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Shrinkage and Mechanical Resistance of Steel Fiber Reinforced Geopolymer Mortars Containing Industrial By-Product GGBS; Solution to Binder Affect in Oven Curing Condition

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Abstract

Ground granulated blast furnace slag was amalgamated with silica fume to provide binder content (B) and mixed in varying proportions with a solution of diverse alkaline solution (S) to produce Geopolymer mortars (GPMs). The alkaline solution comprised a blend of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), maintaining a steady NaOH concentration of 12 M and a Na2SiO3/NaOH mass ratio ranging from 0.3 to 0.45. The GPMs were formulated with varying S/B ratios of 0.3, 0.35, 0.4, and 0.45. All mixtures were cured under 60 ^{0}C oven conditions. To evaluate the effect of the S/B ratio on the GPMs, the compressive strength, tensile strength, and shrinkage of hardened GPMs were examined at 7 and 28 days of age. The experimental findings indicated that altering the S/B ratio affected the compressive strength of GPMs. The compressive strength was superior at an S/B ratio of 0.35 compared to both higher and lower ratios. At this optimal S/B ratio, a compressive strength of up to 11.25 and 24.23 MPa was observed at the 7days and 28 days.

Keywords: Geopolymer mortar, shrinkage, oven curing, granulated blast furnace slag, silica fume

1- Introduction

The expenditures associated in revitalizing infrastructure worldwide are immense. As an illustration, in the United States, the projected requirements amount to more than 1.6 trillion dollars for the next 5 years. Approximately 27% of all highway bridges require repair or replacement, while the expenses associated with corrosion degradation caused by deicing and sea salt impacts are predicted to exceed 150 billion dollars [1]. Approximately $21 billion in yearly investments is needed in the United States alone to ensure sufficient infrastructure for wastewater treatment. Estimates indicate that the yearly expenses related to the operation and

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maintenance of wastewater infrastructure exceed $25 billion [2]. Approximately 84,000 reinforced and pre-stressed concrete bridges in the European Union need maintenance, repair, and strengthening. The yearly budget for these infrastructure projects amounts to £215 million, excluding the expenses related to traffic management. Decades ago, a significant number of deteriorated concrete structures were constructed without sufficient consideration for durability concerns [3,4]. As Kavitha [5] correctly pointed out, extending the durability of concrete from 50 to 500 years would result in a tenfold reduction of its environmental effect, therefore underscoring the significance of durability in the context of eco-efficiency of construction and building materials. Materials exhibiting poor durability need regular maintenance and conservation activities, or even complete replacement, due to their association with the consumption of raw materials and energy. The "Law of Fives" referenced by Selvarani asserts that a $1 investment in design and construction is equal to $5 invested when damage starts and before it spreads, $25 after degradation has started to spread, and $125 after significant damage has taken place. This notion emphasizes the need of taking action as soon as possible to avoid concrete buildings from reaching a stage when significant damage has taken place and the expenses of restoration have increased enormously. Within that particular framework, it is crucial to evaluate the effectiveness of existing repair materials in meeting the rehabilitation requirements of concrete infrastructure [6].

An urgent and growing demand exists for repair-in-place technology specifically designed for big diameter storm pipes and culverts [7]. The repairs must possess both structural integrity and long-lasting durability suitable for challenging and varied environments. Pipes and other structural components in sanitary, storm, and combined sewer systems are subjected to very corrosive and challenging environments [8]. The factors contributing to these circumstances encompass freeze-thaw cycles, recurrent wet-dry situations, traffic loading, pressure exerted by movement in earth and rock embankments, mechanical deterioration caused by particles and grit in the storm water, as well as chemical and biological contaminants [9]. Storm water conveyance systems frequently have failures, particularly during storm events, leading to the formation of sinkholes, road washouts, and floods [10]. Often, malfunctioning storm water pipelines and culverts necessitate a "dig up and replace" method. These development projects often result in disarray, high costs, and disturbance to road infrastructure and other logistical operations. There are several "no dig" alternatives for rehabilitation, but, each of them has some constraints, particularly when addressed with pipes of significant diameter. The issues highlighted are prevalent throughout both the Department of Defense and municipal governments [11]. One viable approach is to employ a fiber reinforced geopolymer that may be sprayed by spraying to create a liner along the pipe [12]. Geopolymer (cement) mortars are distinct from Portland cement mortars in terms of their material composition [13]. Polymer-modified Portland cements are products that substitute a portion of the cement hydrate binders in traditional cement with polymers1. The geopolymer mortars employed in centrifugal

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applications are based on aluminosilicate matrix and can incorporate latexes or emulsions, essential polymer powders, water-soluble polymers, liquid resins, monomers, and various reinforcing fiber components [14]. Geopolymer mortars exhibit a far faster curing time compared to Portland cement mortars, make them more appropriate for centrifugal application because to their ability to achieve exceptional uniformity, and have a lower occurrence of shrinkage cracking. After the curing process, the geopolymer mortars exhibit enhanced strength and resemble ceramic or synthetic stone properties [15].

Substantial research efforts are focused on enhancing the strength of geopolymer products and comprehending the process of geopolymerization. For the purpose of determining the impact of metakaolin addition on the ultimate binder strength, Kalyana et al. [16] investigated the evolution of binder structure in sodium silicate-activated slag-metakaolin blends. Luo et al. [17] examined the setting and hardening reaction of the geopolymer system, which is influenced by the ratio of Al_2O_3 to SiO_2. The obtained ratio illustrates the impact between the duration of setting and the ultimate strength of the geopolymer. Al-Oran et al. [18] investigated how mixtures of SiO_2/Al_2O_3 and Na_2O/SiO_2 affect the setting time, workability, and ultimate strength of geopolymer systems. The optimal ratios for SiO_2 to Al_2O_3 were found to be between 2.87 and 4.79, while for SiO_2 to Na_2O, they were within the range of 1.2 to 1.4 to form the geopolymer binder. The endurance of alkali-activated materials was examined by Faridmehr et al. [19], particularly focusing on their recent advancements and future prospects. Their study included accelerated degradation testing techniques to assess the impact of increased levels of CO_2, sulphates, and chlorides on the durability. Geopolymer have been widely used as protective coating materials for maritime concrete and transportation facilities throughout the years [20]. The selection of geopolymer as repair materials is contingent upon the binding strength between the substrate concrete and the repair material [21]. The characteristics of GPC, such as its modulus of elasticity, Poisson's ratio, and tensile strength, closely resemble those of Ordinary Portland Cement (OPC) concrete. The compatibility between GPC and OPC concrete is well demonstrated. Moreover, like traditional concrete, GPC may undergo curing at room temperatures [22-25].

Commonly, the restoration of concrete is carried out using commercial repair materials that have excellent mechanical properties and bond strength [26]. Nevertheless, they are fairly costly. Therefore, there is a need for more cost-effective alternative repair materials that have similar characteristics. In an effort to employ geopolymer as a repair material, a number of studies [27–30] conducted slant shear, pull-out, and direct shear experiments. A study conducted by Mehta and Siddique [31] investigated the adhesive strength between mortar substrate and geopolymer in sandwich specimens. Geopolymer demonstrated superior adhesive strength compared to a similar interfacial polymer composite mixture. The binding strength between concrete substrate and glass powder matrix (GPM) generated from tungsten mine

Power System Technology
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waste including calcium hydroxide was investigated by Verma and Dev [32]. Their findings indicate that geopolymer binders have much superior bond strength, even at a young age, in comparison to commercial repair materials. In their study, Reddy et al. examined the adhesive strength between rebar and concrete substrate by employing geopolymer paste as the chemical bonding agent. Their observation revealed that the binding strengths of rice husk ash and silica fume glass-polymer composites are around 1.5 times greater than those of epoxies. Therefore, the bond strength of geopolymer materials is sufficiently strong, which makes them a viable option as a bonding medium for structural repairs [33].

According to Patil et al. [34], OPC is a very energy-intensive product due to its significant energy consumption and the production of a large volume of greenhouse gases. Previously, attempts have been undertaken to decrease the use of OPC by including alternative additional cementitious materials. Furthermore, an alternative type of cement known as geopolymer has arisen as an ecologically sustainable alternative. Progression in the synthesis, characterization, and deployment of geopolymer composites is occurring rapidly [35, 36]. The primary goal of this study is to present a comprehensive analysis of the historical evolution, current advancements, and future potential of GPMs in the construction industry. Emphasis is placed on the viability of utilizing GPMs as efficient repair materials for damaged concrete and structural protection. The prospective application of geopolymer as a building material with improved sustainability, energy efficiency, decreased CO_2 emissions, and suitability for usage in challenging conditions is also discussed. Furthermore, the efficient utilization of recycled industrial wastes and the prevention of decreasing natural resources are also subjects of discussion. The findings on the endurance of geopolymer in terms of the mechanical properties, shrinkage are also reported through the results of paper. Advocates contend that the extensive use of ecologically friendly geopolymer can be a pivotal step towards achieving a reduced carbon footprint.

2. Experimental program

In this section, the materials and mix design preparation is presented. The Fig. 1 is indicated the mixture's advantages and geopolymerization preparation of concrete.

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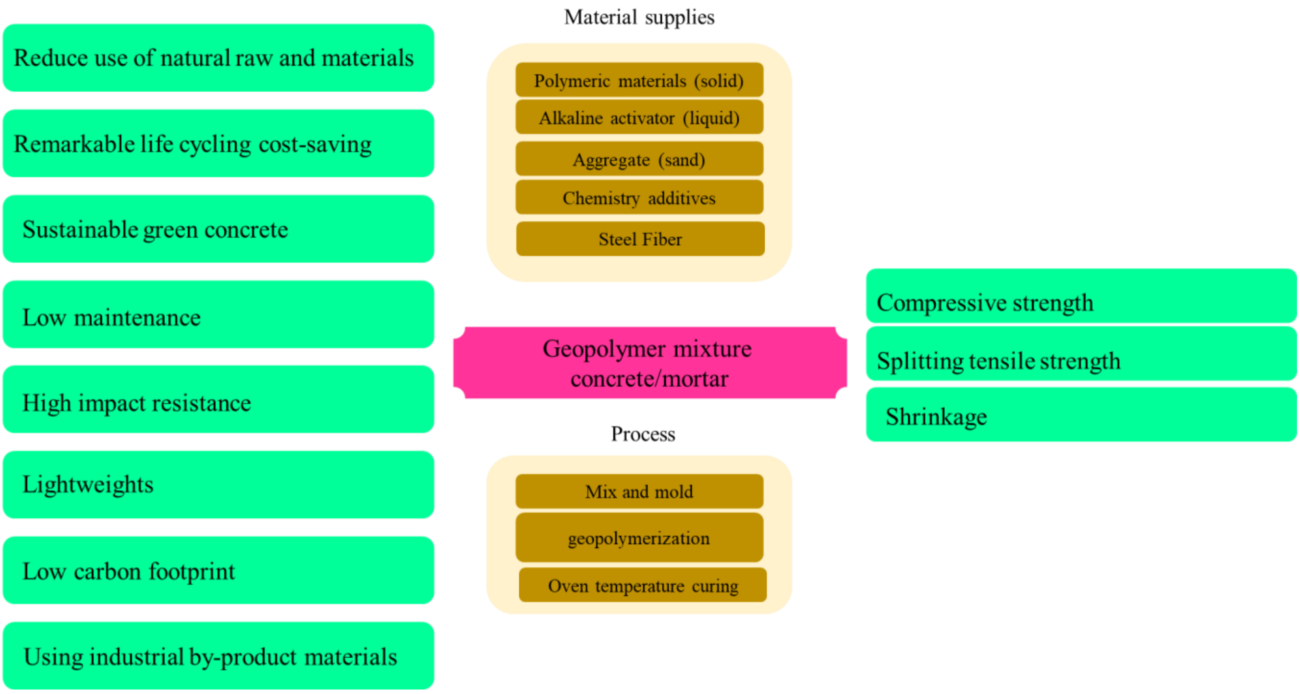

Fig.1: Geopolymerization process of concrete

2.1. Material specifications

(a) The GGBS with a granule density of 2.66 g/cm3 was sourced from Foolad Mobarakeh in Esfahan. The combined concentration of Al_2O_3, SiO_2, and Fe_2O_3 in the GGBS was around 80%. The observed result exceeds the minimum recommended threshold of 70% as stipulated by ASTM C618 for natural pozzolans. Table 1 provides the chemical characteristics and loss on ignition (LOI) of the specific pozzolans that were employed. In the provided table, the rounding of the data results in a sum of the percentages of various components that does not equal 100%. Finally,

Table 1: Chemical composition of utilized materials (%)

Component (%)	MS	GGBS
SiO_2	52.1	32.57
Al_2O_3	44.7	16.98
Fe_2O_3	0.8	1.26
CaO	0.09	34.07
MgO	0.03	9.69
SO_3	-	0.84
Loss of ignition (LOI)	0.7	0.39

Power System Technology
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(b) Alkaline solution

The activating agent for the solid-phase membrane was an alkaline solution consisting of glass water (sodium silicate or Na_2SiO_3) and sodium hydroxide (NaOH). A 96% solid sodium hydroxide solution was created as a water-soluble formulation. The SiO_2 / Na_2O ratio of the sodium silicate solution used in this study was 2.27 (SiO_2 = 35.9%, Na_2O = 15.8%).

(b) Fibers

An experimental study was conducted to produce environmentally friendly and structural geopolymer mortars alloys utilizing a combination of steel (ST) fiber manufactured at Kimiax company, Iran. Table 2 provided the specific parameters of the fibers employed. In this investigation, the best mixes were developed using hooked-end steel fibers with a maximum length of 5mm and a diameter of 0.12 mm. To achieve this, St at 2 vol% were included into the GPC mixture combinations.

Table 2: Fiber properties

	ST
Length (mm)	12
Density (gr/cm^3)	7.8
Tensile strength (MPa)	2500
Water absorbency	No
Alkaline and acid resistance	Excellent
Diameter (mm)	0.12

(c) Aggregates

The fine aggregate comprised of natural sand obtained from a nearby quarry with a fineness modulus of 3.05, falling within the acceptable range specified by ASTM C33 [37]. In Table 3, the sieve analyses for the fine coarse aggregates are presented.

Table 3: FA sieve analyses for geopolymer mortars.

FA	Sieve size (mm)	9.5	4.75	2.36	1.18	0.6	0.3
	Passing percentage (%)	100	87.6	63.5	41.9	23.3	4.5

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2-2. Mix design, sample preparation and testing process

Figure 2 illustrates the preparation of GPC mortars in a mixer. To achieve this objective, the dry ingredients, including FA, and SCMs, were mixed in the mixer for up to 3 minutes. Then, the alkaline solution was added and the wet mixing was continued for 4 to 6 minutes until a homogeneous mixture was achieved. The newly prepared solutions were poured into steel cube molds measuring 150×150×150 mm and cylindrical specimens measuring 100×200 mm. The molds were filled in two layers and each layer was subjected to vibration for about 25 seconds onto a vibrating table. The mixture design of reinforced GPC mortars is presented in Table 4.

Fig. 2: The geopolymer mortars specimens

Figure 3 shows that the prepared specimens were placed in an oven set at a temperature of 60 ^{0}C for a duration of 24 hours. The specimens were then taken out of the molds and cured at a temperature of 24 ± 2 ◦C and a relative humidity of 20% ± 2% until they reached the required temperature as per the ISO-834 standard fire curve for testing purposes. After curing for 28 days, four cubical specimens and two cylindrical tests were conducted to evaluate the strength of CS and TS evaluation. All the mixes shown in Table 4 featured a constant solution to binder ratio of 0.3- 0.45. The water composition included both the mixing water and the water containing NaOH and Na_2SiO_3. Furthermore, the solid materials consisted of GGBS and MS,

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as well as the solid component of the NaOH and Na_2SiO_3 solutions. Furthermore, the concentration of the Na_2SiO_3 / NaOH was 1/5. The effect of employed SCMs, S/B and fibers on the geopolymer mortars (GPM) properties was studied by producing 12 mixes at the oven curing condition. In these mixtures, MS were substituted 1.5%-4.5% of mixture proportion.

Table 4: Mixture proportions of reinforced geopolymer mortar

Sample ID	S/B	SCMs (Kg/m^3)	GGBS (Kg/m^3)	MS (Kg/m^3)	FA (Kg/m^3)	ST ($\%V_f$)
GPM1	0.3	500	350	150	1500	1
GPM2	0.3	500	400	100	1500	1
GPM3	0.3	500	450	50	1500	1
GPM4	0.35	500	350	150	1500	1
GPM5	0.35	500	400	100	1500	1
GPM6	0.35	500	450	50	1500	1
GPM7	0.4	500	350	150	1500	1
GPM8	0.4	500	400	100	1500	1
GPM9	0.4	500	450	50	1500	1
GPM10	0.45	500	350	150	1500	1
GPM11	0.45	500	400	100	1500	1
GPM12	0.45	500	450	50	1500	1

3. Results and discussion

3.1. Compressive strength

For each geopolymer reinforce mortars, 12 cube specimens were examined in accordance with the ASTM C 39 standard [38], with three specimens picked for the 28-day experiment. Based on the experimental data presented in Fig. 3, the compressive strength (CS) of the GPM varies, as do the contents and quantities of the SCMs and fiber content.

Power System Technology
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Fig. 3: CS test procedure of the geopolymer reinforce mortars specimens.

In this study, the ratio of the alkaline liquid to the binder, namely the combination of GGBS and alkaline solution, is between 0.3 and 0.45. Fig. 4 and 5 presented the CS results of the geopolymer reinforce mortars in terms of different solution to binder ration at the age of 7 and 28 days. The laboratory results showed that the highest amount of CS in the short term was observed in the ratio of 0.35. In the S/B=0.35, GPM4 containing 150 kg/m^3 MS was achieved the 11.25 MPa strength. The mixture was highly viscous and rigid, although it attains more strength than a higher ratio. The compressive strength diminishes when the solution-to-binder ratio increases because to the higher water content. In this study, the increase of 0.1.5% MS and 1% steel has caused changes in the CS of concrete. Figure 5 illustrates the compressive strength of the GPMs at 28 days, considering various combinations of alkaline binder ratio (S/B) and the mass ratio of NaOH to Na_2SiO_3 for 12 M. The strength is maximized with an increase in the Na_2SiO_3 ratio at 28 days, peaking at an Na_2SiO_3 ratio of 3.0, beyond which it declines. The findings indicated that an alkaline activator/GGBS ratio of 0.35 provides the optimal quantity of alkaline liquid, demonstrating the greatest rate of geopolymerization relative to other ratios. A strength of 24.23 MPa was attained using an activator/ GGBS ratio. The type of activator base material and the processing method in GPM are very important in the strength characteristics. In the comparison made between two GPC and OPC, it was found that the strength of geopolymer mixtures is higher than OPC at early ages and that is because of the structure of geopolymer mixtures. According to Fig. 5, the results of the CS evaluation presented that in 7 days and 28 days, the CS of the fiber reinforced GPM samples improved by 53% during the 7-days curing to 28-days curing.

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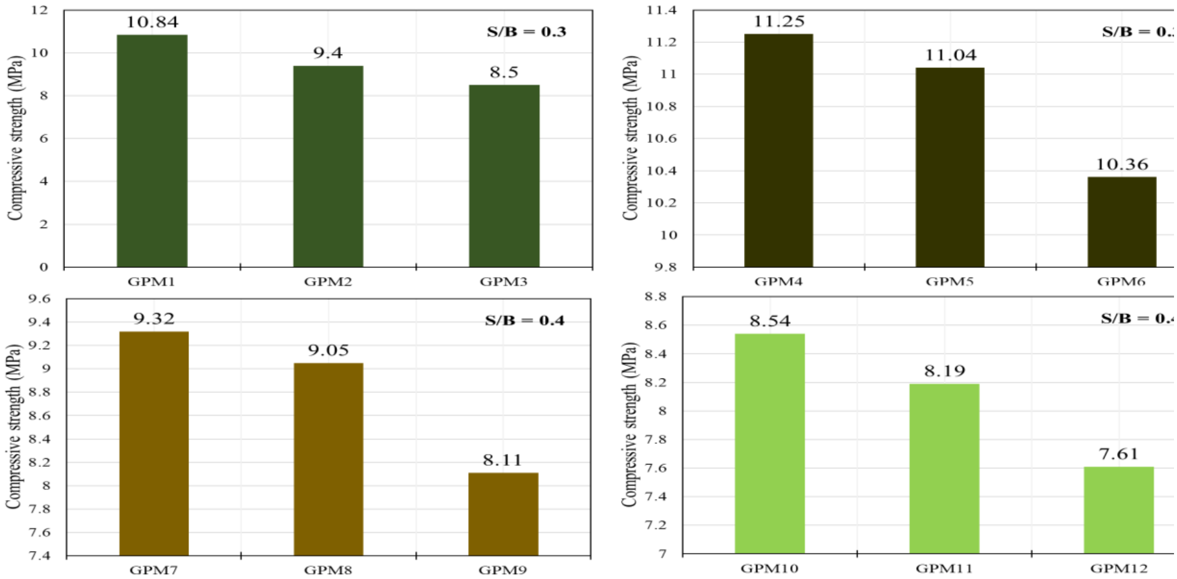

Fig. 4: Compressive strength result of geopolymer mortars; 7-days.

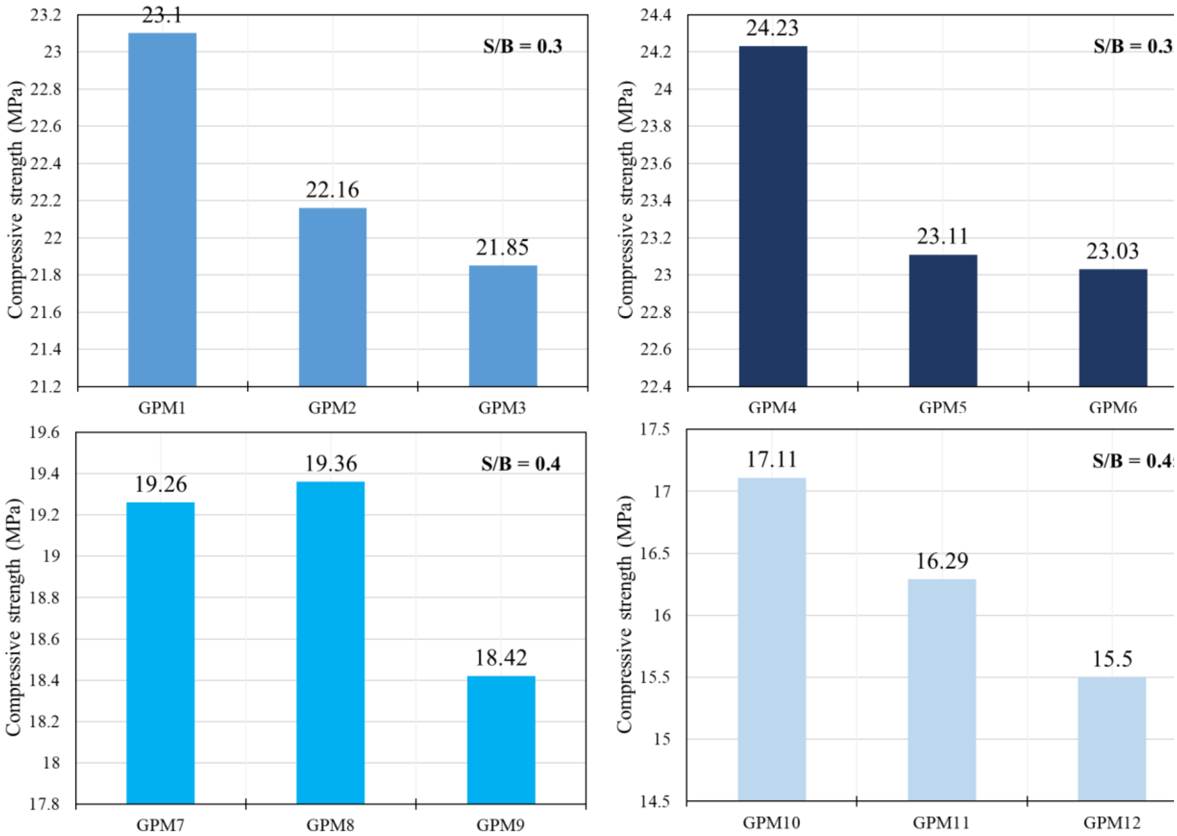

Fig. 5: Compressive strength result of geopolymer mortars; 28-days.

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3.2. Tensile strength

The experimental results of the tensile strength for the geopolymer reinforce mortars was presented in Fig. 6 based on ASTM standard [39]. The tensile strength characteristics of GPM at 28 days are illustrated in Fig. 6, indicating a little enhancement for both S/B=0.35 and S/B=0.3. The experimental assessment presented that the highest amount of TS was measured in the ratio of 0.35. In the activator/ GGBS ratio =0.35, GPM4 incorporating of 350 kg/m^3 GGBS and 150 kg/m^3 MS was achieved the 2.64 MPa strength.

The obtained results presented that according to the obtained tensile strength and the overlap of the results, reinforced GPM containing hooked-end steel fibers (S/B=0.35) have the highest strength. The amount of adhesion of geopolymer concrete is higher than that of ordinary concrete, and this adhesion is directly related to their compressive strength. In fact, the factors in GPM that affect its strength also increase its adhesion. The convergence rate of compressive and tensile strength results in this study was 88%. The results indicated that GPM had excellent tensile strength to withstand bending in structural elements.

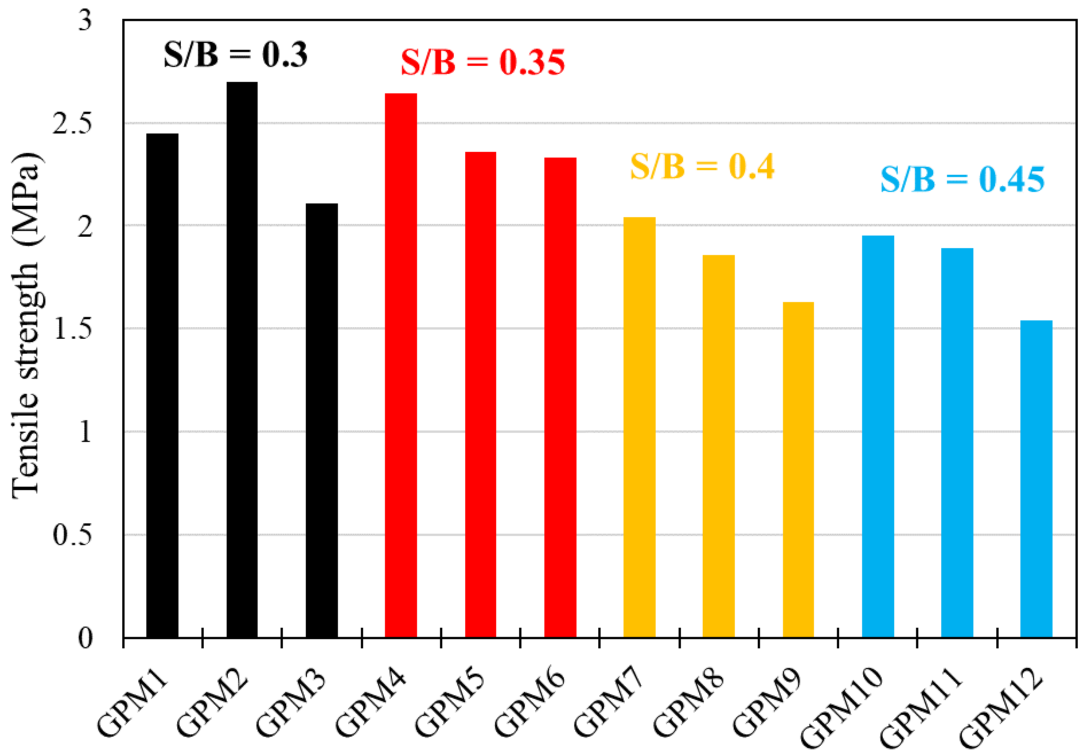

Fig. 6: Tensile strength result of geopolymer mortars.

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3.3. Shrinkage

Concrete shrinkage refers to the reduction in length or volume of concrete due to variations in moisture content or chemical reactions. All concrete experiences shrinkage, which may be classified into four distinct kinds. The study attempted to evaluate the drying shrinkage of the geopolymer mixture. It is optimal to define a maximum length change of 28 days in accordance with ASTM C157 Standard Test Method [40]. The mixture shrinkage evaluation of the study was performed using the following set up. In Fig. 7. Concrete undergoes volumetric or induced phase shifts. This phenomenon is referred to as concrete shrinkage.

Fig. 7: Shrinkage test set up.

Constant variation in volume is a highly detrimental characteristic of concrete. Engineering speaking, the modification of concrete volume is significant as it leads to the formation of unsuitable fissures in the concrete. These fractures impact its structural integrity and extended

Power System Technology
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lasting resilience. Concrete shrinkage refers to the gradual reduction in the volume of concrete during time, resulting in a decrease in its dimensions. In hardened concrete, shrinkage is the consequence of moisture loss. Vacancy of tiny holes in concrete leads to the generation of negative capillary pressure, therefore decreasing the volume of the concrete. This phenomenon is the process of water evaporation from the surface of recently mixed concrete or its absorption into the concrete or substrate. Hydraulic contraction is a reduction in volume caused by the migration of water from the concrete during its plastic or pre-set condition. Water migration can occur either during the hydration process or due to environmental factors causing water to evaporate on the wet concrete surface. Thus, the higher the bleeding of the concrete, the more significant the plastic shrinkage should be. The extent of this shrinkage is contingent upon the quality of the cement. Studies on the w/c ratio indicate that the weight ratio of water to cement in the concrete mixture is inversely proportional. Fig. 8 indicated the aggregation results obtained in this work. The present work involved the fabrication of 12 samples to examine the pattern of moisture decrease in self-compacting and self-compacting geopolymer samples during a 28-day timeframe. This test is conducted under controlled settings, including regulated temperature and humidity, on predetermined samples. The implementation of geopolymer has resulted in a reduction in the level of shrinkage in the blended materials. The concrete shrinkage test was conducted using a device designed to measure the shrinkage of self-compacting geopolymer concrete, as shown in Fig. 8, following the ISI8592 standard protocol.

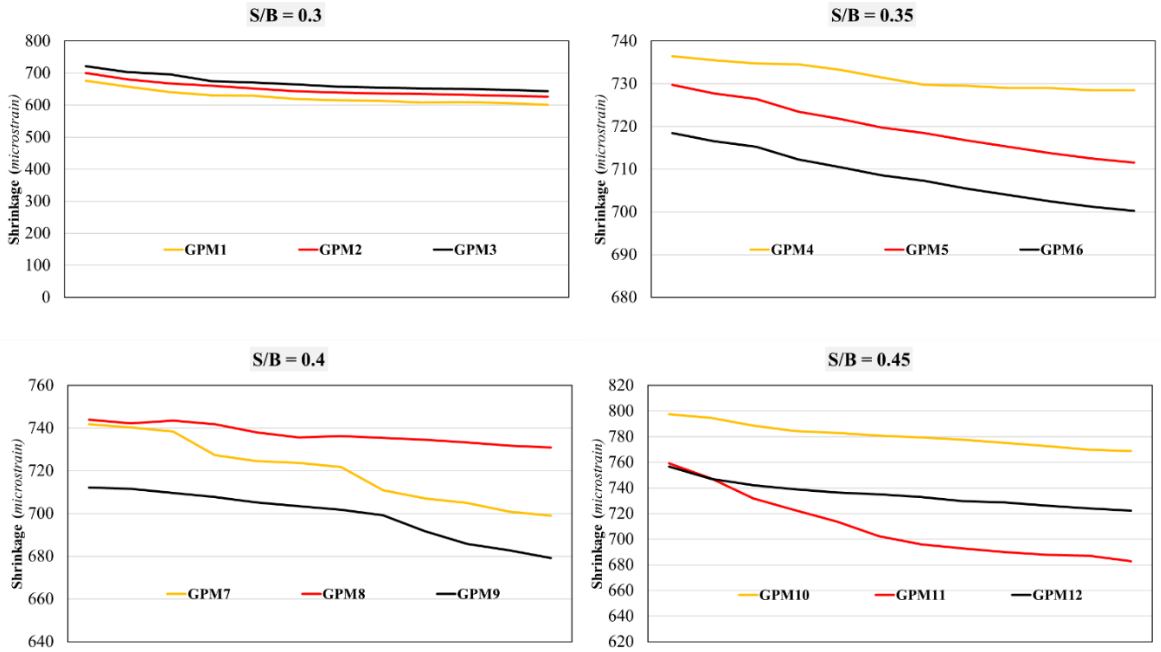

Fig. 8: Shrinkage of the geopolymer reinforce mortars.

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The data presented in Fig. 8 clearly demonstrates a reduction in the moisture content in all test samples of the reinforced geopolymer mixtures. In this study, the highest shrinkage was achieved by GPM12 mixture (from 756.75 micro strain to 722.25 micro strain). Drying shrinkage occurs due to the loss of surface-adsorbed water from the calcium silicate hydrate (C-S-H) gel and the decrease of hydrostatic tension in the minute pores. Inflation is the opposite of contraction. The principal factor contributing to this contraction is the deformation of the concrete matrix. The aggregate's hardness considerably affects it. The bulk of drying shrinkage occurrences transpire within the early months of the concrete structure's existence. The removal of water from the concrete, held in the unsaturated air voids, leads to dry shrinkage.

4. Conclusion

The mechanical and shrinkage behavior of a geopolymer reinforce mortars containing GGBS and MS was investigated in this attempt. This experimental investigation identifies the obstacles and opportunities associated with alkali activated binders and indicates that these binders possess significant potential to supplant traditional Ordinary Portland Cement. The following result were obtained for this study:

- In all specimens, an increase in the S/B ratio correlates with a decrease in drying shrinkage and an enhancement in ductility.
- The values of compressive strength are the highest at 28 days for 12 M when S/B is 0.35.
- The results of evaluating the resistance properties in mortars also indicated that in 7 days and 28 days, the CS of the GPMs was increased by 1.5-3% MS.
- The tensile strength of GPMs at 28 days are indicating a little enhancement for both solutions to binder ratio of 0.35.
- In all specimens, as both the MS content and the S/B ratio increase, the drying shrinkage increases.

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