Performance of slag-metakaolin-based geopolymer concrete (GPC) with recycled plastic eco-aggregate

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Abstract

The high demand for concrete in the construction industry leads to a high cement production rate, thereby increasing carbon emissions (CO_2), resulting in global warming and detrimental effects on human survival. One-part "just add water" geopolymer binder is a potential sustainable binder that could substitute ordinary Portland cement. Currently, there are limited studies on the mechanical properties of one-part slag-metakaolin-based GPC with plastic waste as a substitute for fine aggregate. This paper presents the performance of a one-part slag-metakaolin-based geopolymer using anhydrous sodium silicate, sodium hydroxide and calcium hydroxide as activators. Also, the influence of 5% and 10% replacement of natural sand with RESIN8 (recycled plastic waste containing Resins 1-7) is also reported on the composite's fresh properties. Furthermore, the effects of two curing methods on the mechanical properties (compressive and flexural strength) are presented. Adding plastic waste as fine aggregate in concrete improved the workability, but there was a reduction in the mechanical strength of GPC as the percentage of RESIN8 increased. However, the compressive strength of 28 days water cured (WC) GPC with 5% and 10% RESIN8 were 25.6 MPa and 23.4 MPa, respectively, and ambient cured (AC) GPC with 5% and 10% RESIN8 were 24.1 MPa and 21.7 MPa, respectively.

Keywords: geopolymer concrete, RESIN8, metakaolin, slag, mechanical properties.

1. INTRODUCTION

Over the past few decades, due to global warming, there has been a high demand for sustainable concrete binder development. The intensified demand for concrete in the construction industry has led to a high cement production rate and increased Carbon emissions (CO_2). The International Energy Agency [1] and Wan-En et al. [2] reported that 7% of the global CO_2 emission was generated by the cement industry and 0.83 kg of CO_2 per kg of ordinary Portland cement (OPC) [3]. According to Davidovits [4], the production of 1 tonne of cement generates an almost equivalent quantity of carbon emissions (0.99 tonne) during the calcination of limestone and combustion of carbon-based fuel. Furthermore, Andrew [5] reported that the global cement CO_2 emission in 2016 was 1.45±0.20 Gt out of the accumulated 39.3 Gt of CO_2 from 1900-2016, and South Africa emitted more than 6 Mt of CO_2 from 1950-2016. Hence the need for sustainable Portland cement (PC)-free binder.

Geopolymer is a new generation and PC-free binder for concrete production comprising aluminosilicate precursors and activators, with promising performance and capable of replacing

PC in concrete. There are various aluminosilicate precursors, such as fly ash, ladle slag, red mud, metakaolin (MK), ground granulated blast furnace slag (GGBS), etc. However, the abundant availability (over 5000 Mt) [6] and physicochemical stability properties of MK have made it more suitable and recognised for engineering applications [7]. MK is produced by de-hydroxylation of kaolin between 650 °C and 800 °C [8], constituting an excellent amount of about 55% of SiO_2 and Al_2O_3 but deficient in CaO. On the other hand, ground granulated corex slag (CS) is rich in CaO; hence, it has been used in this study to fill the gap. GGBS is obtained in the metallurgical process of pig iron ore or ignition of coke at a temperature of 1500 °C with an approximate annual production of 270-390 million tonnes [6], while CS is obtained from the production of iron steel through the smelting reduction process.

The first invention of geopolymer started from a two-part application which required a corrosive, viscous and hygroscopic liquid activator that limited its practicability in cast-in-situ and mass concrete production to precast concrete [9]. Hence, the need to develop a one-part geopolymer which is user-friendly. One-part, otherwise referred to as "just add water" geopolymer requires anhydrous activators, which makes its application similar to PC and eradicate the transportation of large quantity of corrosive liquid activators for construction purposes. The most widely used anhydrous activators in one-part geopolymer are Na_2SiO_3 and NaOH. However, producing Na_2SiO_3 from the direct fusion of sand and sodium carbonate is energy-intensive, requiring 850-1088 °C [9] and generating a significant amount of carbon emission but lower than PC [10]. Therefore, there is a need to reduce the demand on Na_2SiO_3 by partially or fully replacing it with other viable activators; hence, NaOH and $Ca(OH)_2$ were used to replace anhydrous sodium metasilicate pentahydrate ($Na_2SiO_3.5H_2O$) partially.

The activation of MK-GGBS at equal proportion leads to the formation of C-S-H gel, which produces more stability in the matrix by filling the pores. Still, the high content of GGBS in the mixture reduces the durability properties through shrinkage cracks [11]. Hence, in this study, CS:MK at a proportion of 70:30 was chosen from trial mixes due to its performance over others while incorporating PVA fibre to avoid plastic shrinkage cracks.

The use of recycled aggregate is inevitable in concrete production based on the high demand for natural aggregates (fine and coarse aggregates). According to Babafemi et al. [12], aggregates amount to 75-80% of the volume of the concrete, with fine aggregate constituting 35-45%. Hence, the incorporation of recycled aggregate in concrete production has become crucial for sustainable development in the construction industry and a solution to the shortage of natural sand. Geyer et al. [13] estimated the global plastic produced from 1950 to 2015 to be 8,300 Mt, of which 30% was in use as of 2015, while 9% was recycled, 12% incinerated and 60% discarded and ended up in landfill, oceans and rivers (see Figure 1). In addressing this challenge, researchers have investigated the performance of concrete using recycled aggregate [12,14]. Hence, incorporating recycled plastic waste in concrete to mitigate environmental pollution and develop sustainable and economical concrete holds potential [12].
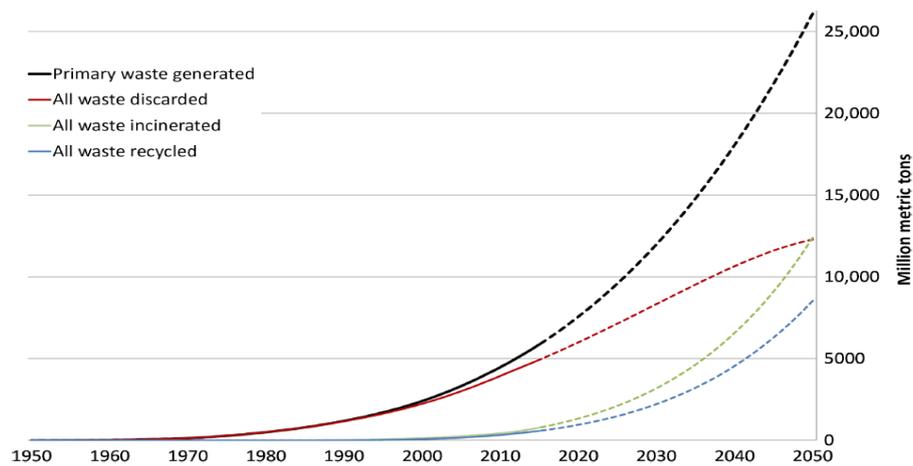
Figure 1: Global trend of plastic production and disposal in million metric tonnes from 1950-2015 and its projection to 2050 [13].

2. EXPERIMENTAL PROGRAMME

2.1 Materials

The materials used in this study are MK and CS (aluminosilicate precursors), locally sourced Malmesbury sand and 13 mm Greywacke stone, recycled plastic waste (sub2 mm), activators ($Na_2SiO_3.5H_2O$, NaOH, and $Ca(OH)_2$, water and admixtures. The MK was obtained from Kaolin Group, and the CS was produced by Arcelor Mittal Steel Plant and supplied by PPC Ltd, South Africa. The recycled plastic waste, patented as RESIN8, is a plastic aggregate that comprises all 7 types of plastics and has been modified to improve the performance of cement-based materials. It was supplied by Centre for Regenerative Design and Collaboration (CRDC), Cape Town. The chemical composition of the aluminosilicate precursors was determined by X-ray fluorescence (XRF) analysis, and the result is presented in Table 1. Figure 2(a-d) shows the precursors and aggregate used. The retarder (trisodium phosphate (NP)) and activators were purchased from Kimix Chemical Lab in Cape Town, South Africa. The specific gravities of MK, CS, sand and RESIN8 are 2.41, 2.90, 2.67 and 1.03, respectively. Polyvinyl alcohol (PVA) fibre having a specific gravity of 1.3 g/cm^3 was used to reduce the shrinkage of the mixes. The oxide molar ratio of the mix is 0.51, 4.45, 0.12, 0.76 and 21.38 for NaO_2/Al_2O_3, SiO_2/Al_2O_3, NaO_2/SiO_2, $(Ca+Mg)O/SiO_2$ and H_2O/SiO_2, respectively, which are within the recommended molar ratio by Davidovit [15].

(a) (b) (c) (d)
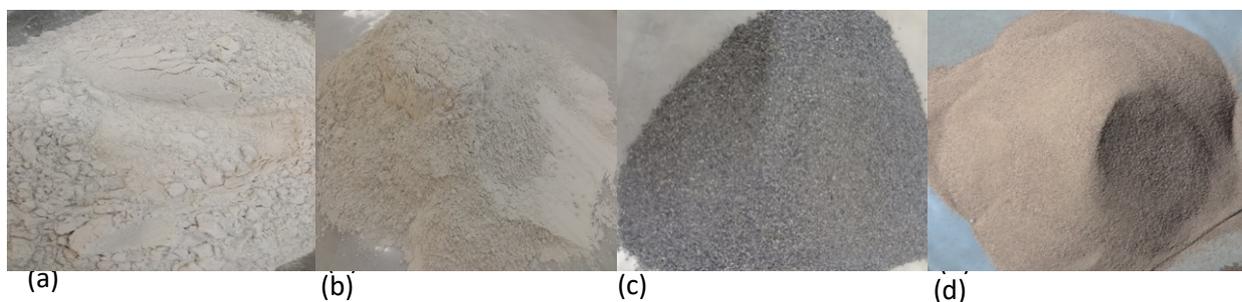
Figure 2: Aluminosilicate precursors and fine aggregates (a) corex slag (b) MK (c) Resin8 (d) Malmesbury sand

Table 1: Chemical composition of aluminosilicate precursors

Compound	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	others
CS	14.49	38.46	1.35	0.6	11.92	0.16	32.96	0.55
MK	24.52	0.04	1.88	3.89	1.03	0.33	67.14	0.87

The moduli of sand, RESIN8 and Greywacke stone are 2.34, 2.53 and 6.75, respectively. Thorneycroft et al. [16] noted that the performance of plastic in concrete could be improved by matching the particle size distribution of plastic aggregates with the replaced sand. Hence, the plastic aggregate and sand used in this study were pre-treated to match the aggregate particle size distribution, which were both below 2 mm aggregate sizes, as shown in Figure 3.
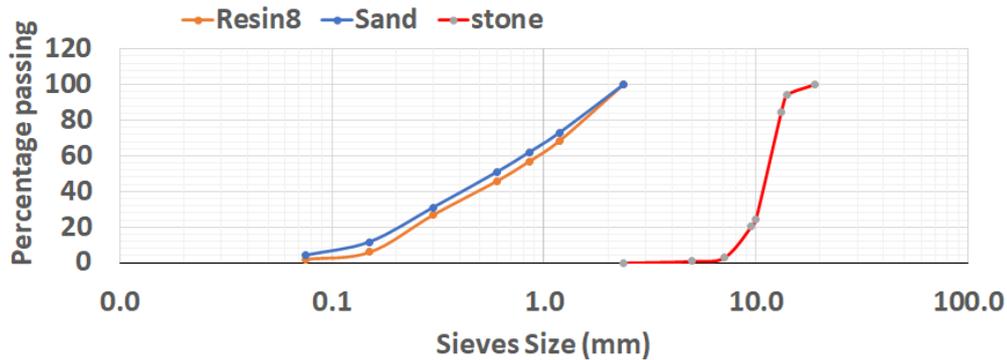
Figure 3: Particle size distribution curve of sand, RESIN8 and 13 mm Greywacke stone

2.2 Concrete Mix Proportion

The aggregate proportions and mix design were obtained by the packing density method [17], and the optimum proportion of the aluminosilicate precursors and activators was obtained through trial mixes using the Taguchi approach [18]. The proportion of CS to MK was 70:30, and 12% activator by weight of the binder was used. The optimum percentage combination of Na_2SiO_3: NaOH: $Ca(OH)_2$, hereafter referred to as SS:SH:CH, obtained from trial samples was 6:3.6:2.4 (% by weight of the binder). The admixtures used were 1.2% modified polycarboxylate superplasticiser and 1.5% PVA by wt. of the binder. The reference mix (0%) and RESIN8 mixes are presented in Table 2. The sand was replaced with RESIN8 by volume at 5% and 10%, which is denoted as R5% and R10%, respectively, and the targeted class of concrete for reference mix was C20/25 (strength of 20-25 MPa) with class S3 slump (100-150 mm).

Table 2: GPC mix design (kg/m^3)

Mark	MK	SL	SS	SH	CH	NP	CA	FA	RESIN8	PVA	water
0%	94	265	21.60	12.96	8.64	9	1167	778	0	2.6	221.7
R5%	94	265	21.60	12.96	8.64	9	1167	739	15	2.6	221.7
R10%	94	265	21.60	12.96	8.64	9	1167	700	30	2.6	221.7

3. EXPERIMENTAL TESTS

3.1 Fresh Properties

The workability and density of all the freshly mixed concrete samples were determined using a slump cone following BS EN 12350-2 [19].

3.2 Strength Tests
3.2.1 Concrete density and compressive strength

The concrete cube (100 mm) samples were cast and compacted using a vibration table in accordance with BS EN 12390-2 [20]. The concrete samples were cured for 7 and 28 days under ambient conditions and complete water immersion. The hardened concrete samples' densities were determined following BS EN 12390-7 [21], and compressive strength was determined following BS EN 12390-3 [22] using a KingTest Contest machine at a loading rate of 180 KN/min until the samples failed. The average failure loads of five samples were computed for each mix.

3.2.2 Flexural Strength

Three prismatic concrete replicates of 300 x 100 x 100 mm were cast per mix and cured for 7 and 28 days under ambient conditions as per BS EN 12390-1&2 [20, 23]. A four-point bending test was conducted on the specimens using a Zwick Z250 material testing machine at a load rate of 0.06 MPa/s according to BS EN 12390-5 [24].

4. RESULTS AND DISCUSSION

4.1 Workability of Mixes

The workability of the mixes increases with an increase in the percentage content of RESIN8, as shown in Figure 4a. The physical characterisation of the aggregates shows that sand has a high-water absorption (1.42%) than RESIN8 (0.68%) due to the hydrophobic nature of plastic, while sand is hydrophilic. Hence, the improved workability with the increase in RESIN8 [12, 25]. The fresh density of the mixes (Figure 4b) decreases with an increase in the percentage of RESIN8; this can be attributed to the light weight of plastic.
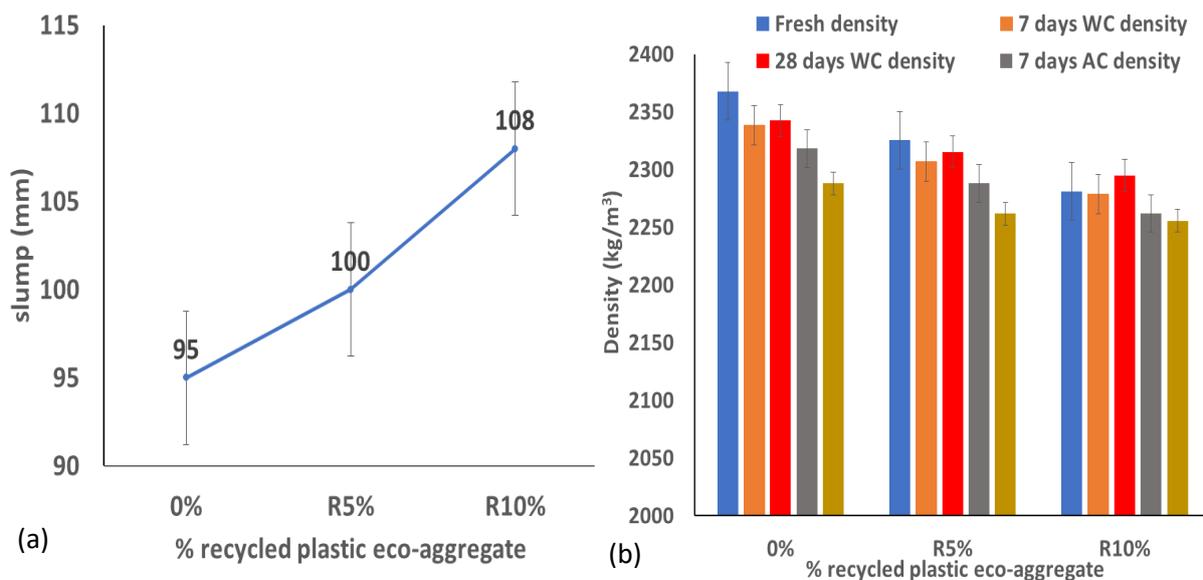
Figure 4. (a) Workability and (b) density of GPC with resin8.

4.2 Hardened Density

Similar to the fresh density, the hardened density of the samples reduced with an increase in the percentage content of RESIN8, and this is attributed to the lightweight characteristic of plastic with a specific gravity of 1.03, compared to sand with 2.67. The density of the concrete samples with 5% and 10% RESIN8 decreased by 1.14% and 1.4% for AC and 1.15% and 2% for WC, at 5% and 10%, respectively, compared to the control samples at 28 days. The density reduction with an increase in the percentage of plastic was also reported by [25, 26].

4.3 Compressive and Flexural Strength

The compressive and flexural strength of GPC are presented in Figure 5. From the 7- to 28-day, the compressive strength of the control samples increased by 6.9% and 9.4% for AC and WC samples, respectively. This implies an early age strength development in GPC. However, there is a 15.9%, 24.1%, and 14.7%, 22.2% decrease in the compressive strength of AC and WC samples containing R5% and R10%, respectively, compared to the control sample at 28 days. This is attributed to the weak interfacial bond around the plastic aggregates (interfacial transition zone, ITZ), increased porosity and lower stiffness of plastic compared to sand. In contrast, according to Thorneycroft et al. [16], the strength of a conventional concrete sample with plastic waste increased when the fine sand and plastic particle sizes were matched. The decrease in strength was also reported by [12, 25, 27, 28]. However, structural strength is achieved at a R5% content.

The flexural strength of the GPC samples decreased at R5% and increased at R10% at 7 days AC, but the strength at 28 days of AC samples decreased progressively with increased RESIN8 content. The flexural strength of the GPC samples at 28 days was 14.2%, 15.3%, and 14.1% of the compressive strength for control (0%), R5%, and R10%, respectively.
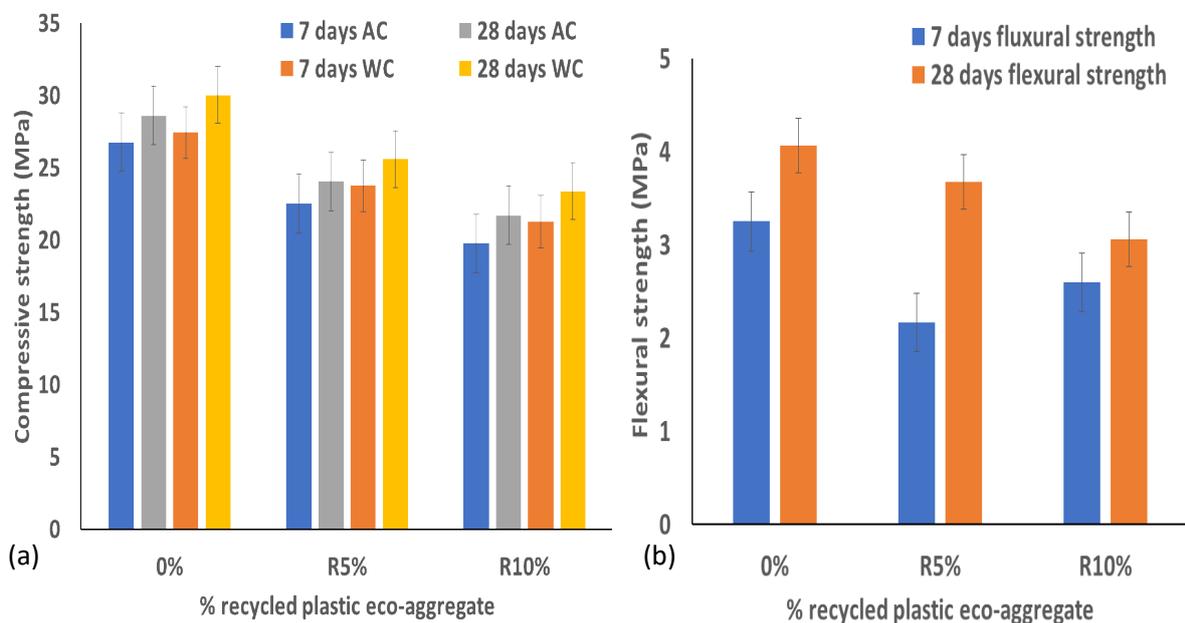
Figure 5. Mechanical properties of ambient and water-cured GPC (a) compressive strength (b) flexural strength (ambient cured).

5. CONCLUSIONS

This study investigated the effects of plastic waste (RESIN8) as a partial replacement of natural sand (5% and 10% by volume) on the fresh and hardened properties of slag-metakaolin- based geopolymer concrete. The workability, fresh and hardened density, and compressive and flexural strength were investigated. The following conclusions are summarised from the investigation.

1. The addition of RESIN8 increases the workability of slag-metakaolin-based geopolymer; however, it reduces the fresh density of the concrete mix.
2. Geopolymer can be effectively cured under ambient conditions and water curing methods. However, the concrete samples cured in the water exhibited higher compressive strength than those cured in ambient conditions.
3. The hardened density and the compressive strength of the geopolymer samples decreased with increased content of RESIN8 by 1.4% and 2% for density and 24.1% and 22.2% for compressive strength at R10% at 28 days AC and WC samples, respectively.
4. The flexural strength also decreased with an increase in the percentage content of RESIN8. However, RESIN8 can substitute fine aggregates up to 10% by volume in slag (CS)-metakaolin-based non-structural geopolymer concrete and 5% in structural geopolymer concrete.

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