The Effect of the Utilization of Sustainable Materials on Some Mechanical Properties of Geopolymer Mortar

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ABSTRACT

Geopolymer concrete has been developed as a means of reducing carbon dioxide (CO_2) emissions due to concrete manufacturing, which account for around 5–10% of the total global CO_2 emissions. Additionally, this innovative material aims to utilize industrial waste as a sustainable resource. This study concentrates on developing a geopolymer mortar composition comprising 70% fly ash and 30% metakaolin. The mixture also includes 14 molars of sodium hydroxide, sodium silicate, saturated surface dry sand, water at a volume of 10% of the mix, and 1.5% superplasticizer. The solution-to-solid materials ratio was established at 0.55 while the ratio between sodium silicate and sodium hydroxide was established at 2.5:1. The geopolymer mortar was enhanced by rice husk fibers at varying volume percentages of 1%, 1.5%, and 2%. Additionally, waste paper, in the form of paper ash, was introduced as filler at a volume percentage of 5%. Following the demolding process, the specimens were cured in the controlled environment of an oven, with the temperature set at 60 °C for a period of 24 hr. Subsequently, the cured samples were stored for 7 and 28 days and then were tested. When different amounts of rice husk fibers were mixed in with a fixed amount of 5% paper ash, the flexural resistance of the geopolymer mortar increased significantly. After 7 days of curing, it was seen that the flexural strength experienced an increase of 4%, 13%, and 25%, and a further increase of 11%, 18%, and 31% after 28 days of curing. The results of the impact test showed a notable enhancement in impact resistance and energy absorption when incorporating paper ash and rice husk fibers. Specifically, the initial crack results exhibited a 50% rise, while the specimen failure after 28 days of curing showed a 66% improvement.

Keywords-geopolymer mortar; fly ash; metakaolin; rice husk fibers; waste paper ash; impact test; flexural strength

I. INTRODUCTION

The issues of global warming and pollution have emerged as significant challenges in contemporary times. The manufacture of Portland cement results in the emission of significant amounts of gases, leading to atmospheric pollution [1]. Concrete is extensively regarded as the primary construction material, with its utilization projected to escalate in line with global population growth, economic advancement, and the need for upkeep or replacement of aging infrastructure. Unfortunately, a primary constituent of the aforementioned material, which is cement, is accountable for approximately 5–10% of global CO_2 emissions. Consequently, there is a pressing need for a comprehensive reevaluation of both the industry as a whole and the particular material in question [2]. It is possible to minimize the CO_2 emissions due to cement production and contribute to the recycling of industrial wastes that have a major effect on the environment by using sustainable materials in civil engineering projects [3]. The term geopolymer was introduced in 1978 to designate a group of mineral binders that demonstrate chemical characteristics similar to zeolites. Geopolymers, in contrast to conventional Portland cement, utilize the polycondensation process of silicon (Si) and aluminum (Al) precursors to generate the matrix and impart structural stability [4]. Geopolymers consist mostly of two essential components, namely source materials and alkaline solutions. The constituents required for the synthesis of alumina-silicate geopolymers should possess a substantial concentration of Si and Al. The minerals in question may be composed of naturally occurring substances such as kaolinite, clays, and similar compounds, characterized by empirical formulas that include Si, Al, and oxygen (O) [5]. The usage of slag, fly ash, rice husk, metakaolin, red mud, activated bentonite clay, and other alumino silicate minerals as the primary supply materials are imperative. Geopolymer cement is produced through the alkaline activation of the aforementioned raw components. The utilization of natural pozzolana is recommended for the production of geopolymers that are predominantly composed of alumino-silicate compounds. Alkaline liquids are obtained by soluble compounds of alkali metals, namely sodium or potassium. Sodium hydroxide, a caustic liquid, is commonly employed in conjunction with sodium silicate at a 2.5:1 ratio. Sodium is favored over potassium due to its comparatively cheaper cost [6]. The primary objective of this research is to investigate the flexural strength of fly ash-metakaolin geopolymer mortar reinforced with rice husk fibers and the effect of waste paper ash addition. This investigation target is to develop our understanding of the structural geopolymer mortar characteristics. It will also highlight the prospect of reducing CO_2 emissions by manufacturing environmentally friendly concrete through the application of sustainable and waste materials in place of traditional cement.

Authors in [7] investigated the impact of different amounts of slag as a potential substitute for fly ash while also assessing the influence of slag on geopolymer concrete characteristics. The ratios of slag to fly ash were 0.25:0.75, 0.35:0.65, and 0.45:0.55, expressed in terms of material weight. Subsequently, the aforementioned compositions were subjected to a comparative analysis with a reference mixture of conventional concrete, which adhered to a mix of 1:1.5:3 (Portland cement: natural sand: coarse aggregates), respectively. The utilization of copper fiber obtained from discarded electrical devices has been employed to improve the characteristics of geopolymer concrete. Curing was done by heat at a temperature of 40 °C. The findings of this study indicated that the combination of 45% slag and 55% fly ash yielded the most favorable outcome [7]. Authors in [8] employed a series of experimental combinations to produce geopolymer mortar incorporating 1% micro-steel fibers. In order to see how fly ash changed the properties of geopolymer mortar, different weight percentages of 50%, 60%, and 70% of the slag weight were used. Combining fly ash and slag in a 50:50 ratio with micro-steel fibers at 1% produced the most advantageous ratio that created the most notable results. The samples were subjected to an oven curing temperature of 240 °C for a duration of 4 hr. Fiber incorporation resulted in an increase in the compressive resistance of the geopolymer by 11%, 11.5%, and 14% after 3, 7, and 28 days of curing, respectively. Flexural resistance demonstrated enhanced rates of 28%, 30%, and 33%, respectively [8]. Authors in [9] aimed to investigate the impact of incorporating rice husk fibers at 1% of mix volume on the characteristics of Reactive Powder Concrete (RPC). The samples were oven cured at 60°C and tested after 28 days of curing. Based on the results, it was observed that the compressive strength of the RPC increased by 7.4%, while its dry density decreased by 0.69%. In contrast, the workability of the RPC exhibited a drop of 5.62% in comparison to the reference combination. Authors in [10] investigated the impact of including paper fibers on the characteristics of hardened and fresh concrete. The conducted tests indicate that the incorporation of waste paper into concrete leads to a substantial enhancement in both compressive and flexural strength. After a curing time of 90 days, the compressive strength exhibited a notable rise of 34.21%, while the flexural strength demonstrated a substantial increase of 42.4%. In that study, waste paper comprised 1% of the total volume of concrete [10].

The most important goal of the current research is the environmental benefit of reducing CO_2 emissions from the cement production industry and produce cheaper concrete with high strength and quality. Therefore, this study explored the flexural strength and impact strength of fly ash-metakaolin geopolymer mortar. The possibility of utilizing rice husk as fibers and waste paper ash as filler, is highlighted since there are only a few published studies regarding this subject.

II. EXPERMINTAL WORK

A. *Fly Ash (FA)*

Class-F FA was used. The classification of FA is determined according to the specifications outlined in ASTM C618-19, as depicted in Table I. The aforementioned category of FA exhibits pozzolanic characteristics [11].

TABLE I. CHEMICAL REQUIREMENTS OF FLY ASH

Oxide	Content, %	(ASTM C618-19) requirement
Fe_2O_3	5.31	Total Sum. > 50%
Al_2O_3	18	
SiO_2	64.73	
SO_3	0.25	Maximum 5%
MgO	0.87	--
CaO	2.3	Maximum 18%
K_2O	3.52	--
Na_2O	2.22	--
L.O.I	2.8	Maximum 6%

B. *Metakaolin (MK)*

Class N-metakaolin, a natural pozzolana, was used. It is categorized according to the specifications stated in ASTM C618-19, as indicated in Table II.

TABLE II. CHEMICAL REQUIREMENTS OF METAKAOLIN

Oxide	Content, %	(ASTM C618-19) requirement
Fe_2O_3	1.93	Total sum.> 70%
Al_2O_3	40.45	
SiO_2	51.4	
SO_3	0.32	Maximum 4%
MgO	0.47	--
CaO	2.3	Maximum 18%
K_2O	0.272	--
Na_2O	1.018	--
L.O.I	1.84	Maximum 10%

C. *Sodium Hydroxide (NaOH)*

A NaOH solution was prepared by adding distilled water to caustic soda flakes (99% purity). The variety of molar concentrations can be determined by considering the ratio between water and soda flakes. The NaOH solution is explained in greater detail in the ASTM E291-2009 standard. The concentration of NaOH utilized in this study is 14 mol/L [12].

D. Sodium Silicate (Na_2SiO_3)

The sodium silicate used in this study was made in the UAE, and its concentration was determined by calculating Na_2O to SiO_2 and H_2O ratios.

E. Water

The water used for mixing complied with IQS 1703-2018 [13].

F. Fine Aggregate (Sand)

In this investigation, sand was employed as the fine aggregate. It was classified as zone two and was found to be in accordance with the requirements specified in IQS (No. 45-2019), as demonstrated in Table III. The fineness modulus was 2.84 [13].

TABLE III. SIEVE ANALYSIS OF FINE AGGREGATE

Sieve no.	Accumulative passing %	IQS (45-2019), zone 2
10	100	100
4.75	96	90-100
2.36	84	75-100
1.18	69	55-90
0.6	50	35-59
0.3	15	8-30
0.15	2	0-10

G. Wastepaper Ash (PA)

The paper pieces were cut into small pieces with dimensions of 8 mm, 2 mm, and 0.1 mm. Subsequently, the specimens were burned in a furnace operating at 700 °C. The resulting residue was subjected to sieving using a 600 µm sieve. A 5% volume fraction of wastepaper ash was incorporated into the cementitious components. Table IV presents an overview of the chemical properties of wastepaper ash.

TABLE IV. CHEMICAL REQUIREMENTS OF WASTEPAPER ASH

Oxide	Content %
SiO_2	20
Al_2O_3	4.2
Fe_2O_3	0.76
CaO	78.74
MgO	0.88

The papers had been cut into small pieces with 8 mm, 2 mm, and 0.1 mm dimensions. Subsequently, the specimen was burned in a furnace operating at a temperature of 700°C. Following the process of burning, the resulting residue was subjected to sieving using a 600µm sieve. A 5% volume fraction of ash wastepaper was incorporated into the cementitious components. Table IV presents an overview of the chemical properties of wastepaper ash.

H. Rice Husk Fibers (RHF)

Table V and Figure 1 show the length and other parameters of the RHF employed in this investigation.

TABLE V. RICE HUSK FIBERS MECHANICAL PROPERTIES

Propertys	Value
Diameter (mm)	0.5
Length (mm)	5
Aspect ratio	10
Density kg/m³	700
Color	Gold or hay

Fig. 1. Rice husk fibers.

I. Super Plasticizer (SP)

The research utilized BETONAC-1055, a substance supplied by the local region. It adheres to the ASTM C494 Type F standard and was employed for the purpose of enhancing the workability of the geopolymer mortar [14].

III. MANUFACTURING OF GEOPOLYMER MORTAR

A. Mixing

It is necessary to prepare the NaOH solution one day in advance of the intended mixing. The concentration of sodium hydroxide (NaOH) was established at a molarity of 14 M for the geopolymer mortar. The ratio of Na_2SiO_3 to NaOH was established at 2.5:1, whereas the ratio of the solution to cementitious material was determined at 0.55. In the first step of the mixing process, NaOH solution, Na_2SiO_3, 1.5% superplasticizer, and 10% water (by weight of cementitious material) were mixed together. This mixture was blended for 2–5 min. Subsequently, the dry components, namely FA (70%), metakaolin (30%), and sand in a Saturated Surface Dry (SSD) state, were meticulously mixed manually for about 5 min. Therefore, 75% of the liquid components were included in the dry constituents and manually blended for an additional duration of 10–15 min. Following this, a resting period of 15 s took place prior to the addition of the remaining 25% of the liquid components, which were then mixed for an additional 10 min. Homogeneity was achieved after approximately 30 min of mixing. The paper ash was added at 5% for all mixes. The RHF and the wastepaper ashes were added at 1%, 1.5, and 2% by volume of the mixture. Table VI illustrates the mix design of geopolymer mortar.

TABLE VI. MIX PROPORTIONS OF GEOPOLYMER MORTAR FOR 1m³, WEIGHT IN Kg/m³

Mix	FA	Metakaolin	Sand	NaOH	Na_2SiO_3	SP	RHF
GPr	287	123	1476	64	161	6.15	-
GP1	287	123	1476	64	161	6.15	1%
GP2	287	123	1476	64	161	6.15	1.5%
GP3	287	123	1476	64	161	6.15	2%

B. *Curing*

The specimens were oven-cured at 60 °C for 24 hr, followed by a transfer to a separate oven for cooling and temperature maintenance until the scheduled test date. As seen in Figures 2 and 3, the specimens were tested at 7 and 28 days. Elevated temperatures accelerate chemical reactions, promoting a more rapid solidification of the substance. The importance of this matter lies in construction projects. The 7-day age is indicative of the initial strength, whereas the 28-day age is widely accepted as the standard for assessing the material's intended long-term strength and durability.

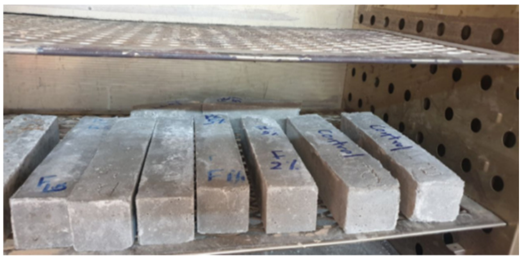

Fig. 2. Geopolymer prisms while curing.

Fig. 3. Impact samples while curing.

C. *Testing*

1) *Flexural Strength*

The flexural strength of the geopolymer mortar was assessed by conducting a one-point load test, following the guidelines provided in ASTM C 293M-16. The flexural strength of each combination was measured using the average of two prism specimens (250 × 50 × 50 mm) after curing for 3 and 28 days [15].

D. *Impact Test*

As suggested by the ACI 544.2R-10 standard, a hardened steel ball with a diameter of 6.35 cm was dropped from a height of 1.5 m onto a 500 mm × 500 mm × 50 mm slab [16].

IV. RESULTS AND DISCUSSION

Geopolymers are a suitable, environmentally friendly alternative to Ordinary Portland Cement (OPC) for use in structural applications [18].

A. *Flexural Strength*

The flexural strength test was performed after 7 and 28 days of curing at 60 °C. The samples included one without any fibers or paper ash and 3 samples with varying percentages (1%, 1.5%, and 2%) of fibers and 5% paper ash. The test results are illustrated in Table VII and Figures 4 and 5. The incorporation of RHF resulted in an improvement in flexural strength through the reduction of cracking. The initial cracks on the bending specimen were not easily seen due to the role of fibers as bridges between cracks which enhanced the strength of the fiber-reinforced concrete. These findings align with the conclusions presented in [9]. Furthermore, the addition of paper ash showed a significant upgrade in flexural tensile strength as the curing period progressed. The observed increase in gain can be attributed to the utilization of paper ash as a filler material, which effectively fills voids in concrete and consequently ameliorates its flexural strength. These findings are in accordance with the ones reported in [18].

TABLE VII. FLEXURAL STRENGTH TEST RESULTS

Mix	Flexural strength, MPa	
	7 days	28 days
GPr	4.15	4.43
GP1	4.32	4.9
GP2	4.7	5.24
GP3	5.2	5.81

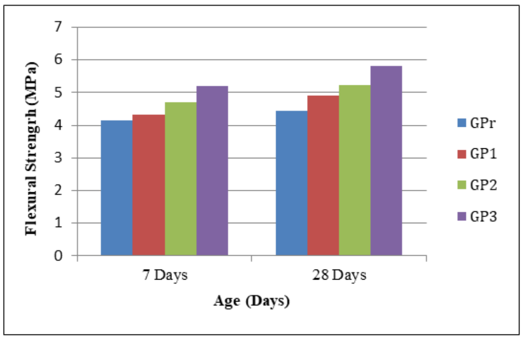

Fig. 4. Flexural strength of geopolymer mortar after 7 and 28 days of curing.

Fig. 5. Geopolymer prisms while testing.

B. Impact Strength

After a curing period of 28 days, impact resistance test was conducted on 2 samples: a control sample and a sample including 2% RHF and 5% paper ash. The findings of the impact test are presented in Tables VIII and IX and Figures 6-8. The presented data indicate a positive correlation between the presence of fibers and the impact strength of the material. As fibers are added, the total number of strikes necessary for the sample to reach a state of crushing and failure exhibits a likewise increase. The enhanced ability to resist impact can be attributed to the interlocking of the fibers that are distributed randomly within the mortar, resulting in better energy absorption due to the incorporation of additional fibers. These results comply with the findings of [19, 20].

TABLE VIII. IMPACT TEST RESULTS AT 28 DAYS OF CURING

Sample	First crack-no of blows	Failure crack-no of blows
GPr	6	58
GP3	9	96

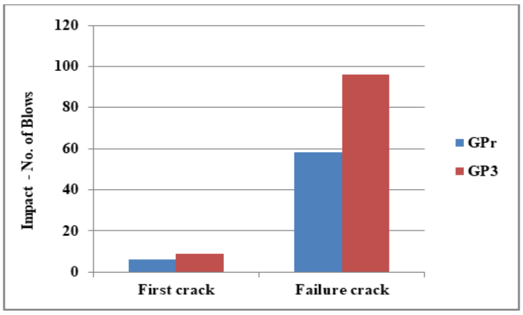

Fig. 6. Impact test results.

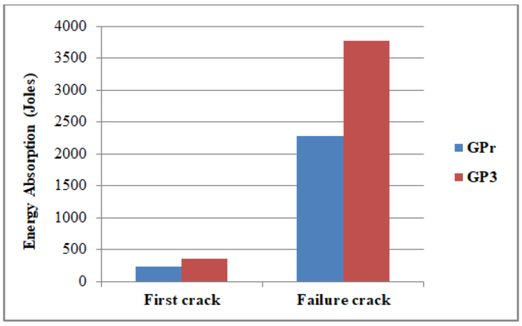

Fig. 7. Energy absorption results.

Fig. 8. Impact test.

V. COMPARISON WITH PREVIOUS WORKS

Authors in [10] investigated the impact of including paper fibers on the characteristics of hardened normal concrete. After 90 days, the flexural strength demonstrated a substantial increase of 42.4%. Authors in [9] explored the impact of incorporating RHF similarly to this study at 1% of the mix volume of RPC. After 28 days of curing at 60 °C, the results showed that the compressive strength of the RPC samples increased by 7.4%. In this research, we designed a new geopolymer mortar with 30% metakaolin, 70% FA, RHF as reinforcement, and 5% waste paper ash as filler. The specimens were cured at 60 °C for 24 hr and then stored until the age of testing (7 and 28 days). The addition of 1%, 1.5%, and 2% of RHF and 5% of paper ash increased the geopolymer mortar flexural strength by 4%, 13%, and 25% at 7 days of curing and by 11%, 18%, and 31% at 28 days of curing. Although, only a 31% rise in flexural strength was achieved, it should be noted that most of the materials used in this research were sustainable and cost-effective compared to normal concrete.

VI. CONCLUSIONS

In this paper, a new geopolymer mortar with 30% metakaolin, 70% fly ash, rice husk fibers as reinforcement, and 5% waste paper ash as filler was designed and tested. The specimens were cured at 60 °C for 24 hr and then stored until the age of testing (7 and 28 days). Geopolymers are a suitable, environmentally friendly alternative to Ordinary Portland Cement for use in structural applications due to the utilization of sustainable and waste materials in its production. The following conclusions were achieved:

- The addition of 1%, 1.5%, and 2% of rice husk fibers and 5% of paper ash increased the flexural strength of the geopolymer mortar by 4%, 13%, and 25% at 7 days of curing and by 11%, 18%, and 31% at 28 days of curing.
- Impact tests showed that adding paper ash and rice husk fibers increased the impact and energy absorption by 50% for the first crack and by 66% for the sample failure after 28 days of curing.

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