste consisting of brick and concrete materials. These types of waste account for over 80% of the total C&D waste produced in China, the United States, and India. According to a report by (1), in 2018, these countries generated 2,360 million, 600 million, and 350 million tons of C&D waste, respectively. Cement has long been a widely used binding material in various construction materials. However, its widespread use is being challenged due to sustainability, cost, and durability concerns (2, 3). Cement production releases significant amounts of CO2 and consumes large quantities of natural resources and energy, contributing to approximately 5-7% of global CO2 emissions (4-7).

In recent years, alternative, environmentally-friendly hybrid alkaline cements and alkali-activated binders have been developed to address the issues associated with the production of Portland cement [8]. In alkali activation systems, industrial waste materials have been used to partially or completely replace cement. Alkali activation involves the reaction of solid aluminosilicate materials with alkali hydroxide and alkali silicate solutions, which encourages the dissolution of Al3+ and Si4+ ions from the starting materials and the subsequent formation of an alkali-activated gel with favorable mechanical and durability properties in the hardened phase [9]. Among these materials, fly ash and ground granulated blast furnace slag are the industrial by-products which are alternative sustainable materials for the construction industry. Owing to high CaO content (>30%) of ground granulated blast furnace slag, upon activation in geopolymer composites a calcium silicate hydrate (C-S-H) gel-like structure is formed [10].

Industry competition, unequal regional distribution, and coal and combustion process constraints have made fly ash, ground granulated blast furnace slag, and metakaolin harder to use (11). Thus, recycled brick/concrete aggregate and powder are increasingly used in geopolymer manufacture. This method could cut carbon emissions, aluminosilicate use, and construction and demolition debris (11,12). The study seeks to demonstrate this method's environmental benefits, including reduced use of aluminosilicates and building and demolition waste. Tests will examine the effects of replacing WBP with GGBS geopolymer grout on fresh, mechanical, and durability qualities.

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2.Experimental program

2.1 Materials

As shown in Fig. 1, WBP and GGBS were used to make geopolymer grout from aluminosilicates. Waste brick (WB) from a Baghdad demolition site was ground into WBP in northern Iraqi manufacturers. GGBS was obtained from a Basra steel mill. Laser diffraction with a Mastersizer 2000 measured the material particle size distribution (Fig. 2). Table 1 lists the physical and chemical features of aluminosilicate sources. Aluminium, silicon, and oxygen peaks appear in EDS micrographs. EDS spectra show WBP powder alumino-silicate particle composition (Fig. 3). XRF data in Table 1 and EDS results from Mahmoodi et al. [31] support this observation. This study used sodium silicate and NaOH as alkaline activators. Sodium hydroxide solution was made one day before combining with (5M) molar concentrations using locally available 97-98% purity NaOH beads mixed in tap water. Alkaline activator was prepared with Na2SiO3/NaOH = 1 . WBP, GGBS, and sodium silicate's liquid chemical and physical characteristics are shown in Table 1.

(a) WBP	(b) GGBS

Figure 1. Waste sources of aluminosilicates

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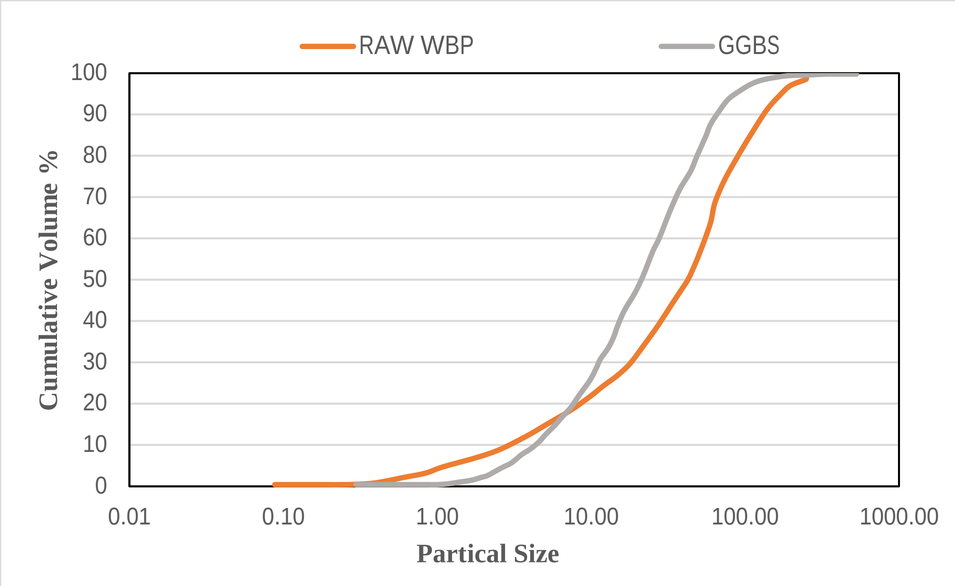
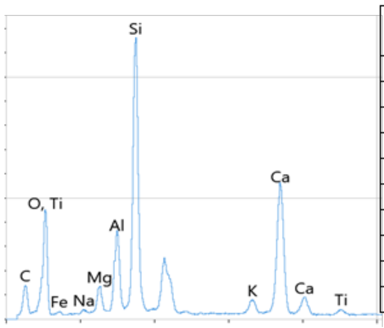


Figure 2 Particle size distribution



Element	Wt %	Ϭ
C	17.0	0.3
O	40.7	0.6
Na	0.5	0.1
Mg	2.5	0.1
Al	5.4	0.1
Si	18.0	0.1
K	1.0	0.0
Ca	10.3	0.1
Ti	0.5	0.0
Fe	4.1	0.1

Figure 3 EDS analysis of WBP powders

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Table 1 chemical and physical properties of WBP, GGBS, and sodium silicates

Constituent (%)	GGBS	WBP	(Na_2SiO_3) liquid
a) Chemical composition			
Cao	34.19	9.5	
SiO_2	40.42	55.6	29.4
$Al2O_3$	10.6	17	
Fe_2O_3	1.28	5.7	
MgO	7.63	2.6	
SO_3	0.68	1.92	
K_2O	0.0128	1.58	
Na_2O	0.64	0.65	14.7
Modulus ratio			2
H_2O			55.9
b) Physical properties			
Specific surface (m^2/g)	1.69	0.67	
D_{50} (μm)	22	34.25	

2.2 Geopolymer Preparation

For typical geopolymer preparations, sodium hydroxide (NaOH) beads were dissolved in tap water at a molarity of 5 and weighed. The mixing operation caused an exothermic reaction, making the NaOH solution too hot. Therefore, the liquid was cooled to ambient temperature and kept until chemical equilibrium was reached before use. Conventional geopolymer activation involved adding sodium silicate (Na2SiO3) to the cooled sodium hydroxide liquid. This careful approach ensured safe handling of the extremely alkaline NaOH solution and reduced exothermic reaction hazards.

GGBS replaced WBP in 0%, 15%, 30%, and 45% ratios. The CG-0S-100B code specifies that the grout was conventionally activated geopolymer with 0% GGBS and 100% WBP. Table 2 shows CG-based grout mixture amounts.

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Table 2 Mix proportions of CG and MG-based grout**.**

	Aluminosilicate Materials %		Alkaline Activator %		Na_2SiO_3 / NaOH	w/b ratio (g)
CG-0S-100B	80	0	10	10	1	500
CG-15S-85B	68	12	10	10	1	500
CG-30S-70B	56	24	10	10	1	500
CG-45S-55B	44	36	10	10	1	500

3.2 Testing methods

All specimens were prepared in the lab at 23±3 oC. According to (13) mini-slump flow test examined the fresh characteristics of geopolymer grout. A small cone of 19 mm upper diameter, 38.1 mm lower diameter, and 57.2 mm height was used to assess grout spread diameter in millimeters during the slump flow test. The grout's ultimate spread diameter was an average of two perpendicular measurements. To establish grout mixture setting periods, Vicat needle penetration tests were performed according to ASTM C191-19 [14]. Only final setup times were discussed in this study.

For mechanical characteristics, grout mixes were poured into 100-mm-high, 50-mm-diameter cylindrical molds. The samples were cured at 23 ± 3 ºC for 7, 28 and 90 days before testing. Then, the unconfined compressive strength (UCS) of grout samples was tested by standards [15]. For the durability test, the geopolymer samples were immersed in a solution containing 5% weight of Na2So4 and 5% volume of H2SO4 for 28 days, after being cured for 28 days. This process is illustrated in Figure 7. Subsequently, the unconfined compressive strength (UCS) of the exposed samples was examined.

3. Results and Discussion

3.1 Fresh properties

3.1.1 Flowability test

Fig. 4 illustrates CG mixture flowability tests with varied GGBS/WBP ratios. Slump flow values of CG were 245–300 mm. The reference mixes (CG-0S-100B) with 100% WBP had the lowest slump flow. Due to the porous surface of unreacted brick debris, debris Brick Powder bead geopolymer grout flows less. This surface quickly absorbs water from the new mixture, lowering its free water content [16]. The uneven form of brick

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powder particles may further reduce geopolymer workability [17]. Hwang et al. [17] observed that alkali-activated paste mixes with only waste brick powder had the lowest slump flow values, which were improved by adding GGBS. Fig. 4 shows that GGBS concentration considerably influences flowability of all mixtures, independent of geopolymer type. CG-0S-100B had slump flow values 24%, 10%, and 5% lower than CG-15S-85B, CG-30S-70B, and CG-45S55B. As GGBS concentration increased to 15% and 30%, slump flow increased in both blends. when seen in Fig. 4, slump flow decreased when GGBS increased over 45%. The porous surface of unreacted WBP may reduce workability in high WBP mixtures [18].

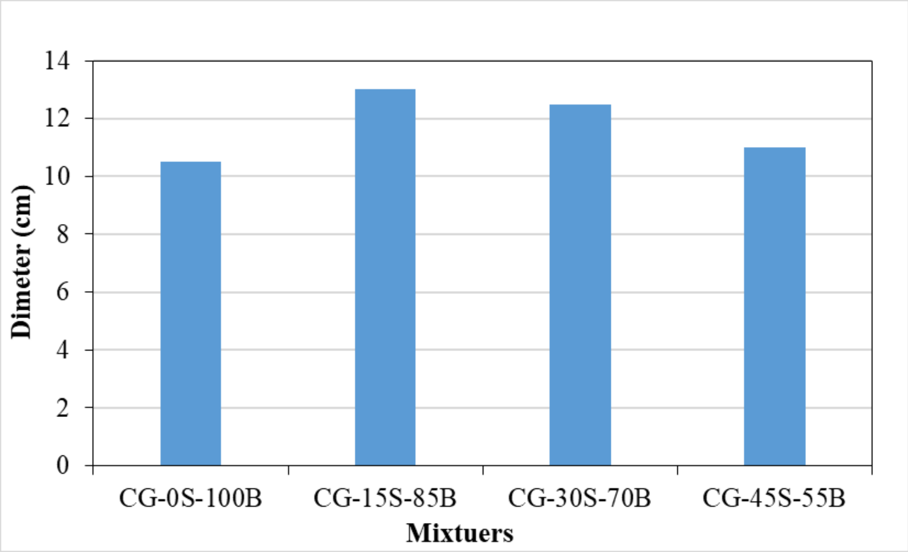

Figure 4 workability of grout based geopolymer of mixtures

3.1.2 Final setting times

In grouting applications, a short setting time might harm the machines, whereas a long setting time slows construction [19]. Fig. 5 shows how WBR/GGBS affects CG grout setting times. The longest final setting time for CG was 255 min for 100% WBP combinations. GGBS concentration significantly reduces WRP-based geopolymer setting time. As GGBS content increased to 15%, 30%, and 45%, setup time fell to 132 min, 110 min, and 90 min. Due to its stronger responsiveness than WRP, GGBS decreases setting time [20]. The enhanced dissolution of Ca2+ions from GGBS may also accelerate setting [18]. Migunthanna et al. [21] found that greater GGBS levels enhance reaction medium CaO. This CaO dissolves faster than silica and alumina, adding nucleation sites to WBP-based geopolymers, speeding up setting. This increased dissolution releases

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hydration heat, forming calcium silicate hydrate (C-S-H) or C-A-S-H gels and increasing polymerization [18]. Excess GGBS in WBP-based geopolymers accelerates setting time. However, this shortened setting time may jeopardize grouting machinery. Rapid setup may put too much pressure on equipment, causing wear and failure. The rapid setting procedure may also impair geopolymer workability and usage. GGBS ratio must be carefully regulated in WBP-based geopolymers to ensure optimal setting time and workability while maintaining quality and performance.

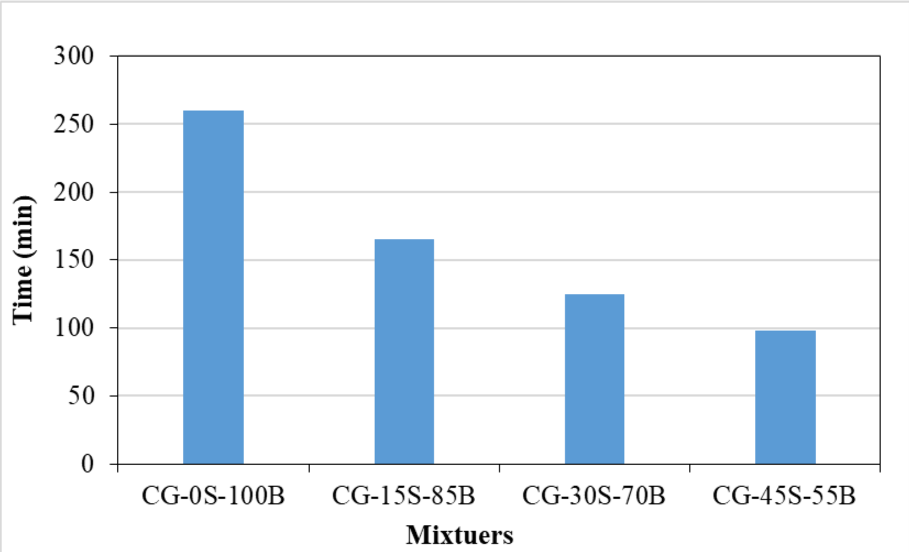

Figure 5 final setting times of grout based geopolymer of mixtures

3.2 Mechanical properties

3.2.1 UCS

UCS of geopolymer mixes with different WBP/GGBS concentrations is shown in Fig. 6. Three UCS experiments were conducted at geopolymer paste ages of 7, 28, and 90 days. All blends' UCS values improved from 7 to 28 to 90 days. This improvement is due to geopolymerization completion and microstructure densification at older ages [22]. The mixture with solely WBP powder as an aluminosilicate precursor had the lowest 7-day UCS (0.9 MPa). Fořt et al. [23] found that WBP lacks hardening properties and required GBFS supplementation. Higher CaO level in GBFS/WBP mixture produced a denser C-A-S-H gel with improved strength [17]. Fig 8 shows that replacing WBP powder with GGBS increased strength linearly. The geopolymer mix's UCS values increased 90%, 174%, and 227% at 90 days when WBP was replaced with 15%, 30%, and 45% GGBS. Due of its stronger cementing and reactivity than WBP, GGBS had a significant impact on the

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UCS. High CaO content boosts activation and early age strength [24]. The high CaO component can also form C-S-H/CA-S-H gels, changing the microstructure of the geopolymer grout mixture and improving its mechanical properties [24].

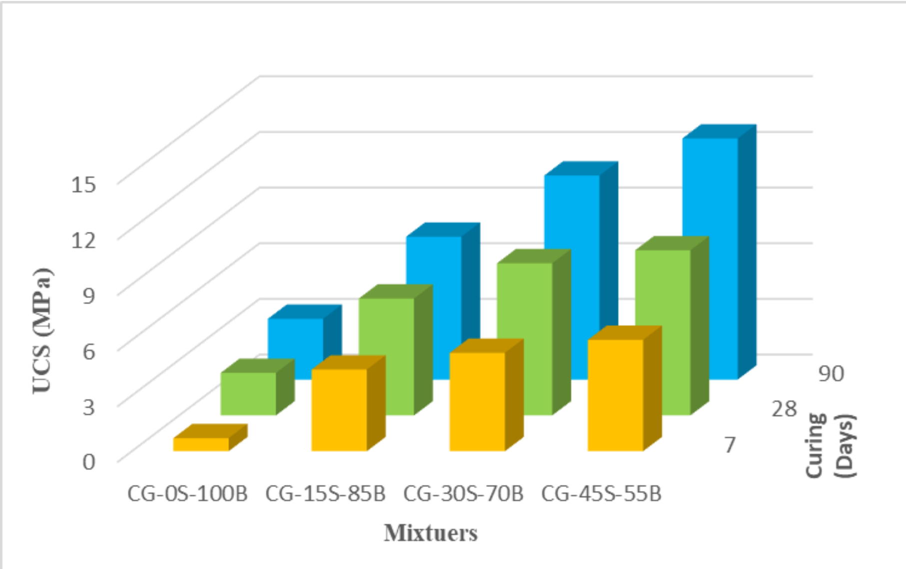

Figure 6 Unconfined compressive strength (UCS) of CG based grout, (a) 7, 28 and 90 days.

3.2.2 Durability

The durability of geopolymer samples with varying WBP ratios (100%, 85%, 75%, and 55%) has been tested. After 28 days in H2SO4 (5%vl) and Na2So4 (5%wt), geopolymer strength was measured**.** Soaking in sulfuric acid may damage the geopolymer matrix's aluminosilicate bonding. This may degrade the geopolymeric network, particularly the aluminosilicate bonding, leading to increased Al-OH and Si-OH generation and reduced compressive strength. High GGBS content reduced strength somewhat. Fig. 14 shows 45% GGBS reduced UCS by 12%. Geopolymer grout samples were acid-resistant and durable. The gel matrix type and intact geopolymer network structure of Si-O and Al-O may contribute to this resilience. According to [25], Alkali-activated slag/fly ash-based pastes are more resistant to phosphoric acid attacks compared to ordinary Portland cement-based pastes. The compressive strengths of Na2So4-immersed samples are shown in Fig. 15. Immersion in slag did not exceed 10% strength change at 45°, with small variations at higher ratios. Overall, geopolymer base grout samples were durable in H2So4 and Na2So4 settings. The highest residual strength ratio was observed at 45% slag. The increase in slag percentage led to reduced pore volume, dense matrix, and

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greater resistance to acid and salt attacks in the binder. Please note that samples in this investigation were only submerged in chemical solutions for 28 days.

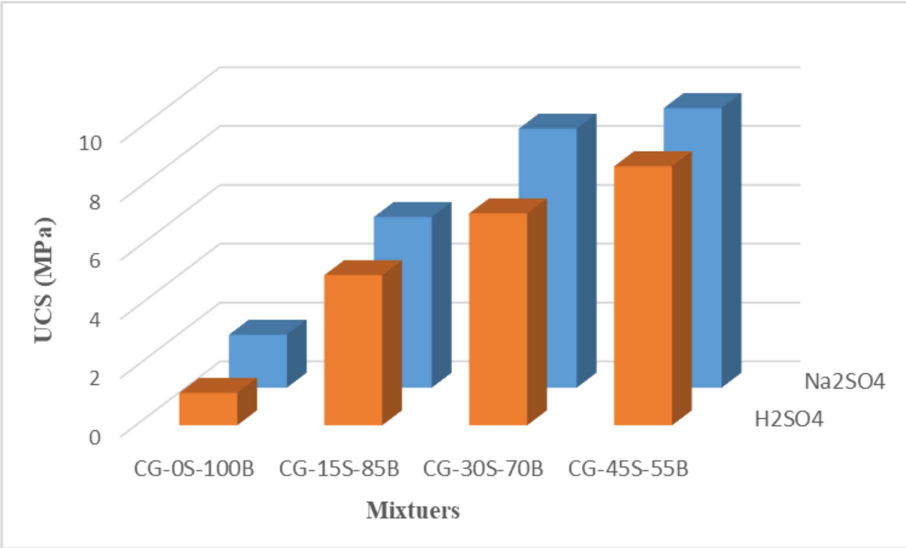

Figure 6 compressive strength of geopolymer samples immersed in H_2SO_4 and Na_2SO_4 solutions.

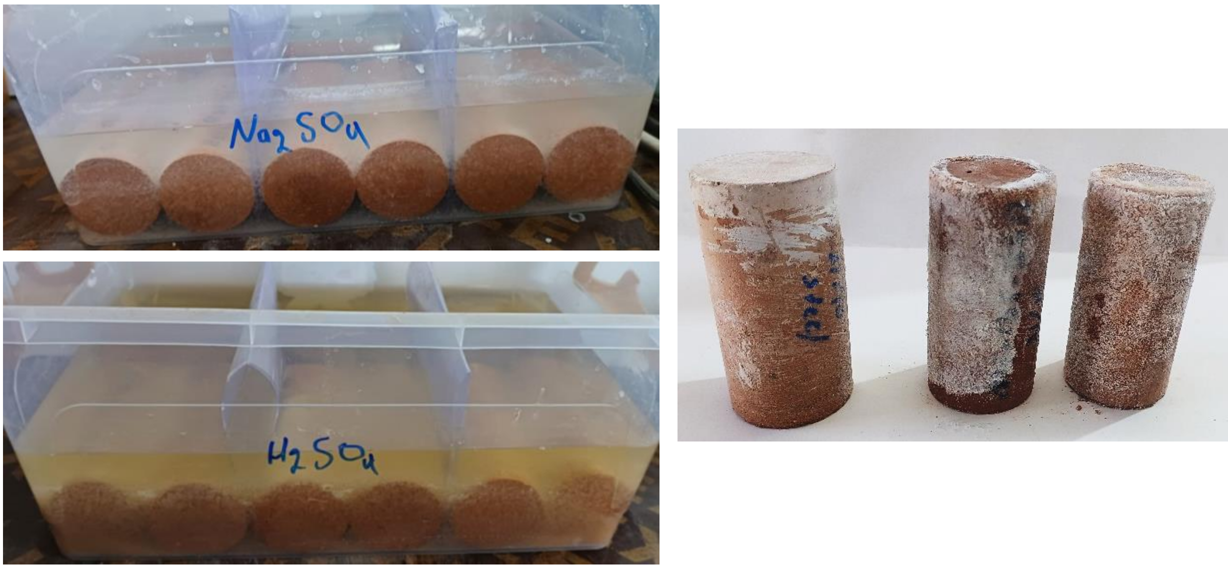

Figure 7 samples treated with H2SO4 and Na2SO4.

4. Conclusions

This research examined geopolymer grout replaced WBP with GGBS using fresh (mini-slump flow and setting time) and mechanical (unconfined compressive strength and durability) qualities. Conclusions were: 1. Full WBP lowered geopolymer grout workability. However, geopolymer grout worked better with WBP as

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a partial GGBS alternative. Substituting 10–45% WBP with GGBS increased MG grout slump flow by 4.5–41%.

2. Setting time for WRP-based geopolymers mixes is reduced from 250 to 95 min by adding 10-45%GGBS.

3. The findings show that replacing WBP powder with GGBS enhanced strength linearly with GGBS quantity. The geopolymer mix's UCS values increased 21.2%, 17%, and 8.5% when WBP was replaced with 15%, 30%, and45%GGBS.

4. Acidic and salt sulfate conditions did not damage geopolymer grout samples. UCS decrease was 10% and 38% against sodium sulfate (Na2So4) and acid (H2SO4) with high WBP concentration.

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