Research Article

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Production of geopolymer mortar reinforced with sustainable fibers

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Abstract: Geopolymer has been presented as new evolution in the concrete technology world, where cementitious materials such as ceramic powder and Slag have been replaced by high percentages of cement used in construction. Thus, the activation of such materials was performed by highly alkaline solutions in order to be acted as a binder in the mix. Therefore, the selection of suitable ingredients proportion of geopolymer mortar to achieve desired strength at required workability has been intended in this study. The experimental Program has been implemented for the preparation of geopolymer mortar mixes. The concentration of sodium hydroxide solution was kept constant in the order of 12 M throughout the experiment. The ratio of Water to geopolymer binder ratio was 0.35, alkaline solution-to- cementitious materials ratio was 0.30 and sodium silicate-to-sodium hydroxide ratio was 1.85 by mass. Workability of geopolymer mortar was measured by flow table apparatus and cubes of 50 mm side were cast and tested for compressive strength after 28 days of normal water curing. The study concludes that the combination of ceramic powder and Slag up to 40% (by weight), in the total binder material, can be used for developing the geopolymer mortar. Continuously, the use of 1% steel fibers or 1% steel fiber with 0.5% sisal fibers promotes the level of cement replacement by such cementitious materials (slag and ceramic powder) up to 60%.

Keywords: ceramic powder, slag, geopolymer, mortar, strength, sustainable fibers

1 Introduction

For the last two decades, the increased demand to design and produce green or eco-friendly materials remarkably contributed to develop substitutes for Portland cement, researches on environmentally friendly along with ways of by-products and reusing industrial waste materials. Therefore, geopolymer materials have exhibited a great interest and are still raising their popularity in the field of building and construction industries [1–4].

And for reducing the pollution which evolves from the constructional activity and by-products generated by manufacturing industries, such pollution is continued to become a big concern to the research fraternity across the world. In most of the construction activities, ordinary Portland cement is employed regularly and the increase in its usage is resulting in large amount of CO₂ emission. As cement industry accounts for 5-7% of global CO₂ emissions, looking for alternatives to cement based binders is the need of the hour. On the other hand, many industrial wastes such as fly ash, red mud, slag, ceramic powder, mine tailings, etc., whose generation only are increasing drastically, but not their utilization levels. Therefore, it is inevitable to minimize or utilize the solid industrial waste, due to their serious negative impact on geo environment. Equally, devising novel methods for beneficial use of different wastes is also challenging because their composition invariably differs from a marginal to a considerable extent from waste to waste. In this regard, geopolymer binders are found to be a promising option and reported to be effective. The various industrial wastes as mentioned above are highly suitable for producing geopolymers because most of them are rich in aluminosilicates. The geopolymerization process that are performing of geopolymers of alumina and silica species in the raw material reacting with highly alkaline activator solutions to produce a three-dimensional polymeric chain and ring type structure consisting of (Si-O-Al-O) bonds [4]. Significant numbers of researches on geopolymer materials exhibited great performance that such materials can be suitable for the structural applications, with a workable slump, and compa-

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able grade of strength to ordinary Portland cement concrete [5–9].

Adding fibers to the mortar or concrete can greatly enhance the mechanical properties of such materials [5]. Many studies [9–14] have reported significant advantages due to the use of different fibers in the cement mortar or/and concrete.

Problem statement

Thousands of tons of the waste materials (that can be recycled and reused) fill our city's landfills. The accumulation of waste materials will affect human's health and the appearance of the city. Thus, we must reduce these waste material in different ways. One of these ways is that we use some of these waste materials in the construction.

Since our planet has a limited supply of natural resources, the increase of the rate of population will increase the demand on the natural resources as well as, the global concrete usage is second only to water. The demand for Portland cement increases due to the great demand for concrete as construction materials. The cement industry is held responsible for some of the CO₂ emissions and the climate change due to global warming and environmental protection has become major concerns. Some of the cement proportion in concrete mixes must be exchanged by using the waste material such as slag or ceramic powder or both of them.

The emission of greenhouse gases to the atmosphere by human activities leads to global warming such as carbon dioxide (CO₂). Thus, CO₂ contributes about 65% of global warming. Because the production of one ton of Portland cement emits approximately one ton of CO₂ into the atmosphere, the environment must be protected by preventing dumping of waste/by-product materials in uncontrolled manners [4].

Objectives

1. Design the control concrete mortar mix that is used to product geopolymer concrete.
2. Study the physical and mechanical properties for the control geopolymer concrete mix by the inclusions of different percentages of slag and ceramic powder.
3. Produce the geopolymer concrete using the selected concrete mix that gives the best properties.

2 Materials

2.1 Cement

Ordinary Portland cement (OPC) was used in this study was Produced by "Badoush factory", which conforms to ASTM C150 [15] and it is suitable for use in general concrete construction. The chemical, physical and mechanical properties are provided in Tables 1 and 2.

Table 1: Chemical composition of Portland cement

	ASTM C150	Results
LOI	Not exceed 4	1.4
"Loss on ignition"		
SO ₃	Not exceed 2.8	2.49
Mgo	Not exceed 5	2.75
LSF	1.02-0.66	0.87
IR	Not exceed 1.5	0.36

Table 2: Physical and mechanical properties and specification of Portland cement

Physical and mechanical properties	Test results	ASTM C150.
Compressive strength		
3 days, MPa	22	15 (min)
7 days, MPa	31.5	23 (min)
Soundness (Auto clave method)	0.1	0.8% (max)
Setting time (vicat's apparatus)		
Initial setting, min:	160	00:45 (min)
Final setting, hrs.	3:25	10 hrs (max)
Specific surface area	325	230 (min)
Blaine method, m ² /kg		

2.2 Fine aggregate (sand)

Good quality locally available river sand from (Kanhash Quarry) was used in this study. The specific gravity and fineness modulus of the sand used here are 2.62 and 2.76, respectively.

2.3 Superplasticizer

Is the chemical admixture used to reduce (water/cement ratio) in concrete mixes. superplasticizer reduces the amount of required water to make workable mortar and concrete. Hyperplast PC200 (Formerly known as Flocrete PC200) has been used in this study. Hyperplast PC200 complies with ASTM C494, Type A and G, [16] depending on dosage used. It has been manufactured by Don Construction Products. The technical data for this admixture is depicted in Table 3.

Table 3: Physical properties of superplasticizer

Items	Technical properties @ 25°C
Color	Light yellow liquid
Freezing point	$\approx -3^{\circ}\text{C}$
Specific gravity	1.05 ± 0.02
Air entrainment	Typically less than 2% additional air is entrained above control mix at normal dosages

2.4 Ceramic waste powder

It is a powder of local ceramic (traditional) was used in this study. Powder must be passed from sieve No.325 (0.045 mm). The chemical compositions of the ceramic powder used in this study are shown in Table 4.

Table 4: Chemical composition of ceramic powder

Compositions	Results
SiO ₂	63.29
Al ₂ O ₃	18.29
Fe ₂ O ₃	4.32
CaO	4.46
K ₂ O	2.18
Na ₂ O	0.75
MgO	0.72
P ₂ O ₅	0.16
Mn ₂ O ₃	0.05
CL	0.005
SO ₃	0.10
Loss on Ignition	1.61

2.5 Slag

Slag from the iron and steel industries used in this study, slag must be passed from sieve No.325 (0.045 mm). The chemical compositions of the slag used in this study are listed in Table 5.

Table 5: Chemical compositions of Slag

Compositions	Results
SiO ₂	31.65
Al ₂ O ₃	7.4
Fe ₂ O ₃	16.3
CaO	33.50
MgO	6.7
SO ₃	1.1
Loss on ignition	2.2

2.6 Mixing water

Ordinary potable water destined for drinking was used in this study and was free of soluble salts and organic materials.

2.7 Alkaline liquid

Generally alkaline liquids were prepared by mixing each of the sodium hydroxide solution with sodium silicate at room temperature. Then, the resultant solution have been started to react *i.e.* (polymerisation takes place). Such reaction liberates large amount of heat so it has been left for about 24 hours, thus the alkaline liquid has been considered ready as binding agent.

Sodium-based solutions were utilized as they are cheaper than that of Potassium-based solutions. The sodium hydroxide (NaOH) solution was prepared by dissolving either the flakes or the pellets in water. The NaOH mass solids in a solution may remarkably be varied depending on the concentration of the solution expressed in terms of molar, M. For instance, NaOH solution with a concentration of 12 M consisted of $12 \times 40 = 480$ grams of NaOH solids (in flake or pellet form) per liter of the solution, where 40 is the molecular weight of NaOH [4].

2.7.1 Sodium hydroxide

The solid state of sodium hydroxides is widely available whether of pellets and flakes form. Their cost is mainly varied according to the purity of the substance. The geopolymer mortar is a homogenous material and such material is the main process to activate the sodium silicate. It is preferred to use the lowest cost “i.e. up to 94% to 96% purity” [4].

In this investigation, the sodium hydroxide pellets in 12 molar concentrations were used. The technical data related to physical properties are given in Table 6.

Table 6: Physical properties of sodium hydroxide

Color	Colorless
Specific gravity	1.47
PH	14

2.7.2 Sodium silicate

The compound sodium metasilicate which its common name is sodium silicate is used in this study. Water glass or liquid glass is also referred to Na_2SiO_3 . Such material is abundant in sold form or aqueous solution. The molten sodium carbonate and silicon dioxide will be reacted. In present investigation aqueous sodium silicate solution was used. Silicates as bonding agent were supplied by the manufacturer to the detergent company and textile industry. Same Sodium silicate was used for the making of geopolymer mortar [4]. The physical properties of Sodium silicate are shown in Table 7.

Table 7: Properties of sodium silicate

Color	Colorless
Density at 20°C (gm/cm^3)	1.706
Na_2O %	17,98
SiO_2 %	36,14
Solid material	54,12

2.8 Sisal fiber

Sisal fibers are fully biodegradable, green composites were fabricated with soy protein resin modified with gelatin.

Sisal fibers, modified soy protein resins, and composites were characterized for their mechanical and thermal properties. The chemical compounds are listed in Table 8.

Table 8: Chemical composition of sisal fiber

Compounds	Percentage
Cellulose	65%
Hemicelluloses	12%
Lignin	9.9%
Waxes	2%
Total	100

2.9 Steel fibers

Steel fibers are significantly used as a reinforcing material of concrete or mortar, which provides certain advantages compared with traditional reinforcement. Majix round crimped steel fibers were used in this study. The properties of such fibers are shown in Table 9.

Table 9: Specification of the steel fibers

Properties	Results
Length	13 mm
Diameter	0.2 mm
Aspect ratio	65
Tensile strength	2500 MPa

3 Mix design and process

For 12 M NaOH solution preparation, 480 grams of NaOH pellets have been dissolved in distilled water in a one liter-volumetric flask obtaining 12 M solution. The NaOH solution was kept for settling down up to 24 hours. After 24 hours, NaOH and Na_2SiO_3 solutions were mixed. The mixture was left for settling down up to few hours. Hence, for safety factor, hand gloves were used. The slag, ceramic powder, cement and sand were mixed in dry form. Then, alkaline activator has been added to the dry mix and wet mixing is done for about 3 to 4 minutes. Lastly, steel fibers were added to the wet mix.

3.1 Compressive strength

The compressive strength test was determined according to (C 109/C 109M) [17]. The specimens were tested using testing machine in the laboratory with capacity of 2000 Kn, using three Cube Specimens for each test.

Determine the compressive strength of concrete specimen as follows:

$$\text{Compressive strength (psi, kg/cm}^2, \text{ N/mm}^2) = P/A$$

where: P = the maximum force required for failure (lb, kg); and A = the cross-sectional area (in², cm², mm²).

3.2 Flexural strength

This test was done according to ASTM C 348 [18], by using prisms 40 × 40 × 160 mm. Simply supported prisms with one point loading using compressive strength test machine

Calculations

Calculate the flexural strength of the specimen as follows:

$$R = [3 \times P \times L] / [2 \times b \times d^2]$$

Where:

R = modulus of rupture in (kg/cm², psi, N/mm²) units.

P = maximum total applied load on the beam in (kg, lb).

L = span length (clear span) of specimen, (cm, in).

b = average width of specimen at the fracture, (cm, in).

d = average depth of specimen at the fracture, (cm, in).

3.3 Tensile strength

Standard test method for tensile strength of hydraulic cement mortars (CRD-C 260-01) [19]. This test method allows for the determination of tensile strength of a hydraulic cement mortar by casting and testing briquette specimens.

3.4 Density and absorption

This test is done according to ASTM C642 [20]. At the age of 28 days Three cubes (100mm) were taken from the tap water tank. After removing the samples, surface dried with a towel and weighed. Finally, the cubes were keeping in

oven (105±5°C) for 24 hrs. After removing from the oven, they were weighed and the following calculation were made:

(a) Determine the density of each specimen as follows:

$$\text{Density (g/cm}^3) = M/V$$

Where:

M = the mass of the specimen (g);

V = the volume of the specimen (cm³).

(b) Determine the Absorption of each specimen as follows:

$$\text{Absorption \%} = [(B - A)/A] \times 100$$

Where:

A = mass of oven-dried sample in air, g

B = mass of surface-dry sample in air after immersion, g

4 Results and discussions

4.1 Compressive strength

Compressive strength test was conducted at the ages of 7 and 28 days after successful curing period. Cube specimens of mortar used in the test. Results of compressive strength tests for the mortar specimens are given in the Tables 10-14 and Figure 1.

- a) It is possible to conclude that compressive strengths of the specimens with different rate of cement-replacement mixes without Alkali-Activator decreased when the combination of ceramic powder

Table 10: Compressive strength of cubes (50 mm) replacement of OPC without alkali-activator at 7 days

Comp strength MPa	Slag %	ceramic powder %	Replacement ratio %
21.28	0%	0	0
19.45	20	0	20
24.06	0	20	20
20.64	15	10	25
19.61	20	10	30
15.45	20	20	40
16.46	15	25	40
12.4	25	25	50

waste and slag contents increased as shown in Table 10.

- b) Compressive strengths of the specimens that partially replaced the cement with ceramic powder waste were higher than compressive strengths of the specimens that partially replaced the cement with slag due to higher percentage of silica oxide in ceramic waste [21].
- c) The using of Alkali-Activator liquid improved the results of compressive strength therefore it can be used in increasing the percentage of cement replacement as shown in Tables 11 & 12. The percentage of increase in compressive strength of geopolymer mortar using 40% of combination from cementitious materials (ceramic powder and slag) is 32.3% compared with traditional or control mortar mix. Besides, the use of 50% from the combination of ceramic powder and slag increases the compressive strength by about 10.87% compared with traditional or control mortar mix. Such results are supported by other researches [21–27]. Figure 1 shows the relative compressive strength of geopolymer mortar prepared by different percentages of cementitious ma-

Table 11: Compressive strength of cubes (50 mm) replacement of OPC with alkali-activator at 7 days

Comp strength MPa	Slag %	ceramic powder %	Replacement Ratio %
20.1	15	25	40
18.25	18.75	31.25	50
15.65	22.5	37.5	60
12.73	26.25	43.75	70
11.3	30	50	80
9.8	33.75	56.25	90

Table 12: Compressive strength of cubes (50 mm) replacement of OPC with alkali-activator at 28 days

Comp strength MPa	Slag %	ceramic powder %	Replacement ratio %
30.45	0	0	0
40.3	15	25	40
33.76	18.75	31.25	50
28.17	22.5	37.5	60
20.36	26.25	43.75	70
15.2	30	50	80
11.9	33.75	56.25	90

terials combination. The reinforcement of geopolymer mortar by using steel fibers or hybrid fibers from steel and sisal fibers has shown significant results as depicted in Tables 13 and 14. Thus, the use of 1% steel fibers in geopolymer mortar prepared by 40% from the combination of ceramic powder and slag increases the compressive strength of the geopolymer mortar by about 40.4%. Whereas, the use of 1% steel fibers + 0.5% sisal fibers in geopolymer mortar prepared by the same percentage of combination mentioned above gives an increment in the compressive strength of the geopolymer mortar by about 34.9%. Such behavior can be attributed to the ability of fibers to bridging the cracks propagation which rises the ultimate strength of mortar [23–27].

Figure 1: Relative compressive strength for geopolymer mortar mixes

Table 13: Compressive strength for geopolymer mortar reinforced with 1% steel fibers

specimen	Force (KN)	Average area (mm ²)	Tensile strength (MPa)
1	2.1	750	2.8
2	1.7	675	2.51
3	2.3	702	3.2
Average	2.03	709	2.83

Table 14: Compressive strength for geopolymer mortar reinforced with 1% steel fibers + 0.5% sisal fibers

Specimen	Compressive strength (MPa)	Relative compressive strength (%)
40%	42.76	140.4
60%	26.58	87.3
80%	13.23	43.45

4.2 Tensile Test

The total maximum load indicated by the testing machine and the cross-sectional area of a briquet after failure. Three briquettes used for each mix proportion.

Direct tensile strength test was conducted at and 28 days after successful curing period. The results for such property are shown in Tables 15-18. However, the results of direct tensile strength for traditional mortar has been achieved as shown in Table 15.

Table 15: Tensile strength of traditional mortar

Specimen	Compressive strength (MPa)	Relative compressive strength (%)
40%	41.08	134.9
60%	27.23	89.4
80%	14.17	46.5

Furthermore, the results of tensile strength for geopolymer mortar reinforced by different percentages of combination of ceramic powder and slag are shown in Table 16. It can be seen from this Table that the use of 40% from the combination from cementitious materials (ceramic powder and slag) has increased the direct tensile strength up to 39.2% compared with traditional or control mortar mix. Besides, the use of 60% from the combination of ceramic powder and slag increases the direct tensile strength by about 6% compared with traditional or control mortar mix. Such results are supported by other researches [22–27]. The reinforcement of geopolymer mortar by using steel fibers or hybrid fibers from steel and sisal fibers has shown significant results as presented in Tables 17&18. Thus, the use of 1% steel fibers in geopolymer mortar prepared by 40% from the combination of ceramic powder and slag increases the tensile strength of the geopolymer mortar by about 40.8%. Whereas, the use of 1% steel fibers + 0.5% sisal fibers in geopolymer mortar prepared by the same percentage of combination men-

Table 16: Tensile strength of geopolymer mortar

Specimen	Force (KN)	Average area (mm ²)	Tensile strength (MPa)	Relative tensile strength (%)
40	2.66	675	3.94	139.2
60	2.15	715.5	3.0	106
80	1.83	715	2.56	90.45

Table 17: Tensile strength for geopolymer mortar reinforced with 1% steel fibers

Specimen	Force (KN)	Average area (mm ²)	Tensile strength (MPa)	Relative tensile strength (%)
40%	2.86	718	3.983	140.8
60%	2.57	712	3.6	127.2
80%	2.13	725	2.93	103.5

Table 18: Tensile strength for geopolymer mortar reinforced with 1% steel fibers +0.5% sisal fibers

Specimen	Force (KN)	Average area (mm ²)	Tensile strength (MPa)	Relative tensile strength (%)
40%	2.91	723	4.02	142
60%	2.3	718	3.2	113
80%	2.05	715	2.86	101

tioned above gives an increment in the tensile strength of the geopolymer mortar by about 42%.

4.3 Flexural strength test

The results for flexural strength are shown in Tables 19-22. However, the results for traditional mortar has been achieved as shown in Table 19.

Table 19: Flexural strength of traditional mortar

Flexural strength (MPa)	Specimen
1	5.91
2	6.02
3	5.83
Average	5.92

Moreover, the results of flexural strength for geopolymer mortar reinforced by different percentages of combination of ceramic powder and slag are shown in Table 20. It can be noticed from this Table that the use of 40% from the combination of cementitious materials (ceramic powder and slag) has developed the flexural strength by about 4.7% compared with traditional or control mortar mix. The reinforcement of geopolymer mortar by using steel fibers or hybrid fibers from steel and sisal fibers has shown sig-

nificant results as presented in Tables 21&22. Thus, the use of 1% steel fibers in geopolymer mortar prepared by 40% from the combination of ceramic powder and slag increases the flexural strength of the geopolymer mortar by about 19.6%. Whereas, the use of 1% steel fibers + 0.5% sisal fibers in geopolymer mortar prepared by the same percentage of combination mentioned above gives an increment in the flexural strength of the geopolymer mortar by about 15.7%.

Table 20: Flexural strength of geopolymer mortar

Specimen	Flexural strength (MPa)	Relative flexural strength (%)
40%	6.2	104.7
60%	5.93	100.1
80%	5.08	85.8

Table 21: Flexural strength of geopolymer mortar reinforced with 1% steel fibers

Specimen	Flexural strength (MPa)	Relative tensile strength (%)
40%	7.08	119.6
60%	6.46	109.1
80%	5.89	99.49

Table 22: Flexural strength of geopolymer mortar reinforced with 1% steel fibers +0.5% sisal fibers

Specimen	Flexural strength (MPa)	Relative tensile strength (%)
40%	6.85	115.7
60%	5.63	95.1
80%	4.37	73.81

4.4 Absorption

Absorption values were tested according to ASTM C642 where the results for the traditional mortar are shown in Table 23. The results for geopolymer mortar mixes with and without fibers are presented in Tables 24-26. However, the geopolymer mortar mixes exhibited higher ranges of absorption compared with the traditional mortar. As the

percentage of combination from cementitious materials (ceramic powder and slag) increases, the absorption of geopolymer mortar has also been increased as shown in Table 24. However, the use of fibers reduces slightly the increment in absorption for geopolymer mortar. And the steel fibers exhibited better performance than that of sisal fibers in reducing the porosity of the geopolymer mortar reinforced with fibers [7] as shown in Tables 25 and 26.

Table 23: Absorption of traditional mortar

Specimen	Absorption %
1	4.65
2	4.3
3	4.4
Average	4.45

Table 24: Absorption of geopolymer mortar

Specimen	Absorption %
40%	6.08
60%	7.18
80%	7.69

Table 25: Absorption of geopolymer mortar reinforced with 1% steel fibers

Specimen	Absorption %
40%	5.64
60%	6.44
80%	7.08

Table 26: Absorption of geopolymer mortar reinforced with 1% steel fibers +0.5% sisal fibers

Specimen	Absorption %
40%	6.33
60%	7.1
80%	7.62

5 Conclusions

1. The use of 20% ceramic powder increases the compressive strength of mortar by about 13 %. But, the use of 20% slag decreases the compressive strength by about 9%.
2. Geopolymer mortar strengths are enhanced due to the combination of ceramic powder and slag up to 40% by weight of cement. The increment percentages for compressive, tensile and flexural strengths are up to 32.3, 39.2, and 4.7%, respectively, compared with normal or traditional mortar.
3. The use of 1% steel fibers in geopolymer mortar mix prepared by 40% combination of ceramic powder and slag increases the compressive, tensile and flexural strengths by about 40.4, 40.8 and 19.6%, respectively, compared with normal or traditional mortar.
4. The use of 1% steel fibers+ 0.5% sisal fibers in geopolymer mortar mix prepared by 40% combination of ceramic powder and slag increases the compressive, tensile and flexural strengths by about 34.9, 42 and 15.7%, respectively, compared with normal or traditional mortar.
5. Steel fibers and sisal fiber can be used to increase the tensile strengths of the mixture and increase the proportion of the replacement of cement by about 60% to get effective tensile strengths of structural mortar.

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