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Effects of Waste Glass Powder as Partial Replacement of Cement on the Structural Performance of Concrete

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Abstract Incorporating wastes into concrete as alternative binder is on the increase. The research investigated the influence of milled glass when used to replace cement in the production of concrete. The glass was milled to a particle size finer than 600μm and characterized using X-ray Fluorescence and X-Ray diffraction analysis. Glass powder was used to replace cement at varying level of percentages: 0, 5, 15 and 25%, respectively. Concrete samples were prepared using South Africa mix design method, adopting water-binder ratio of 0.47. The samples were put in water for curing at 7, 28 and 56 days, respectively. Results revealed that the waste glass powder is pozzolanic with a high content of Quartz. Water absorption increases with increasing Waste Glass Powder (WGP) with control samples showing the least water absorption of 6.38% at 56 days followed by 5% replacement with water absorption of 6.86%. The compressive and splitting tensile strengths decreased with increasing content of WGP. However, with 5% WGP content at 7 days of curing, the strengths surpassed the control and attained 99% strength of control sample at 56 days. In conclusion, 5% WGP exhibited the tendency of effective usage as supplementary cementitious material in concrete.

Keywords Recycled Waste Glass Powder, Setting Times, Consistency, Compressive and Split Tensile Strengths, Water Absorption

1. Introduction

The ancient concrete industry depended heavily on the use of Ordinary Portland Cement (OPC) as a major binding ingredient for concrete paste, which had no alternative [1]. In addition, world's expansion and civilization have forced rapid exploitation of natural resources and have resulted in loss of ecosystem. Therefore, concreting became unsustainable. This has motivated recent studies to find supplementary cementitious materials with similar features as cement. Researchers opined that cement production requires high energy-usage and contributes to carbon emission into the atmosphere. Studies revealed that manufacturing of 1 ton of Ordinary Portland Cement produces almost an equivalent amount of carbon dioxide CO_2 into the environment, posing a deleterious impact to the environment [2, 3]. There have been numerous agricultural residues and industrial by-products amongst are fly ash (FA), GGBS, metakaolin (MK), and slag used as alternative to cement in concrete [4-6]. However, some of the supplementary cementitious materials investigated were unable to fully achieve the requirements of sustainable concreting.

Recycled glass constitutes a great environmental hazard as it is a non-biodegradable material since it does not decompose when disposed into landfill. Additionally, glass with particles less than 75 μm has been reported to exhibit supplementary cementitious properties and contain amorphous material with high silica contents [3, 7-8]. Thus,

waste glass powder (WGP) has the prospect of being used in place of cement in the production of concrete. It is inevitable that partial substitution of cement with pozzolanic materials brings about modification of microstructure which aids hydration process and brings an improvement on strength performance and microstructure of concrete with high strength requirement [9].

Glass from broken bottles can be safely recycled for transformation into other useful material either to replace aggregates (coarse and fine) or cement. Numerous studies have been conducted using glass as aggregates (fine and coarse) in the production of concrete. However, little attention has been given to the prospect of using WGP as a potential binding agent in concrete or mortar. Kumar [4] researched the combination of WGP in place of fine aggregates at 0%, 3%, 6%, 9%, 12%, 15% and proportion of recycled steel fibres (RSF) of 0, 0.5, 1 and 1.5%. The project showed that the combination of both materials was effective at optimal combination of 9% WGP and 1% RSF. Also, Abdallah [10] conducted research using waste glass (WG) as filler material in the production of concrete composite. They concluded that at 20% replacement there was enhancement in mechanical properties after being cured for 28 days.

Kumar [11] examined the influence of WGP to replace fine aggregates with percentages from 5 to 50% at an increment of 5% and revealed that WGP material was effective to refine the strength of concrete in the compression zone at the optimum replacement of 25%. The application of glass as coarse aggregate in the range of 15-20% was observed to give compressive strength of 19.91 N/mm^2 for a grade 20 concrete, a value relatively close to that of the control experiment [12].

Despite numerous studies on the applications of WG as alternative aggregates in concrete, limited work had been done in investigating its usage as a binder in the production of concrete. In addition, the issue of durability was silent in most studies, and attention was mostly on the mechanical properties. This study extends the investigation into using WGP as a supplementary cemnetitious material by partial replacement of cement with WGP. The study also looked into both the mechanical and the durability properties.

2. Materials and Method

2.1. Materials Sourcing

The binder material for this study was OPC CEM1 42.5 N with relative density of 3.14. Recycled glass used was obtained from the African Pegmatite (Pty) Limited, South Africa and milled to a very fine particle of 600 microns and below. Particle gradation of the recycled WGP was determined as presented in Figure 1. Crushed stones of size 22.5 mm are supplied by AfriSam, South Africa, being the coarse aggregate used for this research. The relative density and the compacted bulk density of the coarse aggregate are 2.59 and 1609 kg/m^3, respectively. Also, crushed granite sand was used as fine aggregate and was obtained from the same vendor, Afrisam. The fine aggregate has a relative density and fineness modulus of 2.63 and 2.9, respectively. Standard silica sand according to SANS 50196-3 [13] was used for cement paste. Portable water was used for all the mixes. Water/binder ratio adopted for the concrete was 0.47 and 0.5 for mortar mixes.

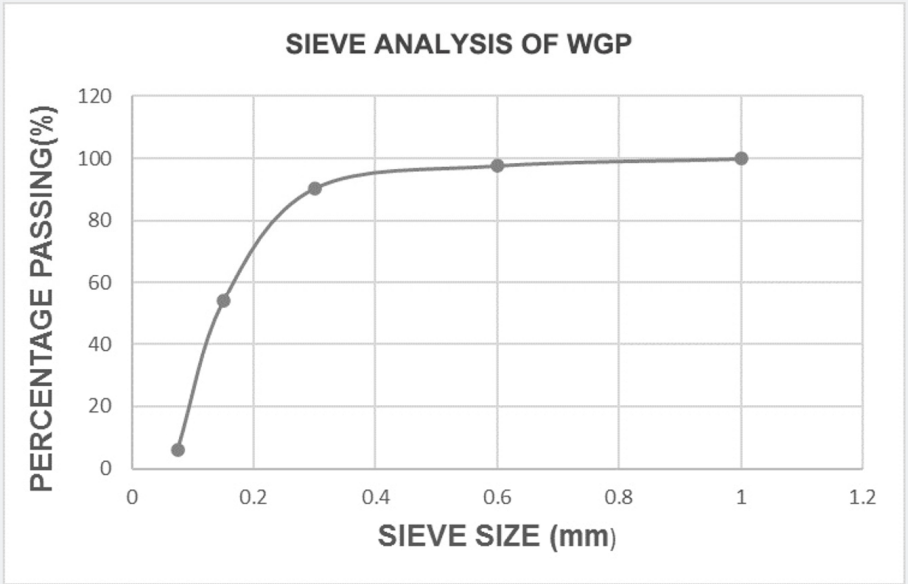


Figure 1. Particle Size Distribution Curve of Waste glass powder

2.2. Methodology

Particle size grading of the WGP sample was done through sieve analysis according to SANS 3001-AG1 [14] using the following set of sieves: 1, 0.6, 0.3, 0.15 and 0.075 mm, respectively. The waste glass powder was poured through the topmost sieve and allowed to pass through succeeding sieves. The analysis was done with the aid of a vibrator. The weight of sample retained on each sieve, and the corresponding percentage passing were determined accordingly. The X-ray Fluorescence (XRF) of the cement sample used was done by Afrisam, while the XRF analysis of the WGP was done at the Mining Engineering department, University of South Africa. The oxide composition of the WGP was done using Bruker S1 Titan 600 Handheld XRF Spectrometer. The mineralogical and phase nature of the waste glass powder was done using X-Ray diffraction (XRD) analyzer. XRD analysis of the WGP sample was carried out at the Department Chemical Engineering, University of Johannesburg.

2.2.1. Consistency and Setting Times of Binder

The mixing of the cement paste was done according to the procedure in SANS 50196-3 [13] and a standard consistence of 32, 31, 31, and 33%, respectively was determined for waste glass powder proportions of 0, 5, 15, and 25%, respectively. Table 1 indicates the mix proportioning that gave the "standard consistency" of the mixes. The initial and final setting times of fresh binder paste containing proportions of 0, 5, 15, and 25% WGP were established by monitoring the penetration of a needle into fresh binder paste until it attained a defined value, in accordance with [13].

Table 1. Mix design for binder paste

Percentage of Glass	Cement (g)	Milled Glass (g)	Quantity of water (g)
0	500	0	160
5	475	25	155
15	425	75	155
25	375	125	165

2.2.2. Batching and Preparation of Concrete Specimen

All materials were weighed based on the calculated mix design values presented in Table 2. Waste glass powder and cement were varied in accordance with replacement percentages of 0, 5, 15 and 25%. However, the amount of water, coarse and fine aggregates remained constant on each mix, with 0.47 being the ratio of water to cement. Thereafter, the workability of the concrete mixes was monitored through slump test. The slump was measured in accordance with [15]. Concrete was designed such that three (3) specimens were tested in each curing duration and average result was recorded as the representative strength. Concrete batches for each mix were cast using cube mould of 100mm x 100mm x 100mm x 100mm. An automatic vibrating table was used to compact all the samples; thereafter, they were covered with plastic and kept for 24 hrs. After which, samples were demoulded and placed in water for curing at 22˚C ± 5˚C for 7, 28, and 56 days, respectively. This was done in accordance with [16].

Table 2. Proportioning of Constituent Materials to Produce Concrete

WGP (%)	C (Kg)	WGP (Kg)	FA (Kg)	CA (Kg)	QW (Litres)	S (mm)
0	496	0	563	1323	4.2	93
5	471	25	563	1323	4.2	92
15	422	74	563	1323	4.2	97
25	372	124	563	1323	4.2	100

Legend:

WPG = Waste Glass Powder, C = Cement, FA = Fine Aggregate, CA = Coarse Aggregate, QW= Quantity of Water, S = Slump

2.2.3. Compressive and Split Tensile Strengths

The compressive strengths of the samples were obtained by subjecting the samples to a compressive load at various ages of curing as described in [17]. The samples were tested sequel to removal from water, wiped clean and weighed. The bearing surface of the platens of the machine is wiped and cleaned and cube is positioned accordingly. The specimen was aligned with the centre of thrust of the spherically seated platen. Thereafter, the compressive load was applied without shock and allowed to increase continuously at a uniform rate of between 0.3 MPa/s ± 0.1 MPa/s until the specimen failed. The split tensile strengths of the samples were obtained according to [18]. As in the case of the compression test, specimens are wiped cleaned and weighed. The test was performed using a compression testing machine complemented with steel load pieces, which were positioned between the platen of compression machine and the packing strips, see Figure 2. The load pieces are of a section of a cylinder, with a radius of 75 mm, so that the load is applied along a line on the surface of the cube specimen.

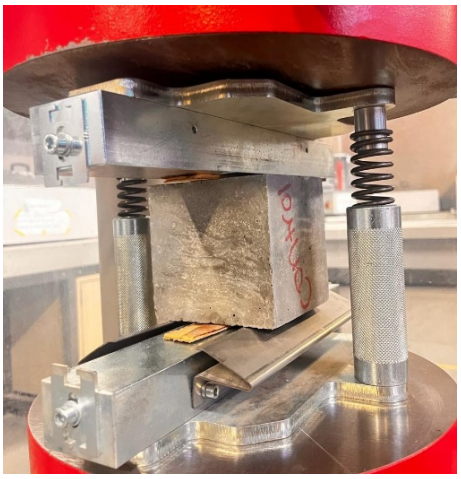


Figure 2. Concrete Cube under Split Tensile Strength Test

The specimens were placed in a central position under the compression machine as shown in Figure 3. Load was applied without any form of shock and continuously increased at a nominal rate of 0.03 MPa/s ± 0.01 MPa/s until failure occurred and maximum load was recorded accordingly.



Figure 3. Concrete Cube Under Compression Load

2.2.4. Water Absorption Test

The water absorption (WA) test was performed in accordance with [14]. At respective curing ages of 7, 28 and 56 days, the concrete cubes samples were removed water. After the removal, the samples were made clean of water with a cloth. With the samples still appearing to be damp, the mass of the samples was recorded as surface-dry mass to the nearest 0.1 g. Each of the samples was transferred to a tared wire basket and completely submerged in a container of water at temperature of 25 °C, and the wire basket and test sample submerged in water were weighed and the mass was recorded as "mass of the saturated test sample in water" to the nearest 0.1 g. Finally, the test sample was removed from the wire basket, allowed to drain off free water and dried to a constant temperature of between 110 ℃ in an oven. The mass of the oven dried sample, after 24 hours of placement in the oven, was recorded to the nearest 0.1 g as "mass of the saturated surface-dry test sample".

3. Results and Discussion

3.1. Particle Size Distribution Analysis

Figure 1 presents the particle size gradation curve of the WGP. Particle size of cement determines its surface area which is greatly dependent on the grinding effort. There is enhancement in the rate of hydration of cement with high surface area. The pattern of the curve is like a typical conventional cement as reported by [19].

3.2. X-ray Fluorescence (XRF) of Cement and WGP

Table 3 shows the chemical composition of the cement and WGP. It shows that sum of silica, alumina, and ferric oxide of WGP is found to be 95.2% which is greater than 70% as stipulated by ASTM 618 [20] for pozzolanic materials. This agrees with the finding by Tognonvi [21] where the addition of the three oxides was found to be greater than 70%. However, the case of cement is different from the waste glass powder with high content of calcium oxide affirming the composition of Portland limestone cement. The replacement of cement with WGP is expected to undergo a pozzolanic reaction.

Table 3. Chemical composition of cement and waste glass powder

Elemental Oxide Composition (%)	Materials	
	CEM1 42.5 N	Waste glass powder
SiO_2	33.39	89.10
Al_2O_3	15.00	3.90
Fe_2O_3	2.61	2.20
MgO	3.75	1.06
CaO	41.94	-
Na_2O	0.25	-
K_2O	0.68	-
TiO_2	0.66	-
SO_3	2.2	-
LOI	2.2	-

3.3. X-Ray Diffraction Analysis (XRD) of Waste Glass Powder

The result of phase nature of the WGP using diffractometer range of angle 10 to 80º is presented in Figure 4 and Table 4. The peak intensity observed on a 2θ copper anode was around 26.5º, which is attributed to quartz (SiO_2) as opined by [21]. Other peaks of quartz were found at around 50 º and 67.9º and this is as reported elsewhere [22]. In addition, the XRD pattern agrees with the result presented by [23]. The 2θ value is a measure of amorphous nature of supplementary cementitious materials, with lower value depicting high degree of amorphous nature, and consequently, good pozzolanic properties [19, 24]. The WGP however, exhibits the tendency of pozzolanic material as in agreement with the chemical composition analyzed in section 3.2 and could be used as supplementary cementitious material in concrete.

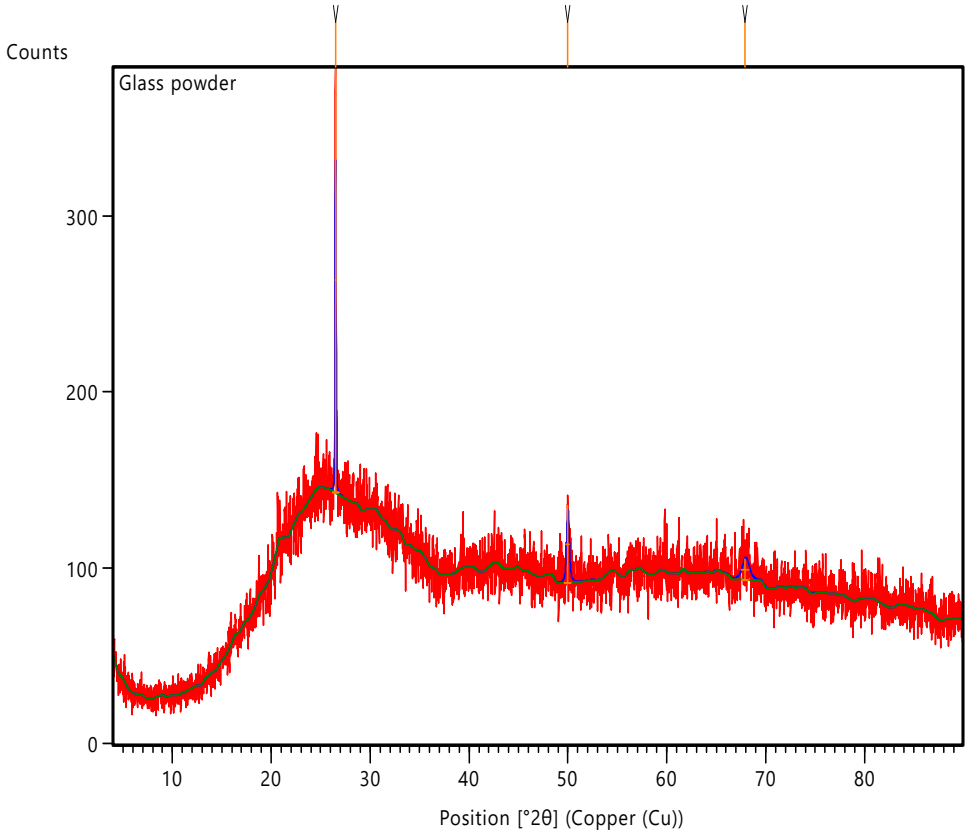


Figure 4. XRD of Waste glass powder

Table 4. XRD Peak values for waste glass powder sample

Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
26.4837	242.81	0.0669	3.36563	100.00
49.9664	43.74	0.2676	1.82534	18.01
67.9322	11.97	0.8029	1.37987	4.93

3.4. Setting Times and Consistency of Waste Glass Powder Blended Cement

Water consistency was ascertained for each sample's cement paste before the setting time test was done. Figure 5 shows the water consistency required for each sample at varying percentages of WGP. The results show negligible difference in the quantity of water needed to maintain the consistency required for setting time test. However, 25% replacement required more water than the other samples. Figure 6 shows the effects of WGP on the setting times of cement. The setting times both initial and final satisfied minimum of 60 mins for the former and 90 mins for the latter as recommended by [25]. The initial setting times increase as the percentage of waste glass powder increases up to 15% replacement. Thereafter, it declined for 25% replacement, but still higher than the control sample's initial setting time. This trend of result agrees as obtained elsewhere [26]. The reason for the decline between 15% replacement and 25% replacement was not ascertained. The Final setting times were observed to increase as the glass content increased. The results generally show that WGP may delay the rate of hydration of cement paste and may take a little time to set as compared to the time required for the control sample to set. Furthermore, the significant difference between the initial and final setting times at 25% WGP content may be attributed to more quantity of water present in there and effect of pozzolanic activity, which in turn could delay the final setting of the composite. This was also evident in the work of Amziane [27] where significant difference occurred between setting times due to effects of pozzolanicity.

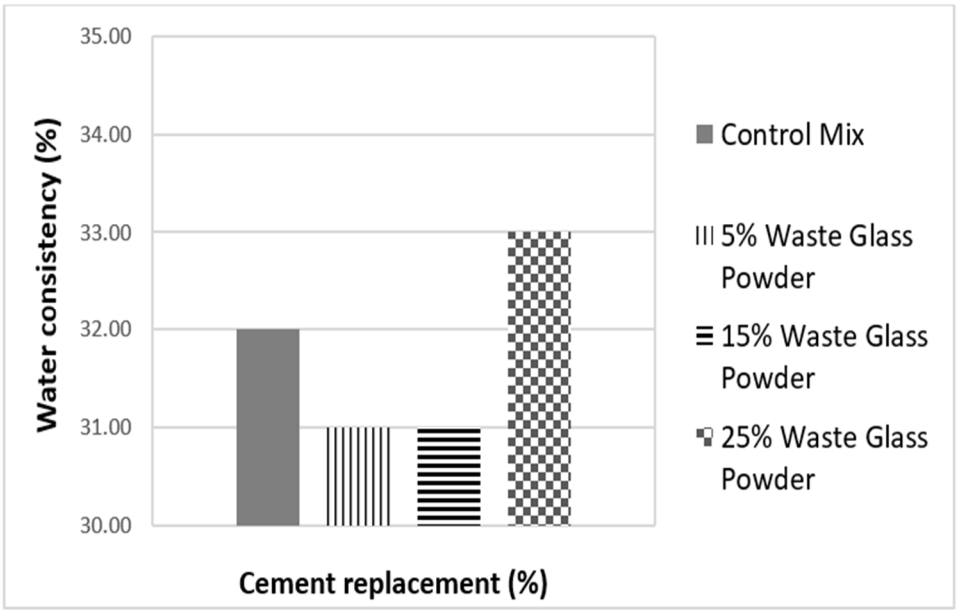


Figure 5. Effect of Waste glass powder the Consistency of the Binder

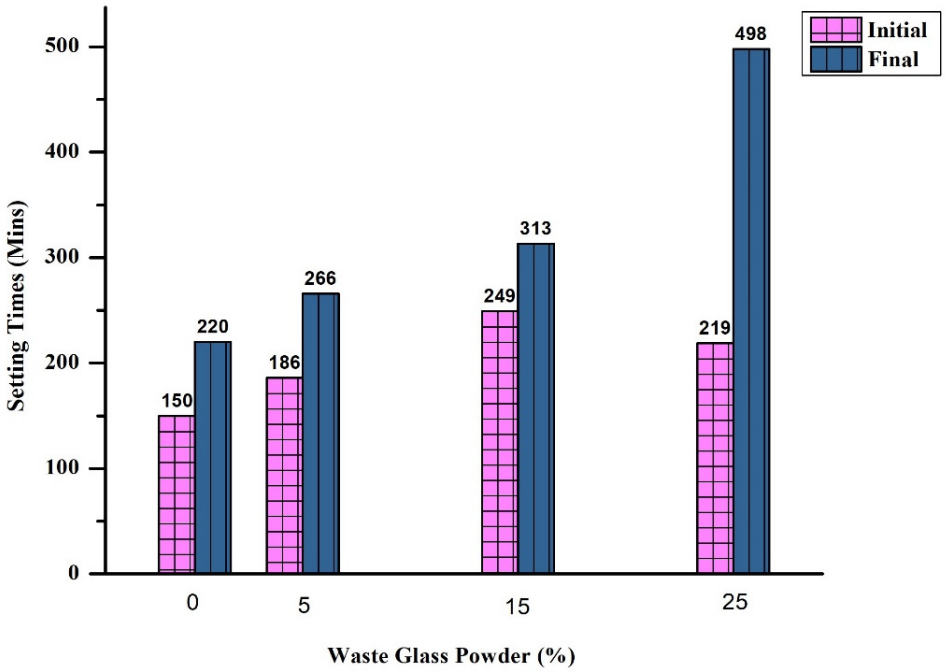


Figure 6. Waste glass powder on setting Times of Blended Cement

3.5. Water Absorption of Concrete Containing Waste Glass Powder

The water absorption of the WGP concrete is presented in Figure 7. The water absorption was observed to increase as the percentage of glass increases. This increment in the percentage of WGP may imply a reduction in the pore refinement tendency of the composite. Hence, increasing the susceptibility of the concrete to moisture. This result is in contrary to the work of Chaid [28] where the permeability of the concrete containing glass and superplasticizer was significantly low compared to the control, and consequently, reducing the inflow of moisture. This variation may be attributed to the presence of superplasticizer as well as the nature or type of the glass.

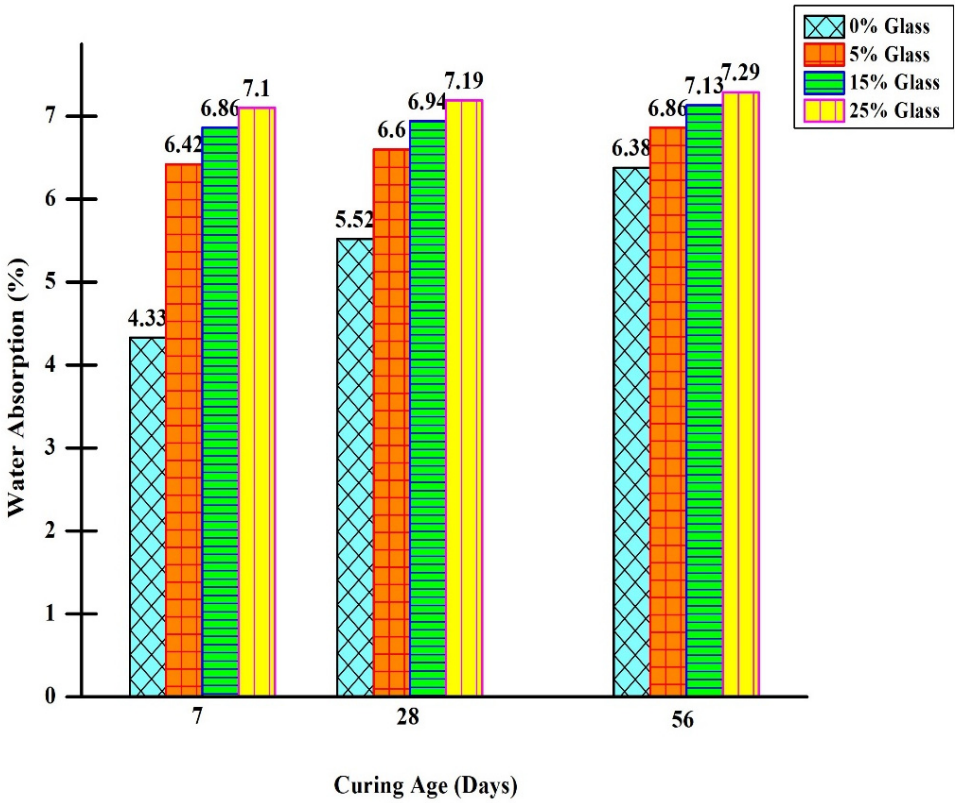


Figure 7. Water Absorption of Concrete with WGP

3.6. Compressive Strength of Concrete Containing WGP

Figure 8 shows the result of the effects of varying percentages of WGP on the strength of concrete in the compression zone. The result indicates that compressive strength is being enhanced as ages of curing increases for all samples and declined with increasing percentages of WGP. At early age of curing, 5% WGP has the greatest compressive strength with a value of 32.95 MPa, which surpassed both the control and other replacement samples. The trend of results changed at 56 days where the strength in the compression zone of the control having a value of 55.32 Mpa was found to be greater than 54.82 MPa of the 5% waste glass powder. However, the percentage increase was about 0.91%. This result is contrary to the work Sadiqul Islam [29] where compressive strength at 7 days was decreased with increasing content of WGP. An enhancement in compressive strength at later age was an indication of pozzolanic reaction and increased production of C-S-H gel within the particles of cement, which became evident in all levels of replacement. This agrees as obtained elsewhere [30].

3.7. Split Tensile Strength of Concrete with WGP

Figure 9 shows split tensile strength of concrete with 5% WGP having the highest value of 1.56 MPa at 7 days relative to that of the control (0% WGP) and other replacement samples. At later ages, the strength of the control was found to be 2.03 MPa, which is higher than 1.88 MPa of the 5% level of replacement. The trend of result is like the compressive strength results. This agrees as obtained elsewhere [30]. Generally, concrete is weak in tensile and the results obtained are satisfactory and deduce that WGP concrete cannot be used for structural purposes without being reinforced. The reinforcement will cater for the tensile strength deficiency.

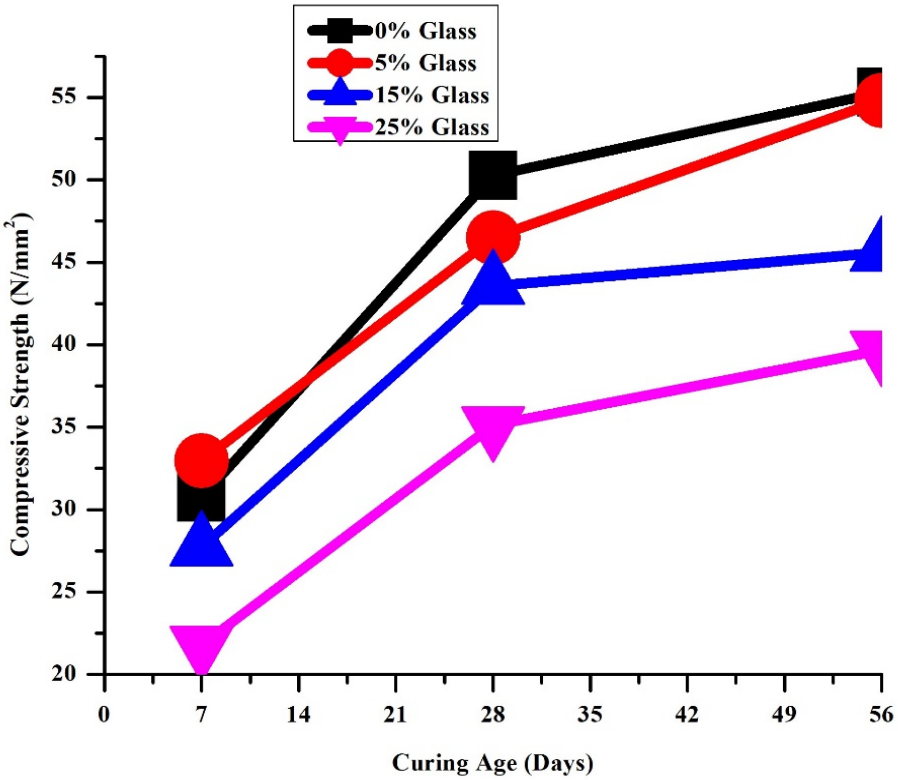


Figure 8. Compressive Strength of Concrete with WGP

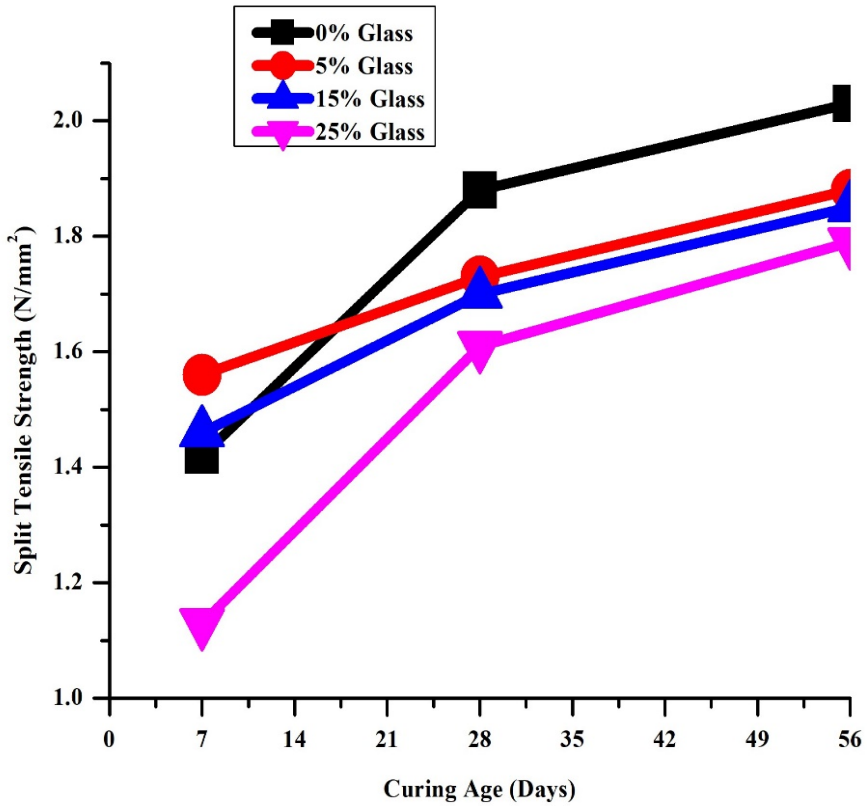


Figure 9. Split Tensile Strength of Concrete with WGP

4. Conclusions

In conclusion, the chemical composition of the WGP used exhibited pozzolanic tendency, which was confirmed by the XRD result. Waste glass powder replacement increases the setting time and water absorption of the samples. The compressive strength results showed that at early age (7 days), concrete with 5% waste glass powder obtained the highest strength as against the control and other level of replacements. However, at later ages (28 and 56 days) control mix showed the highest compressive strength. Similarly, for the split tensile strength, 5% replacement mix obtained optimal split tensile at early age strength and control mix having optimal value at later age. Therefore, recycled waste glass powder material with particles ≤ 600μm exhibits binding properties in the production of concrete. The concrete could be used for low load bearing structures in an area that is not waterlogged, and it's recommended that further investigation should be carried out on the durability performance of waste glass blended concrete.

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