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Properties of Geopolymer Concrete Made With Recycled Concrete Aggregates and Glass Fibers

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Abstract **-** This research aims to evaluate the workability and compressive strength of geopolymer concrete made with recycled concrete aggregates (RCA) and glass fibers (GF). The ambient-cured geopolymer concrete was prepared using a binder blend of slag and fly ash (3:1) and fine aggregates in the form of desert dune sand. Natural aggregates or RCA served as the coarse aggregates, while sodium silicate and sodium hydroxide formulated the alkaline activator solution. The investigated process parameters included the replacement percentage of natural aggregates with RCA, binder content, amount of additional water (added to the alkaline activator solution), particle size distribution of RCA, and volume fraction of GF. Experimental results indicated that replacing natural aggregates with 100% RCA had an insignificant impact on the workability but reduced the compressive strength by up to 25%. Increasing the binder content from 300 to 450 kg/m^3 in RCA geopolymer concrete reinforced with up to 2% GF, by volume, led to up to 28, 106, and 17% higher workability and 1- and 7-day compressive strengths, respectively. Adding up to 50 kg/m^3 of water increased the workability up to 230 mm while decreasing the compressive strength by up to 22%. Meanwhile, sieving the RCA to remove particles smaller and larger than 4.75 mm and 19 mm, respectively, increased the slump to 210 mm and 1- and 7-day compressive strength by 29 and 35%, correspondingly. The addition of 1 and 2% GF, by volume, decreased the workability by 2 and 9%, respectively, in comparison to the plain RCA geopolymer concrete mix, while the compressive strength was unaffected. Experimental findings highlight the possibility of utilizing RCA as a replacement for natural aggregates in slag-fly ash blended geopolymer concrete reinforced with glass fibers without compromising performance. Such beneficial use of RCA serves as a means of alleviating the adverse environmental impact associated with its disposal.

Keywords**:** Geopolymer, recycled aggregates, fibers, concrete, slump, compressive strength.

1. Introduction

Concrete is one of the most widely used construction materials in the entire world. It is typically made with ordinary Portland cement (OPC). In recent decades, the construction industry has experienced a substantial increase in the demand for concrete, driven by several factors such as economic development and population expansion. Unfortunately, the production of OPC has significant environmental implications. It is an energy-intensive process that consumes large amounts of natural resources and releases substantial amounts of greenhouses into the atmosphere, contributing to about 7% of the total global carbon dioxide emissions. In fact, the production of 1 ton of OPC required 1.5 tons of natural resources and released at least 1 ton of CO_2 [1]. Therefore, there is a global need to reduce cement usage or replace it with more eco-friendly sustainable building materials.

In the current decade, supplementary materials have been the most used products to reduce pollution caused by carbon dioxide emissions caused by the construction industry. Such supplementary materials are typically industrial by-products rich in alumina, silica, and/or calcium, such as fly ash (FA) and ground granulated blast furnace slag (GGBS). They can be used as a binder and mixed along with sodium hydroxide and sodium silicate alkali solutions to produce alkali-activated geopolymer concrete, with a 3-D polymeric chain structure consisting of –Si-O-Al-O- bond [2]. The term geopolymer is used to describe a class of inorganic polymers formed by the reaction of aluminosilicate materials with alkaline solutions [3]. Previous studies have shown that the production of fly ash required 60% less energy and 80-90% less CO_2 emissions compared to the OPC [4]. These findings highlight the potential of utilizing geopolymer concrete as a more sustainable alternative to conventional cement-based concrete.

On the other hand, the second main component in concrete is natural aggregates (NA). The extraction of natural aggregates (NA) has a negative impact on the environment. Simultaneously, the ongoing production of construction and demolition (C&D) waste contributes to additional pressure on the existing landfills and the requirement for extra sites to accommodate the large amount of waste. As a sustainable waste management approach, these wastes could be recycle these wastes in the form of recycled concrete aggregates (RCA) and utilize them instead of NA in construction projects [5]. This method not only reduces the environmental impact associated with NA extraction, but also reduces the overall burden on landfills. In fact, it is also useful in reducing the cost of concrete and achieving sustainable goals. Yet, the porous nature of RCA and the presence of existing mortar has led to weak properties of the RCA and poorly performing concrete [6,7].

The synergic incorporation of geopolymer binder and RCA has seen limited investigation. In their review, Parthiban and Saravana Raja Mohan [8] investigated the mechanical properties of geopolymer concrete containing RCA at 0%, 25%, 50%, 75% and 100% by wt. and compared it with conventional concrete made with OPC. Experimental results indicated that the compressive strength of geopolymer concrete containing RCA was higher than the conventional concrete made with NA. On the other hand, it decreased with increasing the quantity of RCA. Furthermore, as per the findings by Faiz Uddin Ahmed Shaikh [9] who conducted a study on the compressive strength of geopolymer concrete incorporating RCA, a decrease in compressive strength was found with the replacement of NA by RCA. However, Mehta and Bhandari [10] reported that glass fibers positively impacted the mechanical strength but had an adverse effect on the workability of the geopolymer concrete. In one study, the optimum percentage of glass fibers to be added by weight was 1%, after which the strength and workability decreased [11].

Based on the literature, it is clear that glass fibers could have the opportunity to improve the compressive strength of geopolymer concrete made with RCA. Yet, no studies have investigated this idea. Accordingly, this study assessed the fresh and hardened properties of slag-fly ash blended geopolymer concrete incorporating glass fibers and RCA. The influence of mix design process parameters on the properties of such geopolymer concrete was also evaluated.

2. Materials

The geopolymer binder consisted of a mixture of slag and fly ash. Low calcium class F fly ash and ground granulated blast furnace slag (GGBS) were obtained from Ashtech and Emirates cement factory, respectively. The activation of this blended binder was carried out using an alkaline solution consisting of a combination of grade N sodium silicate (SS) and sodium hydroxide (SH). Notably, the sodium hydroxide solution was prepared with a concentration of 14 M by dissolving 97% - 99% purity flakes in tap water.

For the aggregates, locally available dune sand originating from the deserts of the United Arab Emirates (UAE), were utilized as fine aggregates. Subsequent analysis of this dune sand disclosed distinct attributes, including a surface area of 5760 cm^2/g, an absorption rate of 2%, and a fineness modulus of 2.40 [12]. Moreover, the coarse aggregates comprised natural aggregates (NA) and recycled concrete aggregates (RCA). It is worth noting that the NA was sourced as crushed limestone with a specified nominal maximum particle size (NMS) of 19 mm. Meanwhile, the RCA consisted of masonry, tiles, asphalt, wood, ceramic, and crushed construction and demolition concrete, having a similar NMS to NA. Both types of coarse aggregates were in saturated surface dry (SSD) condition before being used in the mix. In order to enhance the workability of geopolymer concrete, a polycarboxylic ether superplasticizer was used since it showed a high influence on the slump values compared to other existing types.

In the experimental study, two different types of glass fibers were used. Type ‘A’ fibers had a length of 24 mm, while Type ‘B’ fibers were 43 mm in length. Table 1 summarized the properties of the glass fibers.

Table 1. Properties of glass fibers

Property	Type A	Type B
Length (mm)	24	43
Diameter (mm)	0.7	0.7
Aspect ratio	35	62
Tensile strength (MPa)	> 1000	> 1000
Young’s modulus (GPa)	42	42
Specific gravity	2.0	2.0

3. Mixture proportions

Mixture proportioning stands as a fundamental aspect of concrete design, causing a pivotal influence on the ultimate ultimate performance, durability, and structural integrity of geopolymer concrete. Initially, the purpose of such study was to attain a 28-day cubical compressive strength between 30 and 40 MPa and a slump value more than 150 mm. The proportions of the geopolymer concrete mixtures are provided in Table 2. The impact of various factors on the workability and compressive strength of geopolymer concrete was examined. These factors include the replacement percentage of natural aggregates with RCA, binder content, amount of additional water (added to the alkaline activator solution), particle size distribution of RCA, and volume fraction of GF. Indeed, a blended binder mixture of was created with a composition of 75% slag and 25% fly ash. This particular combination was chosen after confirming the distinct influence of the slag on compressive strength [13,14]. The liquid-to-binder ratio (L/B) was set at 0.5, SS/SH ratio was maintained as 1.5, and the concentration of SH was 14 M. The values were selected based on their positive effect on the performance of geopolymers [15]. The amount of superplasticizer used was consistent across all mixtures, set at 2.5% of the binder weight. In addition, the effect of glass fiber volume fraction and RCA replacement percentage was examined by varying each at 0, 1, and 2% and 0 and 100%, respectively. Meanwhile, the binder content was increased from 300 to 450 kg/m^3.

Geopolymer concrete samples were designated as RxCtWrAkByGFz-S, where x, t, r, k, y, z and S represent specific attributes. For instance, x stands for the percentage of recycled concrete aggregates (RCA), t denotes the binder content (in kg/m^3), r represents the water content (in kg/m^3), k signifies the proportion of 24-mm fibers within the total fiber volume fraction, y indicates the percentage of 43-mm fibers, and z represents the overall fiber volume fraction (%). Additionally, when S is included in the mix designation, it signifies the process of sieving RCA to remove particles smaller than 4.75 mm and larger than 19 mm. For instance, (R100C450W50A1GF1-S) represents a geopolymer concrete made with 100% RCA, binder content of 450 kg/m^3, water content of 50 kg/m^3, a 1% volume fraction of 24 mm glass fibers, and the sieving process was implemented.

Table 2. Mix proportions of geopolymer concrete (kg/m^3)

Mix ID	Aluminosilicate materials		Fine aggregates	Natural Coarse aggregates		RCA	Alkaline activator		SP	Water Content	Glass fiber (%)	Study Parameter
	Slag	Fly ash	Dune Sand	10 mm	20 mm		SS	SH				
R0C450W100A0B0GF0	337.5	112.5	600	330	770	0	161	64	11.3	100	0	R
R0C450W50A0B0GF0	337.5	112.5	600	330	770	0	161	64	11.3	50	0	R
R100C300W100A0B0GF0-S	225.0	75.0	725	0	0	1210	99	66	7.5	100	0	B
R100C300W50A0B0GF0-S	225.0	75.0	725	0	0	1210	99	66	7.5	50	0	B
R100C300W25A0B0GF0-S	225.0	75.0	725	0	0	1210	99	66	7.5	25	0	B
R100C450W100A0B0GF0-S	337.5	112.5	600	0	0	1100	161	64	11.3	100	0	B, R, W
R100C450W50A0B0GF0-S	337.5	112.5	600	0	0	1100	161	64	11.3	50	0	B, R, W, G
R100C450W25A0B0GF0-S	337.5	112.5	600	0	0	1100	161	64	11.3	25	0	B, W
R100C450W50A100B0GF1-S	337.5	112.5	600	0	0	1100	161	64	11.3	50	1	G
R100C450W50A100B0GF2-S	337.5	112.5	600	0	0	1100	161	64	11.3	50	2	G
R100C450W50A0B100GF1-S	337.5	112.5	600	0	0	1100	161	64	11.3	50	1	G
R100C300W75A0B0GF0	225.0	75.0	725	0	0	1210	99	66	7.5	75	0	S
R100C300W75A0B0GF0-S	225.0	75.0	725	0	0	1210	99	66	7.5	75	0	S

4. Sample Preparation

The geopolymer concrete was prepared by mixing the binder materials along with aggregates in a laboratory pan mixture for a duration of 3 minutes. The activation of this binder involved utilizing an alkaline solution comprising a mixture of sodium silicate (SS) and sodium hydroxide (SH). To allow the sodium hydroxide solution and subsequent solution of SH and SS to dissipate its heat of reaction, each of the two solutions were left cool down for a few hours. Then, the alkaline solution, along with water and superplasticizer, were slowly poured into the mixer and kept continuously mixed with the dry mixtures until achieving a uniform and homogeneous mixture. The fresh geopolymer concrete mix was cast in 100-mm cube specimens and compacted using a vibrating table for up to 20 seconds. Subsequently, the specimens were covered by plastic sheets for 24 hours to minimize the evaporation of the water. Finally, all specimens were demoulded after one day, and then cured in laboratory open air until testing date.

5. Performance evaluation

The workability of the geopolymer concrete was evaluated through the slump cone test based on ASTM C143 [16]. Meanwhile, the compressive strength was determined in accordance with ASTM C39 at the ages of 1 and 7 days [17]. To obtain an average, three cube specimens per mix were cast and tested.

6. Results

6.1 Workability

The slump values of slag-fly ash blended geopolymer concrete are presented in Figure 1. The mixtures were grouped into four clusters, each associated with a specific mix design parameter. The first cluster consisted of 6 distinct mixtures designed particularly to evaluate the effect of increasing the binder content from 300 to 450 kg/m^3 on the slump value of geopolymer concrete. Experimental results indicated that the workability of geopolymer concrete improved with 28% increase in the binder content. This enhancement in workability was seemingly due to the better particle packing and arrangements within the concrete, resulting from increasing the binder content, which plays a significant role in filling the gaps and spacing among the large particles [18]. As such, the flowability of the concrete becomes easier, faster, and much better. Similar to the binder content, the change in the water content was impactful on the workability. In fact, when the water content was set to 100, 50, and 25 kg/m^3 in the mixes made with 450 kg/m^3 of binder, the slump values were 240, 230, and 205 mm, respectively. In contrast, for a binder content of 300 kg/m^3, the slump was 225, 180, and 20 mm for the same respective water contents. This improvement of slump values against increasing binder content was consistent with previous studies [19, 20, 21].

The effect of replacing NA with RCA in geopolymer concrete was also studied. Results revealed that RCA replacement had an insignificant impact on the workability of slag-fly ash blended geopolymer concrete. Such results can be attributed to a significant similarity between NA and RCA in terms of physical properties, such as surface roughness, shape, angularity, and frictional texture [22]. This similarity often leads to minimal differences in the slump results making it possible to compare with its NA counterpart geopolymer concrete.

Furthermore, the influence of glass fibers on the workability of geopolymer concrete was examined. The addition of 1 and 2% Type 'A' glass fibers by volume led to slump reductions of 2 and 9%, respectively, in comparison to the plain geopolymer concrete. On the other hand, the inclusion of 1% of Type 'B' glass fibers resulted in a reduction of 24%. From the experiment, it was observed that type 'B' glass fibers have a more pronounced negative effect on the workability of geopolymer concrete compared to type 'A'. This was due to the higher aspect ratio of type 'B', which causes the fibers to get tangled and ball together. Consequently, the concrete workability and slump values decrease. This reduction in the workability is consistence with other outcomes reported in previous studies[10,23]

Sieving the RCA to remove particles smaller and larger than 4.75 mm and 19 mm, respectively, was evaluated to investigate its probable effect on the workability of geopolymer concrete. By comparing 2 distinct mixes, it was obvious that the slump had increased from 0 to 210 mm. By eliminating smaller particles (less than 4.75 mm), the remaining aggregates are typically larger and have a lower surface area. This practice can enhance the workability as there is less surface area for water to be absorb. Similarly, excluding particles larger than 19 mm would reduce the number of voids inside the concrete, thereby improving the workability of geopolymer concrete.

6.2 Compressive strength

The compressive strength (f_{cu}) of 1- and 7-day slag-fly ash blended geopolymer concrete is demonstrated in Figure 2. Due to the similarity in trends, the focus will only be on the 7-day test results. An increase in the binder content from 300 to 450 kg/m^3 in RCA geopolymer concrete led to an average 30% strength gain at the age of 7 days. This enhancement in performance is due to the higher binder content, which leads to a decrease in the volume of voids and consequently enhancing the density, cohesion, and overall performance and strength of geopolymer concrete [24,25].

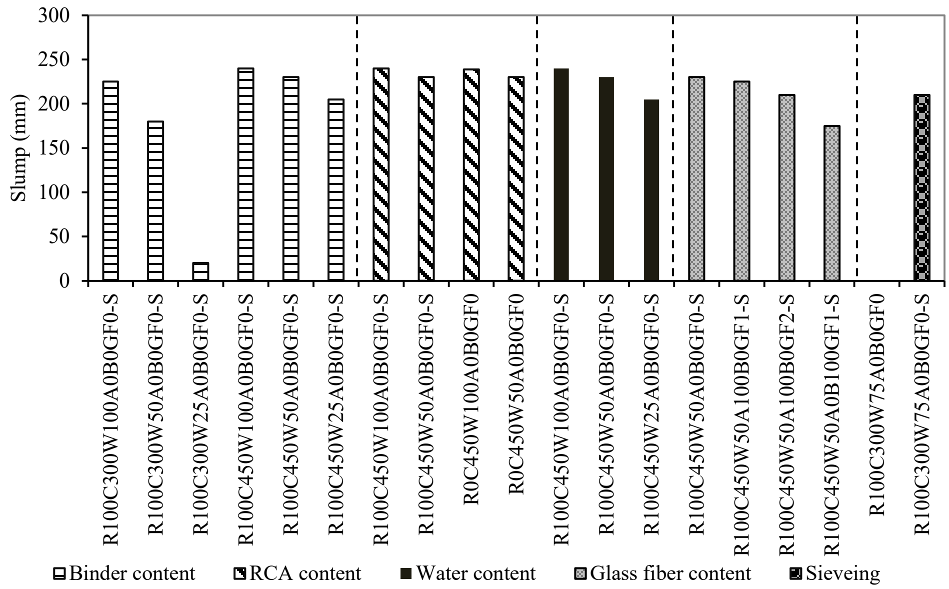

Figure 1. The slump values of slag-fly ash blended geopolymer concrete

The effect of RCA on the compressive strength of slag-fly ash blended geopolymer concrete was studied by comparing 2 mixes with different water content. It is worth noting that the RCA content was changed from 0 to 100%. Increasing the amount of RCA resulted in a reduction in compressive strength. In fact, the 1- and 7-day strength by 11 and 25%, respectively. Such strength reduction is associated to higher void content and weak interfacial bond between the new geopolymeric binder and old mortar on the RCA. Similar findings were noted across different water content. This reduction in the strength is consistence with other outcomes reported in previous studies [15,16].

Figure 2 also shows the compressive strength of concrete specimens proportioned with different amounts of additional water content. It can be noticed that, as the water content increased, the compressive strength decreased. For instance, the compressive strength decreased from 38.7 to 30 and 26.9 MPa for mixtures made with 25, 50, and 100 kg/m^3 of additional water quantity, respectively, representing corresponding reductions of 22 and 30%. This loss in strength was owed to the reduced bond between the concrete ingredients [28]. Furthermore, it can increase the probability of shrinkage occurring within the concrete specimens, leading to higher stress concentration and lower load bearing capacity. It is worth highlighting that, achieving a strength of 30 MPa can be attained by using RCA with a water content of 50 kg/m^3.

The impact of incorporating type ‘A’ and ‘B’ glass fibers on the compressive strength of geopolymer concrete was investigated at the ages of 1 and 7 days. The findings showed that, the addition of 1 and 2% type ‘A’ GF, by volume, increased the 1-day compressive strength by 6 and 8%, respectively. However, they had a negligible effect on the compressive strength of RCA slag-fly ash blended geopolymer concrete after 7 days. Similarly, the addition of 1% type ‘B’ GF, by volume, improved the 1-day compressive strength by 7%. The higher length and aspect ratio of type ‘B’ glass fibers play a crucial role in providing a high resistance against crack formation, leading to concrete mixtures that exhibit enhanced homogeneity, strength, and toughness [29].

Sieving the RCA to remove particles smaller and larger than 4.75 mm and 19 mm, respectively, was evaluated. The experimental results revealed that, by sieving the RCA, the 1- and 7-day compressive strength improved by 29 and 35%, respectively. Such a finding can be associated with the reduction in the fine particle quantities, which required high water content to be absorbed, as well as better density and cohesion of the concrete specimens achieved by eliminating large aggregates that are responsible for having high amounts of voids [30, 31].

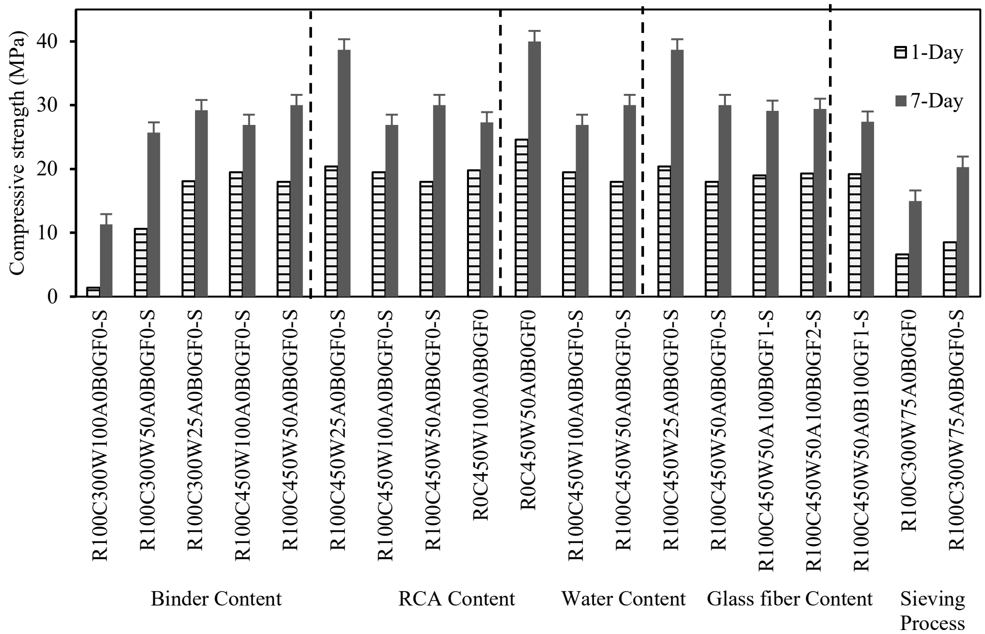

Figure 2. Compressive strength of geopolymer concrete with variations in the mix design parameters

7. Conclusions

This paper evaluated the effect of several mix design parameters, including the replacement percentage of NA with RCA, binder content, amount of additional water, particle size distribution of RCA, and volume fraction of GF, on the workability and compressive strength of geopolymer concrete. From the experimental results, the following conclusions can be drawn:

- Adding up to 50 kg/m^3 of water increased the workability to up to 230 mm while decreasing the compressive strength by up to 22%.
- Sieving the RCA to remove particles smaller and larger than 4.75 mm and 19 mm, respectively, increased the slump to 210 mm and 1- and 7-day compressive strength by 29 and 35%, respectively.
- The addition of 1 and 2% GF, by volume, had a minor effect on the compressive strength of RCA slag-fly ash blended geopolymer concrete. Fibers with larger aspect ratio was more impactful on the 1-day strength.
- The optimum design of RCA geopolymer concrete to be comparable with NA geopolymer concrete was attained by using 50 kg/m^3 of additional water, which leads to a slump of 230 mm and compressive strength of 30 MPa.

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