The Mechanical Properties of Fly Ash and Slag Geopolymer Mortar with Micro Steel Fibers

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Received: 18 February 2022 | Revised: 28 February 2022 | Accepted: 4 March 2022

Abstract-In this study, experimental mortar combinations with 1% micro steel fibers, were examined to create geopolymer mortars. To test the effect of the fibers on the mortar's resistance, the geopolymer mortar was designed with various proportions of more environmentally friendly materials fly ash and slag. The percentage of fly ash by weight was 50, 60, and 70% of the slag. The best results were obtained when a 50:50 ratio of fly ash and slag were mixed with 1% micro steel fibers. The results showed that the mixtures containing fibers performed better in the considered tests (toughness index, ductility index, and resilience index). In the impact resistance test, the mixture contained 50% fly ash by weight of the slag with a temperature of 240°C and a curing period of 28 days, with and without micro steel fibers. Water absorption test results and void content increased when adding micro steel fibers after 7 and 28 days of curing at 24°C.

Keywords-fly ash; slag; alkaline solution; geopolymer mortar

I. INTRODUCTION

The most common kind of cement used in the production of concrete is the Ordinary Portland Cement (OPC). Many environmental concerns have long been related to the production of OPC. Due to the amount of limestone calcination and the necessary burning of fossil fuels, the amount of carbon dioxide produced during the manufacturing of OPC is around one ton for every metric ton of produced OPC. The construction of OPC requires the same amount of energy as manufacturing steel and aluminum [1]. To reduce the amount of CO_2 emitted by cement factories and aid the recycling of industrial waste, environmentally friendly materials were developed for use in civil engineering projects [2]. Cement composites are a viable alternative to traditional forms of concrete. Additional cementitious materials, such as GGBFS, fly ash, and SF, can be used in the production of blended cement [3]. Waste from thermal power plants, such as fly ash and slag, can constitute an environmental threat if not properly handled and reused. In the long run, the fly ash from thermal power plants contaminates groundwater sources and damages croplands, causing long-term environmental impact, while the by-product of combustion is a powdery substance [4]. Fly ash is produced in large quantities each year, posing a threat to the ecosystem.

Some pozzolanic waste materials (siliceous and aluminous) may be reduced [5]. Geopolymers are a category of mineral binders that have a chemical composition similar to that of zeolites. The polycondensation of silicate and alumina precursors, rather than standard Portland/pozzolanic cement, is used in geopolymers to build the matrix and increase strength. Source materials and alkaline liquids make up the majority of geopolymers. Silicon (Si) and aluminum (Al)-rich alumino-silicate raw materials are recommended. Fly ash and silica fume, for example, are by-product minerals that can be used in the mix. Geopolymers are distinct from conventional aluminosilicate compounds (e.g. aluminosilicate gels, glasses, and zeolites). Geopolymerization contains more solids than zeolite synthesis or alumino-silicate gel [6]. Since fly ash and slag are used to make geopolymer concrete, it is a more ecologically friendly and diversified alternative to ordinary concrete [7].

II. EXPERIMENTAL SETUP

A. Fly Ash

The fly ash produced at the ISKEN-MENT power plant in Turkey can be described as a fine, glassy powder that results from coal burning. Table I shows the chemical composition of the fly ash used in this study.

B. Slag

According to Table II, the slag used in this study met the ASTM C618 standards [8].

C. Sodium Hydroxide

NaOH flakes, which are readily accessible in the market, are 99.8% pure. Solids should be dissolved in filtered water to produce a concentrated solution. Geopolymer mortar solutions are made using sodium hydroxide (NaOH). Caustic soda flakes were melted with water to produce NaOH. A variety of molar concentrations can be achieved by altering the amounts of caustic soda flakes in the water.

D. Sodium Silicate

The ratio of Na_2O to SiO_2 and H_2O determines the concentration of Na_2SiO_3. Na_2SiO_3 was produced in the United Arab Emirates.

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TABLE I. CHEMICAL COMPOSITION OF FLY ASH

Oxide	Contents (%)	ASTM C618 Requirements [8]
Fe_2O_3	5.35	Sum more than 70%
Al_2O_3	17.59	
SiO_2	65.63	
SO_3	0.21	Max. 5%
MgO	0.84	--
CaO	0.98	--
L.O. I	2.76	Max. 6%
K_2O	2.33	--
Na_2O	1.36	--

TABLE II. CHEMICAL COMPOSITION OF GGBFS

Oxide	Contents (%)	(ASTM C618) Requirements [8]
Fe_2O_3	0.35	Sum more than 70%
Al_2O_3	25.53	
SiO_2	45.88	
SO_3	4.98	Max. 5%
MgO	4.95	--
CaO	37.21	--
L.O. I	3.89	Max. 6%
K_2O	2.10	--
Na_2O	0.96	--

E. Water

The NaOH solution was produced by dissolving caustic soda flakes in distilled water. To facilitate mixing, tap water was included in the geopolymer mix, compliant with the IQS 1703 [9].

F. Fine Aggregates

The fine aggregates came from the Al-Ekhadir Karbala city region and met the Iraqi standard IQS No.45/1984 for physical and chemical properties [10], as shown in Table III. The fineness modulus was 2.76.

G. Micro Steel Fibers

Table IV shows the properties of micro steel fibers.

H. Superplasticizer

Using a modified sulfonated naphthalene formaldehyde condensate (superplasticizer), the geopolymer mortar's workability was improved to meet ASTM C494 standards [11].

TABLE III. PHYSICAL CHARACTERISTICS OF THE FINE AGGREGATES

Sieve size (mm)	Cumulative percentage pass	IQS (45-1984), zone2 [10]
10	100	100
4.750	91	90-100
2.360	80	75-100
1.180	71	55-90
0.60	53	35-59
0.30	22	8-30
0.150	7	0-10

TABLE IV. MICRO STEEL FIBER MECHANICAL PROPERTIES (ACCORDING TO MANUFACTURER)

Properties	Micro steel fibers
Tensile strength (MPa)	2600
Diameter (mm)	0.2
Density(kg/m3)	7800
Length (mm)	13
Aspect ratio	65
Modulus of elasticity (GPa)	250

III. MANUFACTURING GEOPOLYMER

A. Preparation of Alcaline Solution

When producing the geopolymer mortar for this experiment, the NaOH molar concentration was fixed to 12 molars. Solubility was determined by adjusting the sodium silicate/sodium hydroxide ratio to 2:1 and the solution/cementitious-materials ratio to 45%. The weight of the NaOH flake is shown in Table V.

TABLE V. AMOUNT OF NAOH SOLIDS FOR 1KG OF SOLUTION AT SPECIFIED MOLARITY AND WEIGHT CONCENTRATION [1,12]

Molarity (mole/L)	NaOH weight concentration (w/w%)	Weight of NaOH flakes (g)	Weight of water (g)
8	26.2	262	738
10	31.4	314	686
12	36.2	362	638
14	40.4	404	596
16	44	440	560

B. Mixing

Before use, the alkaline liquid was prepared the day before and was then combined with a superplasticizer. To begin, the dry ingredients (GGBS, fly ash, fiber, and sand) were mixed by hand for approximately 2 minutes before the alkaline liquid and superplasticizer were added at a 75% concentration, and the mixing process was performed a second time. Finally, after another 5 minutes of mixing, the mixture was allowed to sit for about 15s before being blended with the remaining 25% of the mixed alkaline liquid. Table VI shows the homogeneity achieved after 10 to 15 minutes of mixing.

TABLE VI. MIX DESIGN OF GEOPOLYMER MORTAR FOR $1M^3$, WEIGHT IN KG/M^3

Mix	Fine agg.	Water*	FA / slag ratio	Slarg	Fly Ash	Sodium silicate solution	NaOH	Micro steel %
G1	1400	75	0.5:0.5	375	375	225	112.5	-
G2	1400	75	0.5:0.5	375	375	225	112.5	1
G3	1400	75	0.6:0.4	450	300	225	112.5	-
G4	1400	75	0.6:0.4	450	300	225	112.5	1
G5	1400	75	0.7:0.3	525	225	225	112.5	-
G6	1400	75	0.7:0.3	525	225	225	112.5	1

IV. RESULTS AND DISCUSSION

These tests were carried out according to the ASTM C642 [13]. The results measured density, absorption percentage, and void content of hardened G1 and G2 mixtures at 7 and 28-day intervals with heat curing at 80,160, and 240°C. In this test, fracture pieces of concrete mortar were used, and each portion was free of fractures or fractured edges. Each test used an average of three specimens. The results for 7 and 28 days of curing at 240 °C are shown in Tables VII, VIII, and IX and Figures 1, 2, and 3.

TABLE VII. BULK DENSITY OF MIXES G1 AND G2

Mix type	Density, kg/m^3	
	At seven days/240 °C	At 28 days/240 °C
G1	2437	2463
G2	2456	2503

The dry density at 28 days was greater than in 7 days, as it increased from 0.07% to 1.6%. The geopolymerization process continuity and the development of microstructure were linked to this rise in density over time. The results comply with [14], showing that the inclusion of micro steel fiber (G2) enhanced the dry density compared to specimens without fibers (G1).

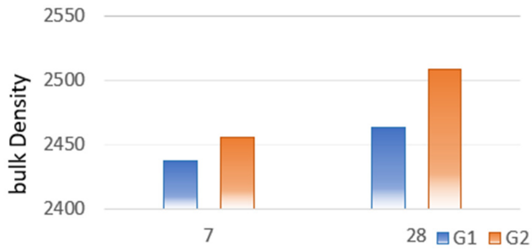

Fig. 1. The bulk density of G1 and G2 mixes.

TABLE VIII. WATER ABSORPTION RESULTS OF MIXES G1 AND G2

Mix type	Water absorption %	
	At seven days/240 °C	At 28 days/240 °C
G1	4.38	3.89
G2	4.45	3.93

As the results show, the improved microstructure of the geopolymer mortar and the increased product properties with rising temperatures and curing age led to decreased amount of water that all mixtures can absorb with time but increased with additional fiber due to the generation of voids around the fibers. The increase was about 1.6% and 1% compared with the mixture without fibers for 7 and 28 days of curing, respectively.

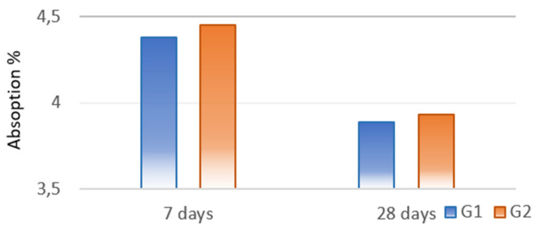

Fig. 2. Water absorption of G1 and G2 mixes.

TABLE IX. VOID CONTENT OF G1 AND G2

Mix Type	Void content %	
	7 days/240°C	28 days/240°C
G1	9.45	7.85
G2	9.51	7.93

Table IX shows the void content of G1 and G2 mixtures at 28 days of curing at 240°C. The void content of all mixtures decreased with aging. A continuous geopolymerization process enhances the microstructure and generates a denser geopolymer mortar. For all mixtures, the void content decreased with time and increased with additional fibers. The variation between G1 and G2 was 0.6% and 1% for 7 and 28 days of curing respectively. The load-deflection curve test was performed by calculating the area under the curve, where a hydraulic device and a measurement deflection carried out the loading by a dial gauge with 0.01mm accuracy. It was used with a prism with dimensions 50×50×250mm, as shown in Figure 4.

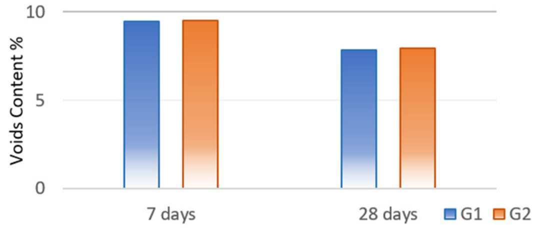

Fig. 3. Void Content % of G1 and G2 mixes.

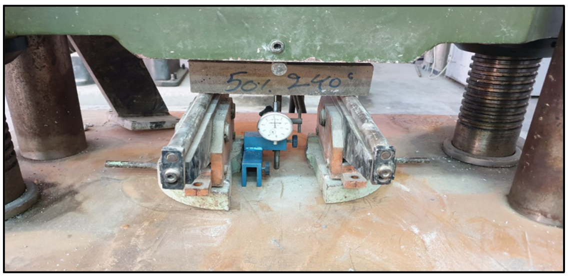

Fig. 4. Testing the load-deflection curves.

The ends were placed on simple support with a space of 200mm to extract the toughness index, ductility index, and resilience. Tables X, XI, and XII show the results of toughness index, ductility index, resilience at 3, 7, and 28 days, respectively, at the curing temperature of 240°C.

TABLE X. FLEXURAL STRENGTH TEST RESULTS AT 3 DAYS

Samples	Load at failure (KN)	Deflection at failure (mm)	Toughness index	Ductility index	Resilience (KN.mm)
G1-1	1.705	0.99	1.15	1.52	0.16
G1-2					
G2-1	1.94	0.77	4.35	3.88	3.91
G2-2					

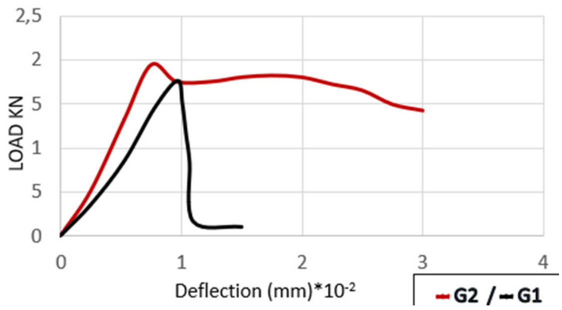

Fig. 5. Load deflection curve at three days.

TABLE XI. FLEXURAL STRENGTH TEXT RESULT AT 7 DAYS

Samples	Load at Failure (KN)	Deflection at Failure (mm)	Toughness Index	Ductility Index	Resilience (KN.mm)
G1-1	1.76	0.86	1.20	1.59	0.23
G1-2					
G2-1	1.84	1.62	4.43	4	3.98
G2-2					

The most significant results of reinforced geopolymer mortar can be based on the mechanical ductility property of pulling and breaking the reinforcement. On this basis, the excellent adhesion between the bonding material and the reinforcement increases the friction resistance of the common interface between them.

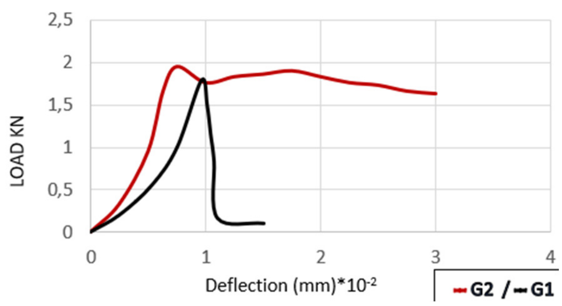

Fig. 6. Load deflection curve at seven days

TABLE XII. FLEXURAL STRENGTH TEST RESULTS AT 28 DAYS

Samples	Load at failure (KN)	Deflection at failure (mm)	Toughness index	Ductility index	Resilience (KN.mm)
G1-1	1.89	0.98	1.19	1.52	0.16
G1-2					
G2-1	2.18	0.77	5.88	5.63	4.97
G2-2					

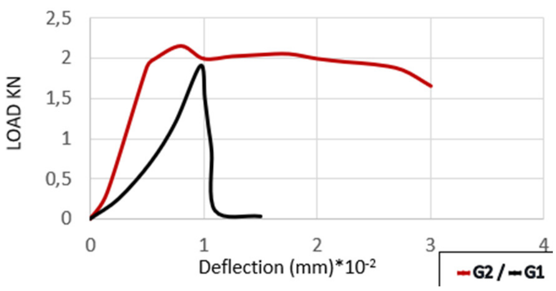

Fig. 7. Load deflection curve at 28 days.

Figures 5-7 show that the black line drops suddenly, opposite of the red line, because the addition of micro steel fibers with uniform random distribution in the mortar increases the resistance of the first crack of the mortar, especially when the reinforcing fibers prevent the expansion of these cracks with high energy absorption when withdrawn from the cracked cement mortar mass, which makes the reinforced specimens with these fibers of high strength and resistance.

Fig. 8. Geopolymer prisms while testing.

V. CONCLUSIONS

- Geopolymers are an ecologically acceptable substitute for OPC in structural applications [15].
- Water absorption and void content increased by adding micro steel fibers at 240°C at 7 and 28 days of curing, which is considered an indication of durability.
- For the mixes G1 and G2 with curing temperature of 240°C, the results of the density test showed increasing values with additional micro steel fibers while decreasing values with curing age.
- Toughness index, ductility index, and resilience increased by adding micro steel fibers for all mixes.

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