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TERNARY COMBINATION OF INDUSTRIAL WASTES FOR SUSTAINABLE GEOPOLYMER MORTARS

Executive Summary:

Considering the high carbon footprint, the adverse environmental impact of Portland cement is evident. On the other hand, the disposal of growing industrial waste is also an environmental concern. The ecological impact of industrial byproducts, including fly ash, Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LS), and Silica fume (SF), is enormous if these used as traditional landfill. Using these in geopolymers are gaining importance as an alternative to Ordinary Portland Cement to achieve sustainability in the construction industry. This research experimentally evaluated the effect of various industrial waste-based binders, alkali concentration, curing temperature and curing age on the compressive strength of geopolymer mortars. The mortar mixes used a ternary combination of binders in the range of GGBS 50-70%, LS 20-30% and SF 10-20% by mass. The Sand, binder and alkaline activator ratio of 2.75:1:0.45 was maintained, and the strengths of alkaline solutions were 4, 6 and 8M. The workability of fresh mortar was evaluated using the flow table test. After 24 hours of casting, temperature curing at 60°C and 80°C was applied for 24 hours. Following that, the samples were cured at ambient temperature and the compressive strength was measured at the ages of 3 and 7 days. A set of the sample was cured at ambient temperature to compare the effect of heat curing. The effect of curing temperature on compressive strength was found to be more prominent than that of curing time. The result indicated 6M alkaline is optimum, and using this, a sample with 60% GGBS, 20% LS and 20% SF in binder content gave the highest compressive strength (48.8MPa) with 145mm flow. In general, the ternary combination of waste binders with heat curing could be a sustainable option for the future of geopolymer concrete.

Keywords: Geopolymer; Ternary combination; Ground Granulated Blast Furnace Slag, Ladle Furnace Slag, Silica Fume.

Research Significance:

The research aims to riddle out the characteristics of GGBS-silica fume-ladle slag based geopolymer binder. Being the principal component of geopolymer, the proportion of alumina and silica in the raw materials influence the properties of mortar produced. Therefore, different proportions of GGBS (50-70%), Ladle Slag (20-30%) and Silica Fume (10-20%) was used as a ternary combination to create varying Si/Al ratio in the mix. This reflected in their Workability, compressive strength and Weight. In addition, the effect of different binder combination, curing temperature, age, and strength of alkaline solution on compressive strength of geopolymer mortar was evaluated. The impetus was given on a relatively less used industrial waste ladle slag to produce eco-friendly cement-free mortar.

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Acronym and Symbols

GGBS : Ground Granulated Blast Furnace

LS : Ladle Slag

SF : Silica Fume

EN : European Standards

CEN : European Committee for Standardization

SS : Sodium Silicate

SH : Sodium Hydroxide

ASTM : American Standard for Testing Materials

Si/Al : Silica-Alumina Ratio

1. Introduction:

Civil engineering has always welcomed effective new material/methods to meet the growing requirements of future construction systems. In the middle of the 18th Century, Portland cement was developed by Joseph Aspdin [1]. Later, it was improved in all forms for a better outcome. Despite its most significant consumption as a binding material, its high environmental burden also started to show its effect on the world. Portland cement is being produced using the technology of 'two grinding and one calcinating' principally using clay and limestone as raw materials. For the calcination process, a temperature of 1450^{o}C is applied. A Chinese study [2] revealed that the country's consumption of limestone, clay, iron powder, coal and electricity was one billion tons, 180 million tons, 50 million tons, 100 million tons and 60 billion kW/h each year in cement production. Each ton of cement production approximately emits around 1 kg sulfur dioxide, 2 kg oxides of nitrogen, and 10 kg dust. The cement industry is liable to produce about 7% emissions of CO_2 each year all over the world [2]

Following this, the impetus to explore the alternative of Portland cement concrete and mortar has become one of the gripping fields for research. To minimize carbon emission from the cement industry and conserve energy while managing the waste material for environmental protection, researchers started developing new mortar and concrete types [3]. Among all these new materials, geopolymer material is the most effective binder that could replace traditional cement either totally or partially. In 1979, Davidoits first introduced geopolymer, alkali-activated base materials consisting of aluminium and silicon with a three-dimensional net-like structure to serve as a binder [2]. The aluminosilicate powder could generally be an industrial by-product such as Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LS), Silica fume (SF), Fly Ash and thermally activated clays or a combination of all these materials, activated by alkaline solution (NaOH or KOH with Na_2SiO_3) for production of alkali-aluminosilicate gel [4] .

The LS is a by-product of iron purifying, and the production industry could be a potential material in geopolymer application that gained less attention [3]. To maximize the utilization of industrial waste, a full replacement of cement by pozzolanic material is recommended. Therefore, geopolymer mortar without using cement clinker could be a greener construction material for sustainable construction practice [2]. Compared to Portland cement, geopolymer has technical advantages, including high early strength development, better durability, lower permeability and shrinkage and greater resistance to acid and fire with the ability to immobilize hazardous atoms [5]. Almost no greenhouse gas is generated in geopolymerization, and the raw material has embodied carbon [2]. The geopolymerization process increases the pH of the mixture and accelerates the rate of reaction between solids [6].

In geopolymer mortar, heat curing plays a significant role in enhancing chemical reaction between the materials and improving compressive strength. Heat curing accelerates the initial improvement of compressive strength [7]. Studies used coal fly ash [4], a combination of rice husk ash and spent diatomaceous earth [8], as a binary combination for geopolymer production. However, an extremely limited study could be found with a ternary mixture of binders. Kumar et al. [9] studied a ternary combination of GGBS, fly ash and SF geopolymer. Besides fly ash, a large amount of slags such as GGBS and LS are produced in the construction sector, while a significant amount is not used. So proper utilization of industrial wastes in mortar and concrete production would be indispensable to achieve sustainable development.

From background study, it is noted that NaOH and Sodium silicate solution give the best outcomes as an alkaline activator and help improve the strength of prepared geopolymer mortars. In this experiment, an alkaline activator to binder ratio of 0.45 is maintained for better results. The strength of NaOH is varied as 4M, 6M, 8M and Na_2SiO_3 to NaOH ratio is taken 2.5. A 10-20% of water can be added to maintain feasible flow, to reduce the concentration of NaOH solution after each mix flow test is performed to assess the workability of the combination.

Duration and degree of heat curing play a vital role in the building method of geopolymer. Molds are kept at ambient temperature for 24 hours and heated at 60^{o}C and 80^{o}C respectively for 24 hours in an oven. The oven is turned off after 24 hours, and samples are kept at ambient temperature for 3days and 7days curing period. Total 216 no of geopolymer mortar samples are prepared, sized of 40mmx40mmx160mm for determining compressive strength.

The study aims to obtain an ideal material combination for preparing geopolymer mortar, including different slag and silica fume under various conditions while keeping the sodium silicate to sodium hydroxide ratio and activator to binder ratio constant. Following are the objectives of the study:

- To evaluate the effect of GGBS, LS and SF combination on the workability of geopolymer mortar.
- To evaluate the compressive strengths of geopolymer mortars combining GGBS, LFS and SF.
- To evaluate the effect of different alkaline activator concentrations and curing temperature on geopolymer mortar properties.

1.1 Geopolymer Mortar:

Geopolymer mortar prepared from calcined materials, such as slag, fly ash metakaolin (calcined kaolin, have more compressive strength than those prepared from non-calcined raw materials. Single material or a combination of materials may be used as the raw material for geopolymerization [10]. According to Davidovits, alkaline liquid might be utilized for creating binders by reacting with aluminium and

silicon [11]. A combination of sodium hydroxide or potassium hydroxide and sodium silicate or potassium silicate is a common alkaline activator used in geopolymeraization [11]**.** As the concentration of NaOH increases, the strength of the mortar sample increases. More reactive monomer bonds are needed for the geopolymer to have good intermolecular bonding strength. A higher strength of NaOH helps to improve dissolving ability, no matter what the binder particles is. There may be fly ash, metakaolin [12], different types of slag like ladle furnace slag, ground granulated blast furnace slag etc.

For geopolymer mortar having 50 mm cube size, suggested optimum curing temperature of 60°C. The given recommendation is founded on the assumption that a smaller cube has a higher surface-area-to-volume ratio than a larger cube. As a result, the smaller cube is more vulnerable to the high curing temperature than the larger samples and will lose moisture during curing. [13] .

It has been seen that Curing time has a favorable impact on the compressive strength of geopolymer mortar, and this effect is more observable at the maximum curing temperature of 80 °C [14]. Furthermore, an increase in curing time will result in a significant increase in compressive power. [15]. In short, geopolymer mortar can withstand temperatures of up to 1000°C. [16].

1.2 Factors affecting Geopolymer Mortar:

Geopolymerization is a chemical process involving reactions of aluminosilicate minerals under different alkaline solution conditions, which provide bonds of Si-O-Al-O. Workability and compressive strength of mortars are influenced by the proportion and properties of the geopolymer constituent. Moreover, various factors such as workability, curing temperature, curing period, the concentration of the alkaline solution, etc. are also important parameters affecting the prepared mortar [17]. Flow value of geopolymer mortar, measured by a flow table test, determines the consistency and flow of the mortar. According to Li et al., adding polymer powder decreased the fluidity of the geopolymer mortars, with a downward trend in fluidity as the polymer powder content increased. [2]. Owing to the more complicated chemical reactions in geopolymer, the temperature of the fresh mortar is observed to be much higher than that of standard cement mortar during mixing. The temperature of the geopolymer mortar is highest directly after mixing, and it gradually decreases over time. Besides that, a higher curing temperature of the mortar yields higher compressive strength, but too high temperatures may crack the mortar too.

The Experimental results of [15] show that :

- The compressive strength of geopolymer concrete is increased as the sodium hydroxide solution concentration is increased.
- Geopolymer concrete compressive strength is increased when the sodium silicate solution mass ratio is higher than the sodium hydroxide solution.
- As the H_2O-to-N_2O molar ratio rises, the geopolymer's power decreases.

1.3 Application of Geopolymer Mortar:

Application of Geopolymer materials in concrete and mortar will limit or exclude the use of Ordinary Portland Cement. Geopolymer mortar is a green solution to conventional cement mortar that adds a new technical concept to the method. Railway sleepers, electric power lines, road pavements, cement mortar, coastal foundations, and various waste storage systems use it.

Thermal insulation, fire resistance materials, low-tech construction materials, decorative stone objects, thermal shock refractories, bio-technologies (medicinal applications), infrastructure repair, low energy ceramic tiles, aircraft interior and vehicle composites, refractory products, and other geopolymer mortar applications are all of the great interest [18].

1.4 Economic Advantage of Geopolymer Mortar:

The related pollution is virtually non-existent for geopolymer as it combines waste products. As a result, expanded use of this waste material would have a favorable environmental effect and significant economic advantages. [19]. The components of geopolymer mortar are by-products of different industries. As a result, the cost of these materials is eventually less compared to that of traditional mortar made by cement. Although the additional materials such as alkali activation may require a little higher cost, the reduction in carbon emission is itself a win-win for geopolymer based constructions. Sarker and Rangan (2014) mentioned that [2], the heat-cured geopolymer mortar's low creep, resistance to sulphate attack, limited drying shrinkage, and strong acid resistance will increase additional cost savings.

2. Materials:

The experimental work involved the manufacture of Geopolymer mortar by using Ground Granulated Blast Furnace Slag (GGBS), Ladle Slag (LS), Silica Fume (SF), Alkaline activator, EN-Sand, and water. During the preparation of geopolymer mortar samples, GGBS, LS and SF were added with alkaline activator to replace cement. A lot of trial mixes were prepared to figure out the best proportions. The properties of mortar samples were examined based on the various combinations of binder components.

2.1 Fine Aggregate:

EN 196-1 sand is used as fine aggregate, an artificial substance of many distinct sand type fractions. Generally, particles have an isometric and rounded profile. It is dried, filtered, and processed in a modern workshop to ensure the desired consistency and quality. The precise grain size distribution of CEN-Standard Sand is one of its distinguishing features. The maximum moisture content is 0.2%. 1,350 (5) g of EN-Sand is portioned in one bag. The grading of EN-Sand is given in the following Table-1

Table-1: Grading of EN-Standard Sand

Sieve Size	Weight, g	Cumulative Weight, g	% Cumulative Weight
#16	97	97	22.1
#30	131	228	52.1
#50	137	365	83.3
#100	73	438	100
#200	62	500	---
Fineness Modulus			2.57

Fig 1: EN-196-1 Standard Sand

2.2 Ground Granulated Blast Furnace Slag (GGBS):

Ground Granulated Blast Furnace Slag (GGBS) is produced as a byproduct during the manufacturing process of iron from iron ore, coke, and limestone in a blast furnace. The molten slag goes through rapid cooling with high pressure, drying and grounding and converting into a very fine powder called GGBS [20]. In this study, GGBS is used as 50-70% replacement of binder in mortar sample. Used GGBS is collected from the local cement industry. Pulverized GGBS used in the study is shown in Fig. 2.

Fig 2: Ground Granulated Blast Furnace Slag

Physical and Chemical Properties of GGBS:

Blast furnace slag is a product comprising alumino-silicate, silicate of Calcium and many other bases [21]. It has both crystalline and glassy phases. Glassy phases help to improve cementitious properties. Depending on the source materials composition in the production process of iron, the physical and chemical properties of GGBS varies. The chemical properties of GGBS are given in Table-2.

Table-2: Chemical Properties of GGBS

Chemical Composition	GGBS (%)
SiO_2	33.4
Al_2O_3	14.3
Na_2O	0.2
K_2O	0.3
CaO	41.1
MgO	3.9
TiO_2	0.6
P_2O_5	0.1
SO_3	2.6
Fe_2O_3	0.6
Loss on Ignition	0.1

2.3 Ladle Slag:

Ladle slag is a byproduct obtained from refining molten steel after coming out of an electric arc furnace (EAF). LFS has a high calcium and magnesium oxide content while having a low ferrous oxide content.

The other major oxides are silicon and aluminium oxides, which account for less than 40% of the overall weight. According to previous research, ladle slag fines have a substantial cementitious property [22]. In this study, ladle slag was used 20- 30% of the total binder. The material is shown in Fig 3.

(a) Physical (b) SEM image

Fig 3: Ladle Slag

Physical and Chemical Properties:

Ladle slag is an inhomogeneous material obtained in a whitish dusty form. Grains of ladle slag is partly dense, partly pours and sharp-edged. It has both isolated round-shaped pores as well as some capillary pores. The solubility of most mineral phases of ladle slag in the water is exceptionally low, and thus it does not affect the environment. Ladle slag can be disposed of at nonhazardous waste disposal site, as it contains no harmful components for the environment. It can be used as a cementing material because of its increased fineness. The chemical properties of Ladle slag are shown in Table-3

Table-3: Chemical Properties of Ladle Slag

Chemical Composition	Ladle Slag (%)
SiO_2	25.0
Al_2O_3	12.3
Na_2O	0.4
K_2O	0.4
CaO	46.4
MgO	4.3
TiO_2	0.2
P_2O_5	2.7
FeO	1.5
Cr_2O_3	0.7
Loss on Ignition	1.1

2.4 Silica Fume:

Silica fume is a highly pozzolanic substance obtained as a byproduct of the ferrosilicon, improving the mechanical and durability properties of concrete [23]. The main physical consequence of silica fume is that it acts as a filler. In addition, it can fit between the cement grains because of its fineness. In this study, silica fume has been used in the range of 10-20% of the binder.

Fig 4: Silica Fume

Physical and Chemical Properties:

The colour of silica fume powder is usually grey. However, varying sources can give different colours. Furthermore, the colour of the powder can be influenced by the quality of metal produced and raw materials. Generally, silica fume contains at least 85% silica. Mean particle size ranges within 0.1 - 0.2 micron. It is spherical and widely used in mortar and concrete production due to its fineness properties [24]. The chemical properties of silica fume are given in Table-4

Table-4: Chemical properties of Silica fume

Chemical Composition	Silica Fume (%)
SiO_2	89.0
Al_2O_3	0.5
Na_2O	0.2
K_2O	1.1
CaO	0.9
MgO	1.6
SO_3	0.4
Fe_2O_3	1.5
Loss on Ignition	2.9

2.5 Alkaline Activator:

In this study combination of Na_2SiO_3 solution and NaOH solution is used as an alkaline activator. Sodium Silicate solution having 30% SiO_2, 14% Na_2O and 56% H_2O in its chemical composition. Solution of Sodium Hydroxide is prepared by dissolving the NaOH flakes into distilled water to obtain the desired strength and allow them to cool down at room temperature. The concentration of NaOH solution was varying from 4M to 8M. The mass ratio of sodium silicate to sodium hydroxide is 2.5; the mass ratio of alkaline liquid to binder is 0.45.

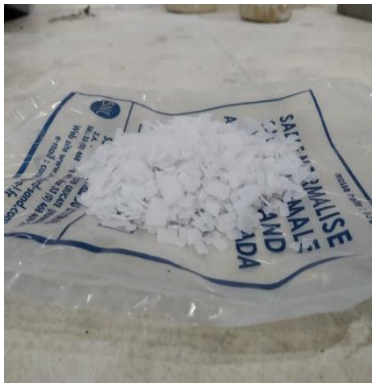

Fig 5: Sodium Hydroxide

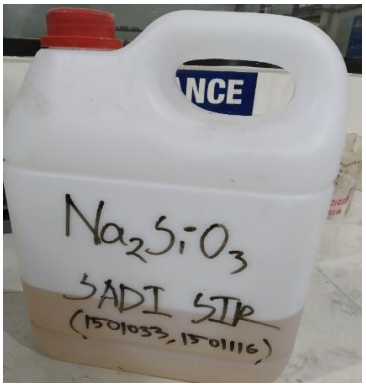

Fig 6: Sodium Silicate

3. Methodology:

3.1 Preparation of Alkaline Activator:

The alkaline activator solution was prepared by mixing sodium hydroxide and sodium silicate. First, the concentration of Sodium Hydroxide varying from 4-8M was prepared by dissolving the NaOH flakes in 1L distilled water to get the desired strength of the solution. The solution was kept for 2 hours and allowed to cool down. After preparing the solution, Sodium Silicate was added to maintain the SS/SH ratio of 2.5.

3.2 Mixing of Materials:

Various standard methods as per demand can prepare geopolymer mortar. The dry materials (EN sand, GGBS, LS, SF) and the alkaline activator were added on by one in the mortar mixture machine. The literature review found that about 7-20% of water can be added as per requirement. So, an extra 13-17% water was added based on the molarity of sodium hydroxide to maintain a balanced liquid proportion in the mortar samples. Finally, all the materials were mixed in the mixture for about 3 minutes with 180 rotations of the paddle. After mixing, the workability tests were done immediately using the flow table apparatus. The flow value was taken for each mixture.

(a) Mortar Mixture Machine

(b) Material Mix

(c) Workability Test of Mortar

Fig 7: Mixing of Materials

3.3 Casting and Compaction:

A total number of 216 nos 40×40×160mm mortar sample were prepared using different combinations. The used mold was properly jointed and oiled with kerosene in between the joints and contact the face of mold to ensure zero escape of water while filling. After oiling, the prepared mixtures were placed in the iron mold in two equal layers. The mold was placed in a jolting machine for the purpose of compaction. Each layer received 60 vibrations for proper compaction. After compaction, a steel trowel was used for giving a smooth finishing to the upper layer.

(a) Jolting Machine

(b) Iron Mold

(c) Cast Sample

Fig 8: Casting and Compaction of Mortar Samples

3.4 Curing:

After finishing compaction, one set of geopolymer mortars specimens were kept in the oven for 24hours at 60^{o}C, one set at 80^{o}C and a remaining set was kept at ambient temperature (25-30^{o}C). In geopolymer, mortar curing conditions play a significant role in intensifying the chemical reaction of materials and improving compressive strength. Heat curing fastens the rising rate of compressive strength initially. Before placing in the oven, the mold was covered with thin transparent plastic sheets to confine the moisture contents of the specimen. The mold was taken out from the oven after 24 hours of heat curing and allowed to cool down at room temperature to avoid the sudden variation in temperature. Later specimens were removed from the mold, and to determine the mass density the weight of each sample was taken. 3days and 7days strength were tested by using compressive strength testing machine.

(a) Wrapped Molded Sample

(b) Unmolded Mortar Sample

Fig 9: Curing of Mortar Specimens

4. Mix Proportion:

Geopolymer is a new material used in modern days of construction. No specific standards are found for the mix proportions of geopolymer. Among the many elements included in geopolymer, this research study involves slag, silica fume, sand and alkaline activators. According to the literature review, the mortar samples were prepared by maintaining a fixed standard ratio of the materials and following the conventional design procedure. Besides, the binder samples were varied by changing the proportion of each component for obtaining different test results. The binder combinations are designated as G70LS20SF10, G65LS20SF15, G60LS20SF20, G60LS30SF10, G55LS30SF15, and G50LS30SF20.

Quantity of Material per mold:

Mortar size = 40mm×40mm×160mm

Volume = (40X40X160/1000) m^3

Volume of 3 blocks = (3 ×1/8000) m^3

Assuming, wet mortar density = 2200 kg/m^3

Wet mortar weight = (3/8000 × 2200) =0.825 kg

For converting the wet mortar weight into dry weight, 2.5 is taken for safety and lack of a standard.

Weight of dry mortar = (0.825 × 2.5) = 2.062 Kg

Ratios maintained:

Sand: Binder =2.75

Alkaline solution: Binder =0.45

Sand: Alkaline solution: Binder =2.75:0.45:1

Sand =1350g

Binder =491g

Alkaline solution =221g

Na_2SiO_3:NaOH =2.5:1

NaOH=61g ; Na_2SiO_3=160g

Table-5: Mix Proportion of mortar sample

Binder Combination	Ground Granulated Blast Furnace Slag		Ladle Slag (LS)		Silica Fume (SF)	
	(%)	(gm)	(%)	(gm)	(%)	(gm)
G70LS20SF10	70	343.7	20	98.2	10	49.1
G65LS20SF15	65	319	20	98.2	15	73.65
G60LS20SF20	60	294.6	20	98.2	20	98.2
G60LS30SF10	60	294.6	30	147	10	49.1
G55LS30SF15	55	271	30	147	15	73.65
G50LS30SF20	50	245.5	30	147	20	98.2

5. Experimental Programme:

5.1 Flow Table Test:

Workability is a property of mortar that affects strength performance. For a mortar to be workable, it must be compacted, placed and set properly to avoid segregation. The workability test was done following ASTM-C 1437-07. The workability of mortar sample is generally performed right after mixing by using a flow table. At first, the cone-shaped mold was positioned on the flow table center, and then the mold was filled with a considerable amount of mortar sample uniformly. The top of the placed mortar was levelled to a plane surface by drawing the edge of the trowel across the top of the mold. After that, the mold was uplifted from the mortar and immediately, the flow table was dropped 25times in 15 seconds manually by the machine. The mortar sample was spread over the table spherically, and the diameter of the spread mortar was measured. Depending on the obtained flow value, geopolymer mortar workability can be classified as high, moderate and stiff.

(a) Flow Table

(b) Mold filled with mortar

(c)Mortar after lifting the mold

(d) Spread mortar

Fig 10: Flow Table Test

5.2 Unit Weight:

Unit weight of materials is the weight per unit volume used in the determination of weight of a structure designed to carry the specific load while remaining within limits regarding deformation. The unit weight of the mortar samples was calculated according to ASTM C138 for a comparative analysis between the samples with different binder combinations. In our study, the volume of iron mold was 40x40x160mm. At first, weight of the empty mold was taken. After that, weight of mold and mortar sample together was taken. The unit weight was then calculated with the observed weight, using the equation given below:

$$Unit\ weight = (W_f - W_e)/V$$

Where,

W_f = Weight of mortar filled mold, kg

We= Weight of empty mold, kg

V= Mold volume, mm^3

5.3 Compressive Strength Test:

Compressive strength is a significant property of materials that measures the material capacity to withstand load and indicates the performance and overall quality of mortar. A compression testing machine was used to measure the strength, and ASTM C109/C109M was followed to conduct the test. The test was done after 3 and 7 days of curing each sample. At first, the cured sample was placed so that the cast face was not in contact with the loading plates, and gradually load was applied. The dial reading of the machine was taken when the samples failed completely under the action of load, and the values were noted for further calculation. From the definition of uniaxial stress, compressive strength was estimated using the equation given below:

$$Compressive\ Strength,\ \sigma = Force/Area$$

Where,

F= Calibrated Load (N)

A= Block area, mm^2

σ= Stress, N/mm^2

The calibrated load was calculated from the observed load. The attached equation with the compressive strength testing machine was used for calculation.

The calibrated equation is:

$$Calibrated\ Load\ (KN) = 1.010 \times Observed\ Load - 15.903$$

(a) Compression Device for Mortar

(b) Compression Testing Machine

(c) Crushed Mortar Sample

Fig 11: Compressive strength test

6. Result and Discussion:

6.1 Workability:

The workability of a mix is classified based on the flow diameter. The minimum flow diameter of 150±5 mm is convenient for placing and compacting the mixture in mold [25]. Flow test results are given in Fig 12. In the mortar preparation process, 13, 15 and 17% excess water was added for 4M, 6M and 8M samples. In general, the flow diameter was found to be within 130-155mm. The samples having workability within this range is defined as moderately stiff [25]. With the increase in activator strength (4-8M), the change in flow value was not significant but was found within the expected range. On the other hand, the binder components used in the sample has a significant influence on the workability. A study [26] indicated increasing slag content in geopolymer mortar can reduce the flow. A higher quantity of LS (G50L30S20) in the combination could also impair the flow. The optimum flow was obtained with 60% GGBS, 20% LS and 20% SF samples. As the amount of excess water applied was increased with the concentration of the activator, the flow value seemed to be in a reasonable range. In general, the use of slag within a limited range and silica fume within 15-20% gives a better result.

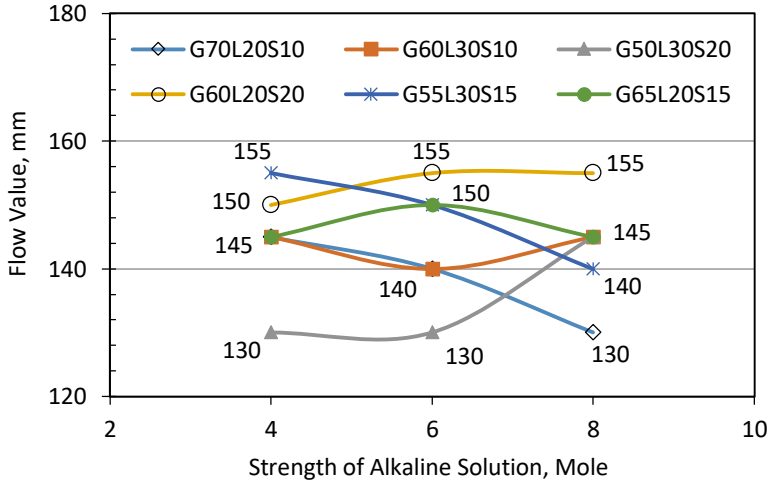

Fig 12: Variation of flow with strength of the alkaline solution

6.2 Compressive Strength:

Compressive strength is a significant property of mortar. For geopolymer mortar, the strength of the binder has a consequential effect on the characteristics of the mortar mix both in the fresh and hardened state. The heat curing of all the specimens helped them to gain the initial compressive strength faster. The following graphs show the correlation between the compressive strength with variation of binder combination, Strength of Alkaline Solution, Curing Temperature, and Curing Age. Plastic wrappers have been used to ensure a lower amount of moisture loss from the mold. No extra water was added to the mortar mixing process.

Table-6: Compressive Strength tests result

Binder Combination	Si/Al ratio	Strength of Alkaline Solution, mole	Flow, mm	Compressive Strength, MPa					
				30°C		60°C		80°C	
				3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
G70LS20SF10	2.98	4M	145	27.83	30.34	30.41	32.23	28.35	34.38
		6M	140	34.2	38	35.88	39	38.6	41
		8M	130	34.51	37.27	35.14	38.28	28.46	31.59
G65LS20SF15	3.39	4M	145	23.01	24.67	25.01	26.83	25.71	29.71
		6M	150	36.22	38.16	38.21	42.96	43.69	46.12
		8M	145	28.56	32.86	30.63	34.12	38.87	42.33
G60LS20SF20	3.85	4M	150	36.71	39.21	38.51	42.35	44.51	46.77
		6M	155	38.63	42.62	42.36	46.12	45.17	48.76
		8M	155	35.16	39.17	37.69	43.59	44.79	47.37
G60LS30SF10	2.96	4M	145	30.35	32.56	34.35	36.01	35.83	37.9
		6M	140	25.29	28.62	26.53	29.7	28.41	31.29
		8M	145	34.25	37.28	26.55	30.34	28.61	30.96
G55LS30SF15	3.37	4M	155	26.38	28.62	28.23	30.71	32.01	36.86
		6M	150	34.65	36.48	35.65	40.12	42.36	45.27
		8M	140	26.01	27.18	28.47	32.23	33.24	36.02
G50LS30SF20	3.84	4M	130	35.35	38.28	36.71	41.38	42.38	46.11
		6M	130	31.07	33.17	35.25	37.91	38.26	42.57
		8M	145	26.21	29.07	36.19	41.69	38.67	43.59

Effect of Curing Temperature:

Fig 13 gives the variation in compressive strength of different binder combination with variation in curing temperature for different strength of the alkaline solution. In this study, all the samples were cured in the oven at 60°C and 80°C for 22-24h, few hours after casting to compare with those cured without elevated heat (25-30°C). Although curing at high temperatures provides high early strength [26], heat curing may not be available for cast in situ construction. Nevertheless, the same mixture can be cured at ambient temperature to achieve reasonable strength gradually over age. With a little exception, all the samples' compressive strength was influenced by curing temperature. In general, a positive trend was noted with temperature rise. However, the strength increase rate was more for 60°C heat curing compared to 80°C. For example, sample G60L20S20 gave the highest compressive strength (46.8, 48.8 and 47.4 MPa) with curing at 80°C regardless of activator strength.

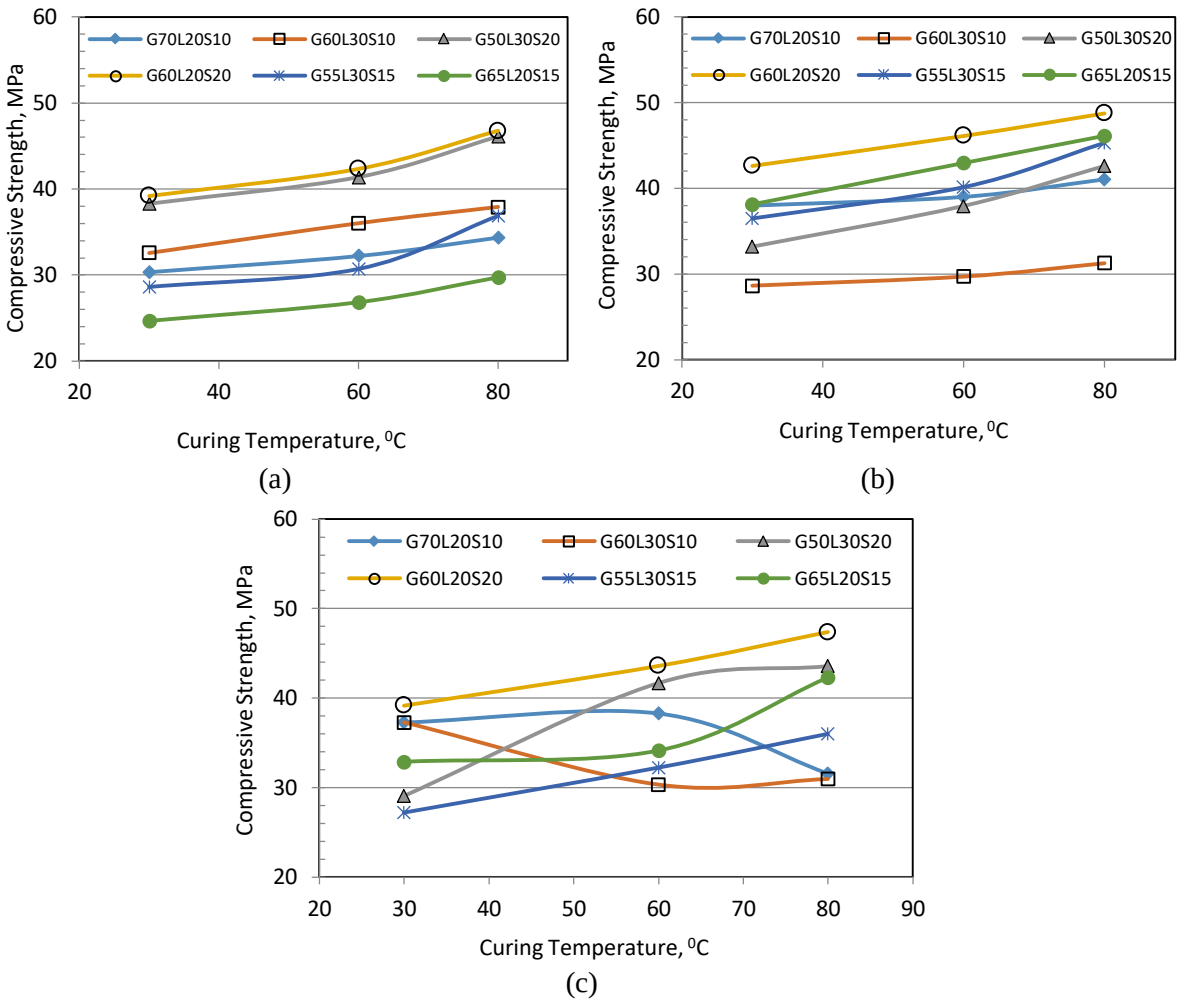

Fig 13: Strength vs. curing temperature (a) 4M NaOH, (b) 6M NaOH and (c) 8M NaOH

In this case, the compressive strength of samples with 4M, 6M and 8M was remarkably similar, indicating the effect of temperature curing on silica fume and GGBS is significant. In contrast, the samples with 10% SF and 30% LS gave relatively much lower compressive strength and again supported the earlier conclusion that the effect of temperature on GGBS and SF is significant. As the amount of GGBS increases in the binder, the compressive strength decrease for both 20% and 30% LS using 4, 6 and 8M alkaline solution. In LS content, better results are found at 30% LS for each percentage of GGBS using a 4M alkaline solution. In comparison, samples with 6M and 8M activator increased compressive strength at 20% LS. The variation of compressive strength is similar for each curing temperature.

Effect of Strength of Activator:

The strength of the alkaline solution is an essential parameter in evaluating the strength of the mortar. In this study, the alkaline activator is a combination of NaOH and sodium silicate solution. Keeping the amount of sodium silicate fixed, 4M, 6M and 8M molarity of sodium hydroxide was used to observe

the influence of the activator on compressive strength. As shown in Fig 14, compressive strength increases around 25% as the strength of the alkaline solution increases from 4M-6M. However, in some cases, the strength decreased (12% in the extreme case) further while the activator concentration increased from 6M to 8M. Therefore, a 6M alkaline solution was found to be optimum for these ternary combined geopolymers.

In the case of 4M alkaline solution, as the percentage of LS increases from 20-30% for the samples with 10% and 15% silica fume, strength increases. However, while the share of silica fume reaches 20%, strength reduces slightly. For samples using 6M and 8M alkaline solutions, ladle slag increases from 20-30% compressive strength decrease for all samples. However, an increase in silica fume up to 20% gives the highest compressive strength for each concentration of the alkaline solution.

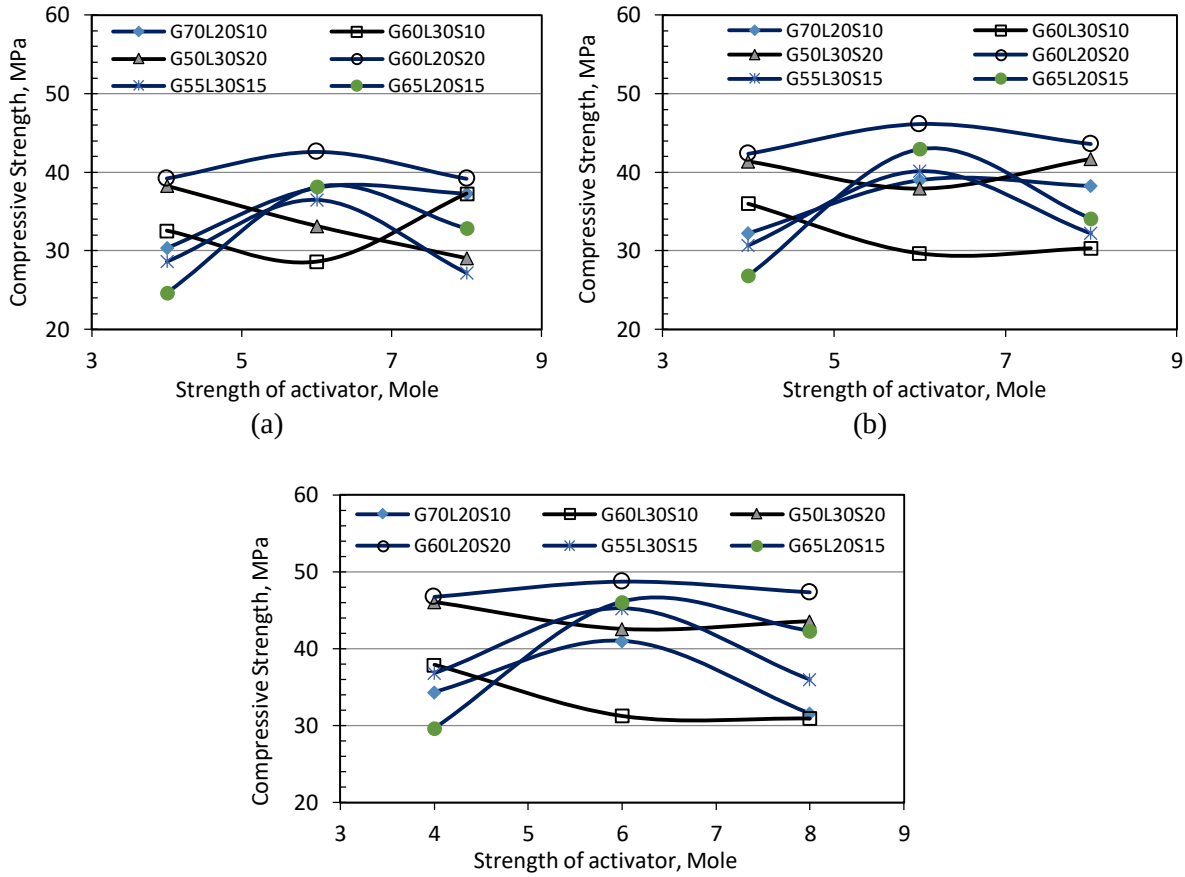

Fig 14: Compressive Strength vs. Activator Concentration at (a) Ambient, (b) 60°C and (c) 80°C

With the 4M alkaline Solution, an increase in GGBS content from 50-60% for 20% SF samples increased the compressive strength. However, with a further rise in GGBS content from 60-70% for 10-15% Silica fume samples a gradual strength reduction was observed. For both 6M and 8M alkaline solutions, an increase in GGBS content from 50-70% increased the compressive strength with all three different percentages (10, 15, and 20%) of SF. A maximum of 20% SF yields the highest compressive

strength for each molarity of the alkaline solution and curing condition. Therefore, the results can be summarized as an increase in alkaline solution strength helps GGBS perform effectively as a binder.

Effect of Curing Age:

The effect of curing age (3 to 7 days) on the strength development of geopolymer mortar is given in Fig 15. Tests were performed on three sets of specimens cured at ambient, 60°C and 80°C temperature. After 24 hours' heat curing in the oven at 60°C and 80°C temperature, the ambient temperature was maintained for the remaining period until the compression test. The increment in compressive strength with time was found to be ranged between 4.8-21.3%.

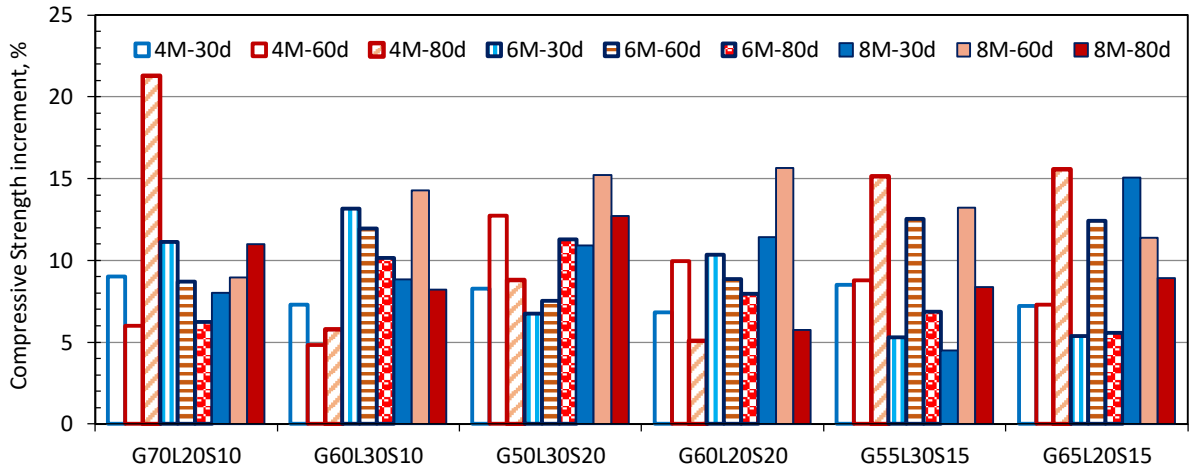

Fig 15: Compressive Strength Increment of mortar samples from 3 days to 7 days

For the set initially cured for three days, almost 92-96% of the ultimate strength (7 days) gain was found. The heat curing influenced mortar samples with all binder combinations for gaining high compressive strength at an early age. The increase in strength further continued up to 7days. On average, a 10% increment was found between 3 and 7 days. A study [27] indicated high temperatures significantly influence the compressive strength of geopolymer mortars.

Effect of Silica Alumina Ratio:

The silica/alumina ratio has a significant influence on the strength of geopolymer mortar. A study [28] indicated compressive strength generally increases with Si content, although the increment is not linear. Theoretically, the bond between Si-O-Si is stronger than the Si-O-Al and Al-O-Al, which means that the strength increases with increasing Si/Al ratio [28] . The lower compressive strength occurs due to the delay of geopolymerization process for low Si/Al. Fig 16 gives the Si/Al ratio with compressive strength. In general, the compressive strength was increased with Si/Al ratio for varying curing conditions and alkaline concentration.

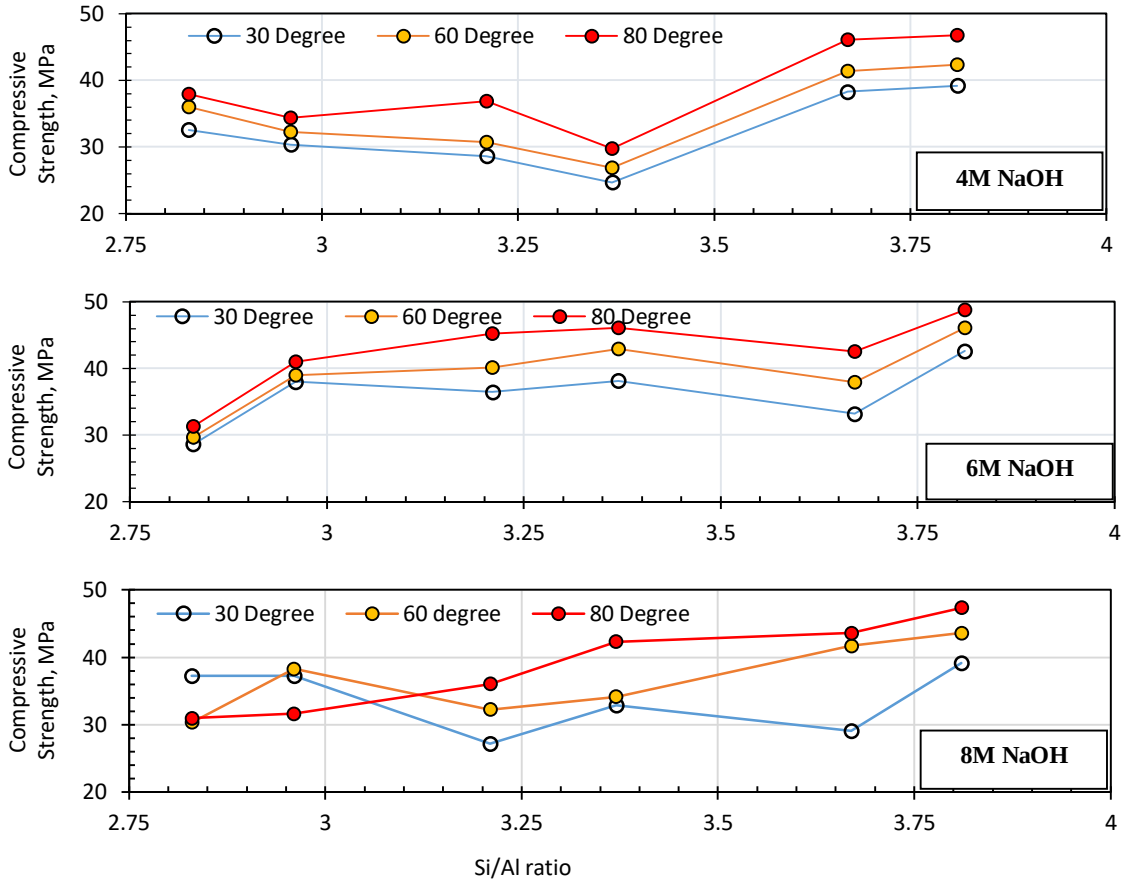

Fig 16: Variation in Compressive Strength with Si/Al ratio

6.3 Variation of Weight:

Weight variation was observed between six different binder combinations of geopolymer mortar samples. Variation in weight occurred due to weight gain or weight loss. Heavier compound reactant formation, water absorption, mortar expansion, and salt deposition in the mortar pore may result in mortar weight gain. On the other hand, weight loss occurs because of drying shrinkage of mortar or lighter compound reactant formation. The highest weight observed for the G60L20S20 binder combination from Fig 17.

Table-7: Variation of the weight of different specimens (8M Alkaline solution)

Binder Combination	Weight, W1 in gm	Weight, W2 in gm	Weight, W3 in gm	The average weight at 7 days curing, gm
G70L20S10	588	572	570	575.3
G60L30S10	577	592	583	584
G50L30S20	584	581	572	579
G60L20S20	593	584	590	589
G55L30S15	578	572	575	575
G65L20S15	580	586	593	586.33

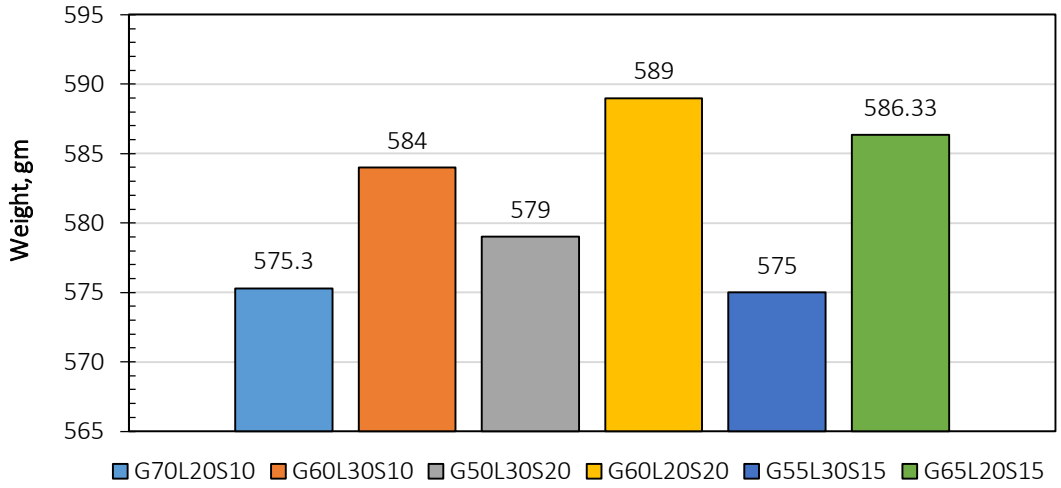

Fig 17: Variation of weight with different binder combination at 7 days

6.4 Cost Estimation:

A comparative analysis has been shown between traditional cement mortar and slag based geopolymer mortar. The comparative analysis shows that cost of geopolymer mortar is relatively higher than conventional cement mortar. However, although the price is slightly higher, geopolymer mortar being prepared from industrial wastes provides carbon saving and effective utilization of waste materials.

Table-8: Comparison between the cost for the preparation of 100 cft of cement mortar and geopolymer mortar (binder only)

Geopolymer Mortar					**Cement Mortar**				
Material	Quantity	Unit	Cost (Tk)	Cost (US $)	Material	Quantity	Unit	Cost (Tk)	Cost (US $)
GGBS	1090kg	Tk 3/kg	3270	38.57	Cement	30 bags	Tk 500/bag	15000	176.95
Ladle Slag	360kg	Tk 2.5/kg	900	10.62					
Silica Fume	360kg	Tk 7/kg	2520	29.73					
Sodium Hydroxide	220kg	Tk 22/kg	4840	57.10					
Sodium Silicate	590kg	Tk12/kg	7080	83.52					
Total			**18610**	**219.53**	**Total**			**15000**	**176.95**

7. Conclusion:

This paper reported the experimental data obtained from the workability and compressive strength tests. Therefore, the conclusions of the study may be reported as follows.

- A high concentration of alkaline media can interface with the workability of geopolymer mortars and need to use excess water.
- The compressive strength of mortar is increased about 10% on average from the initial to final curing period.
- The compressive strength of mortar increased with the rise in curing degree. The increasing rate was more at 60^{o}C compared to 80^{o}C.
- A Higher Si/Al ratio stimulated the geopolymerization process and improved compressive strength.
- The highest compressive strength was found to be 48.8 MPa using 60%, 20% and 20% GGBS, LS and SF, respectively, with a 6M alkaline solution and 80^{o}C temperature.

Considering the results obtained in this study, the proposed ternary blended industrial byproducts-based binders could be sustainable construction materials through the safe management of industrial wastes.

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