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Effect of Ground Waste Glass as Partial Replacement of Cement on the Durability Properties of High Performance Concrete

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ABSTRACT

The global warming is caused by the emission of greenhouse gases such as CO_2 to the atmosphere. The global cement industry contributes to about 7% of greenhouse gas emission to the atmosphere. Consequently, efforts have been made in the concrete industry to use wastes as supplementary cementing materials (SCMs). Waste glass is a materials when ground to a very fine powder exhibits pozzolanic properties which can be used as a partial replacement for cement in concrete. In this paper, an attempt has been made to studied the durability of high performance concrete (HPC) containing ground waste glass (GWG) as partial replacement of cement in the range 0% to 25% at an interval of 5%.The effects of GWG on compressive strength at the ages of 3, 7, 28, 56 and 90 days, water absorption, acid (H_2SO_4) and salt ($MgSO_4$) attack at 7, 14 28 and 56 days immersion period and elevated temperature at a maximum temperature of 500^{o}C were investigated. It was discovered that, GWG improves the compressive strength, water absorption and resistance of HPC to H_2SO_4 and $MgSO_4$ aggression, while the performance is poor when subjected to elevated temperature. Also, the compressive strength improves with curing age while durability reduces with exposure duration. Furthermore, an optimum GWG content of 10% is recommended for grade 50 HPC.

Keywords: Compressive Strength, Durability, Ground Waste Glass, High Performance Concrete, Ordinary Portland Cement, Supplementary Cementing Materials.

Introduction

Concrete is one of the most versatile construction materials, therefore, the knowledge of its properties is very essential. Durability is one of the most important properties of concrete due to its fundamental incidence in the serviceability life of structures. Durability of concrete is defined as its ability to resist chemical and physical attacks that lead to deterioration of concrete during its service life (Ogork and Auwal, 2017). High performance concrete (HPC) is a concrete mixture, which possess high durability and high strength when compared to conventional concrete. HPC relies on very higher content of cement and the addition of super-plasticizers for better workability. The higher cement content affects not only production costs but also produced substantial heat of hydration which leads to cracking. This coupled with the emission of green-house gases like carbon di oxide (CO_2) and methane (CH_4) to the atmosphere due to cement production. The international energy agency (IEA) in the year 2020 reports that the cement industry emits 2.4 billion tons of CO_2 corresponding to 7% of the total global emissions.

These have necessitated a search for an alternative binder which can be used solely or in partial replacement of cement in concrete production. The use of Supplementary cementing materials (SCMs) to offset a portion of the cement in concrete is a promising method in advancing low cost construction materials with the main benefits of saving natural resources and energy as well as reducing the environmental impact from the cement industry (Ogork *et al.*, 2014).

Glass is a non-crystalline amorphous solid that is often transparent and has widespread practical, technological and decorative usage. Glass is an immensely versatile materials, it is used every day in numerous applications. It is produced in many forms such as container glass, flat glass, and bulb glass. The amount of waste glass is gradually increasing over the years due to an ever-growing use of glass products. Most of the waste glasses have been dumped into landfill sites. The land filling of waste glasses is undesirable because they are not biodegradable, which makes them environmentally less friendly. Glass is an inert material that could be recycled and used many times without changing its chemical property (Shayan and Xu, 2004). It is an amorphous material with high silica content, it is therefore reasonable to expect fine ground waste glass (GWG) may be used as pozzolana and/or partial replacement of cement in concrete. This is also a higher value choice than the use of glass as aggregate, not only because it makes full use of its physical and chemical properties, but also because OPC is more expensive than aggregate, thus offering more economic and environmental advantages.

Materials and Methods

Materials

The materials used in this experiment are ordinary Portland cement (OPC), Ground Waste Glass (GWG), fine aggregates, coarse aggregates, super plasticizer and water. Ordinary Portland cement (OPC) grade 42.5, which conforms to recommendation of BS EN 197 (2000) and specific gravity of 3.16 manufactured in Nigeria by BUA group was used. The ground waste glass (GWG) was prepared from soda-lime glass waste. Broken waste glasses were obtained at Kofar-ruwa, after washing, drying, crushing, grinding and then sieved through a 75µm BS sieve. The oxides composition of OPC and GWG was conducted using X-Ray Fluorescence (XRF) analytical method at Spectral Laboratory Services, Kaduna-Nigeria.

Clean river sand collected from River Challawa, Kano Nigeria, the sand is belong to zone II of BS EN 882-(1992) has been used in this project work. The fine aggregates fineness modulus is 2.8 and a specific gravity of 2.63. While the coarse aggregate is a crushed granite rock of nominal size of 20 mm and specific gravity of 2.70 obtained from monkey rock quarry, Kano-Nigeria. Potable tap water at Civil Engineering laboratory of Bayero University, Kano was used for mixing and curing of specimens. Conplast SP 342 MS, which is a chloride free super-plasticising admixture based on selected sulfonated naphthalene polymer. It has a specific gravity of 1.19 as specified by manufacturer. The particle size distribution of GWG, fine and coarse aggregates are presented in Figure 1.

Methods

HPC grade 50 was designed based on ACI 211.1 (1991). Six samples as shown in Table 1 were used, G-0 is the control mix and G-1, G-2, G-3, G-4 and G-5 are mixes containing GWG at replacement levels of OPC by weight at 5, 10, 15, 20, and 25%, respectively. The mixes were used for the determination of the compressive strength, water absorption, effect of chemical attack and elevated temperature. The compressive strength samples were prepared and cured for 3, 7, 28, 56 and 90 days in accordance with BS EN 12390-2 (2009). The water absorption test was conducted in accordance with BS EN 1881-122 (2020).

The chemical resistance of the HPC was studied through chemical attack by immersing HPC samples in aggressive medium. After 28 days of curing, the samples were removed from the curing tank and their surfaces were cleaned. The initial weights were measured and recorded, the samples will then immerse in 5% concentration of H_2SO_4 solution and the solution was replaced at regular intervals to maintain constant concentration throughout the test period. The samples were removed and weighed at 7, 14, 28 and 56 days, and loss in weight was determined. The resistance of GWG-HPC to H_2SO_4 attack was obtained in terms of percentage weight loss. The procedure was repeated to determine the effect of $MgSO_4$ solutions.

The hardened samples of GWG-HPC after curing for 28 days in water were weighed and then subjected to elevated temperature for one hour using Carbolite CWF1100 model furnace at a temperature range of 0°C to 500°C at 100°C interval and then allowed to cool. The effect of the elevated temperature was evaluated after being reweighed. All the tests were conducted in three replicates and the average were evaluated.

Table 1: Grade 50 HPC mix proportions.

Mix Mark	Cement (kg/m^3)	GWG (%)	GWG (kg/m^3)	Fine Aggr. (kg/m^3)	Coarse Aggr. (kg/m^3)	Water (kg/m^3)	Super-plasticizer (kg/m^3)
G-0	539.5	0	0	631.16	979.34	205	6.5
G-1	512.525	5	26.975	631.16	979.34	205	6.5
G-2	485.55	10	53.95	631.16	979.34	205	6.5
G-3	458.575	15	80.925	631.16	979.34	205	6.5
G-4	431.6	20	107.9	631.16	979.34	205	6.5
G-5	404.625	25	134.875	631.16	979.34	205	6.5

Results and Discussion

Physical properties of constituent materials

The oxides composition of the OPC and GWG are shown in Table 2, the result indicates that the OPC used in this study has satisfied the requirement of BS EN 197-1 (2000) for OPC. Thus, the OPC used can be said to be of sound quality in terms of oxides composition and satisfied the standard requirements.

The oxides composition of GWG indicate a combined SiO_2, Al_2O_3 and Fe_2O_3 content of 74.306%, which is slightly above the minimum value of 70% recommended in ASTM C618 (2008) for a good pozzolana and would therefore be a reactive pozzolana. The magnesium oxide content was 1.890% which satisfied the required maximum value of 4%. Calcium oxides content of 4.696% which satisfied the required value of not more than 10%, loss on ignition (LoI) value of 3.221% which is within the acceptable value of ≤ 10% and SO_3 content of 0% which is also within the maximum content of 4%. The high percentage of SiO_2 (72.697%) is beneficial in pozzolanic reaction with time.

This shows that GWG is a good pozzolanic material having being satisfied the recommended limit given in BS EN 197-1 (2000) and ASTM C618 (2008). The result is consistent with the findings of Taha and Nounu, (2008) on conventional concrete made with GWG.

The particle size distribution of GWG, fine and coarse aggregates were presented in a distribution chart as shown in Figure 1. As indicated, the fine aggregate falls in grading zone II based on BS 882 (1992) grading limits for fine aggregates. This shows that there is more medium sand than fine and coarse sand. It is cohesive and well-graded, which is desirable for making HPC.

Table 2: Oxides Composition of OPC (BUA brand) and GWG

Oxides	OPC Composition (%)	BS EN 197-1 (2000)	GWG Composition (%)	ASTM C618 (2008)
SiO_2	15.827	The sum of reactive CaO and SiO_2 shall be at least 50%. The ratio of CaO to that of SiO_2 shall be at least 2%. $MgO \leq 5\%$. $Cl \leq 0.1\ \%$. $SO_3 \leq 3.5\%$. $LoI \leq 5\%$.	72.697	The sum of reactive SiO_2, Al_2O_3 and Fe_2O_3 shall be at least 70%. The reactive SiO_2 shall not be less than 25% The CaO shall be less than 10%. $SO_3 \leq 4\%$ $LoI \leq 10\%$.
Al_2O_3	3.702		1.257	
Fe_2O_3	4.187		0.352	
CaO	72.773		4.696	
MgO	0.124		1.890	
ZnO	0.004		0.001	
MnO	0.040		0.110	
Na_2O	0.000		15.243	
SO_3	2.030		0.000	
TiO_2	0.066		0.041	
Cr_2O_3	0.012		0.011	
Cl	0.112		0.000	
LoI	1.064		3.221	

Also, in Figure 1, the curve indicates that coarse aggregates have dominant particle sizes of 14 mm and 10 mm. This shows that the aggregate size is within the specified limits of a maximum of 20 mm as suggested by Shetty, (2012) for use in HPC. GWG has grain sizes ranging from 75µm to 1.75µm. This implies that the GWG could be used as pozzolana in concrete based on BS EN 196-3 (2005).

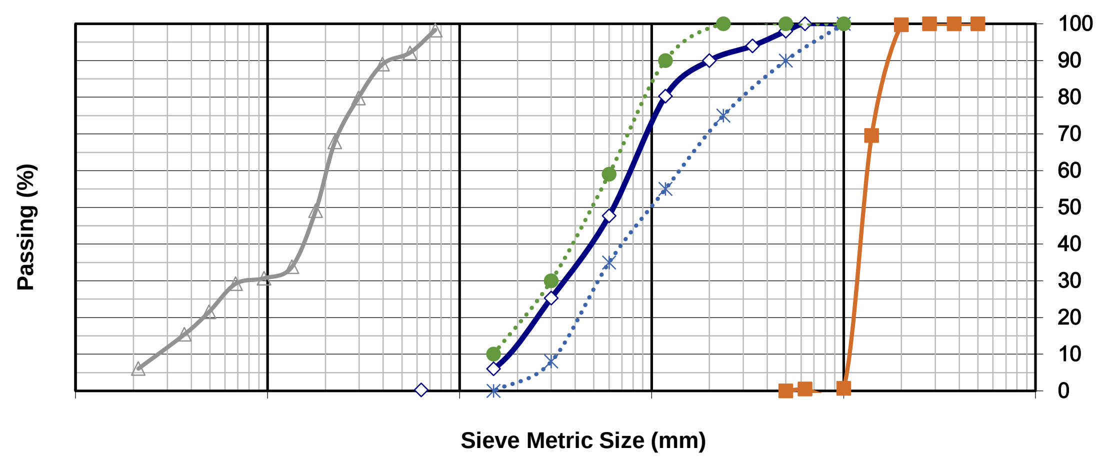

Figure 1: Particle size distribution chart of GWG, fine and coarse aggregates

Compressive Strength of GWG-HPC

The compressive strength test result of GWG-HPC is presented in Figure 2. The result shows an improvement in compressive strength with a continuous increase in GWG of up to 10%, it was then reduces gradually beyond 10%. The 28 days compressive strengths was 54.3N/mm^2, 55.7N/mm^2, 57.0N/mm^2 45.7N/mm^2, 35.0N/mm^2 and 29.7N/mm^2 at 0%, 5%, 10%, 15%, 20% and 25% OPC replacement level respectively.

There was also, an improvement in compressive strength with an increase in age of curing at all replacement levels. The improvement in compressive strength with the curing period could be due to micro filling ability and pozzolanic activity of GWG. The smaller particle size of GWG can fill the micro voids within the OPC particles. Also, GWG is highly reactive, it reacts with calcium hydroxide (Ca(OH)$_2$) (a by-product of cement hydration) in the presence of water to produce calcium silicate hydrates (C-S-H).

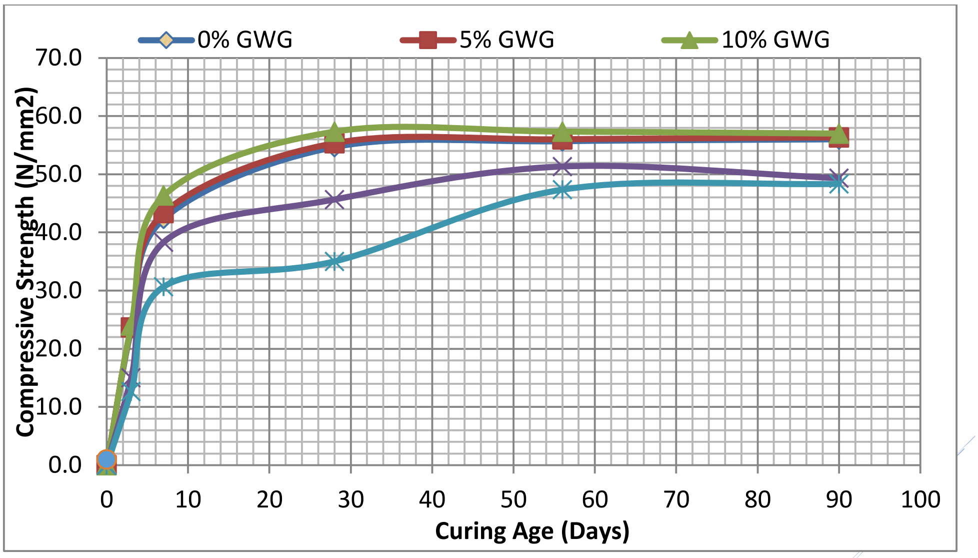

Figure 2: Compressive Strength Development of GWG-HPC.

However, the decrease in compressive strength observed beyond 10% GWG content may be due to the amount of silica available in the hydrated cement matrix is too high and the amount of produced C-S-H is most likely insufficient to reacts with all the available silica and as result of that, the dilution effect of OPC and weaker formation of C-S-H gel due the pozzolanic reaction takes over and the strength starts to decrease. Thus, it can be concluded that 10% was the optimum level for replacement of cement with GWG. The optimum dose of 10% is in agreement with Lalitha *et al.*, (2017) but in conflict with the findings of Veena and Rao (2014) and Shipha and Kumar, (2014) who reported an optimum dose of 15% and 20% respectively.

Water absorption

The test results reveal that water absorption of GWG-HPC decreases with increase in GWG content as shown in Figure 3. This could be due to the beneficial effect of GWG as a pozzolana which produce more homogenous hydration products by filling and segmentation of the capillary voids and producing ultimately denser and impermeable concrete. It could also be attributed to the change occurring in the pore size distribution as a result of using GWG which would react with the calcium hydroxide to form C-S-H gel (Ogork and Auwal, 2017). The result is consistent with findings of Abdulwahab and Uche, (2021) works on Cassava Peel Ash (CPA) as a Pozzolana in concrete. The water absorption values obtained are below the maximum acceptable value of 3% or 2% in critical condition specify by BS 6349-1(2000).

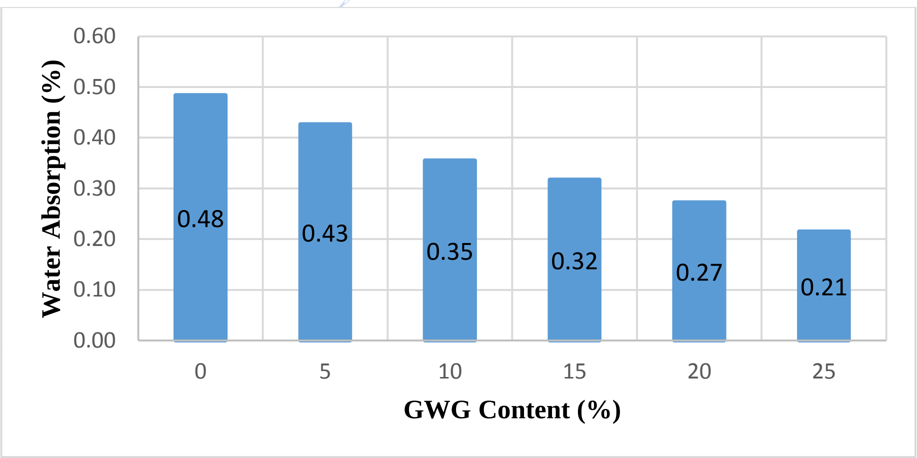

Figure 3: Water absorption of GWG-HPC

Resistance of GWG-HPC to H_2SO_4 medium

The effect of 5% concentration of sulphuric acid (H_2SO_4) on GWG-HPC is shown in Figure 4, the result shows a decrease in weight with increase in exposure duration of H_2SO_4 media. This could be as a result of continuous attack by the sulphate.

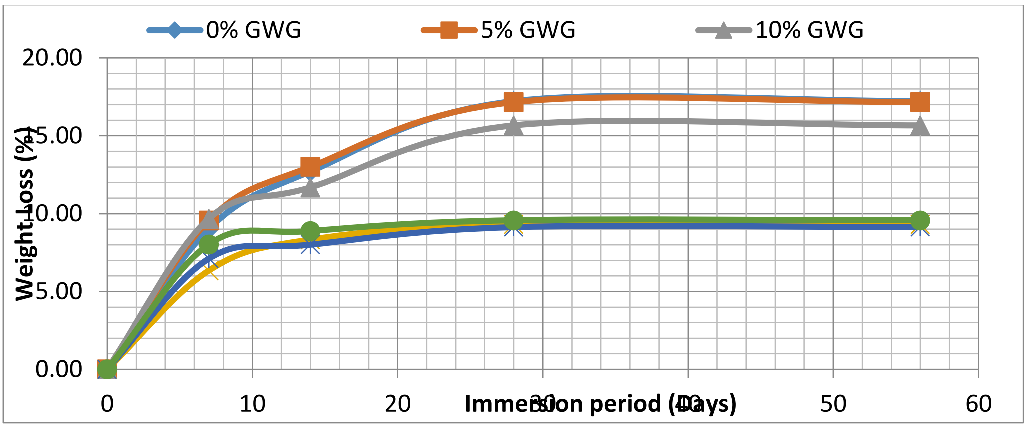

Figure 4: Wight loss of GWG-HPC immersed in H_2SO_4 medium.

This may be explained in the fact that the reaction between sulphuric acid and OPC have influenced the conversion of calcium hydroxide ($Ca(OH)_2$) to calcium sulphate (gypsum) which in turn, may be converted to calcium sulphur aluminate (ettringite). Both of these two products i.e gypsum ($CaSO_4 . 2H_2O$) and ettringite causes expansion which result in cracking of the samples. This is consistent with the explanation of Ogork *et al.*, (2014) in their work on Ground Husk Ash (GHA).

Furthermore, the result showed that incorporation of GWG to HPC offered a better resistance to sulphuric acid (H_2SO_4) than the control mix. The enhanced resistance of GWG-HPC to Sulphuric acid could be due to the depletion in the $Ca(OH)_2$ content released from the hydration process and consumed in the GWG pozzolanic reaction, with less $Ca(OH)_2$ left to react with sulphuric acid.

The result confirms the finding of Veena and Rao, (2014) works on GWG. It could also be as a result of better finishing surface and the filling effect of GWG which make the HPC dense, prevent the entry of acid into the GWG-HPC and improve its resistance against acid attack (Ramesh and Neeraja, 2016).

Resistance of GWG-HPC to $MgSO_4$ medium

The effect of 5% concentration of magnesium sulphate ($MgSO_4$) salt media on GWG-HPC is shown in Figure 5. The result shows an increase in weight loss with increase in exposure duration and decrease with increase in GWG content to aggression of HPC. The reduction in durability with exposure duration of $MgSO_4$ could be due to the reaction of hydroxide and sulphate ions during cement hydration to form brucite ($Mg(OH)_2$) and gypsum (Mohammed *et al.*, 2016). This combined products of gypsum and brucite retards the harmful effect of $MgSO_4$ attack in the early ages. However, at latter ages, this protective skin peels off due to the formation of expansive gypsum and ettringite, which causes cracking in the surface of the brucite layer (Mohammed *et al.*, 2016). The subsequent decomposition of calcium silicate hydrate (C-S-H) gel to magnesium silicate hydrate (M-S-H) gel permits the easy diffusion of sulphate ions into the GWG-HPC. This alteration of C-S-H to M-S-H is the major process of $MgSO_4$ attack.

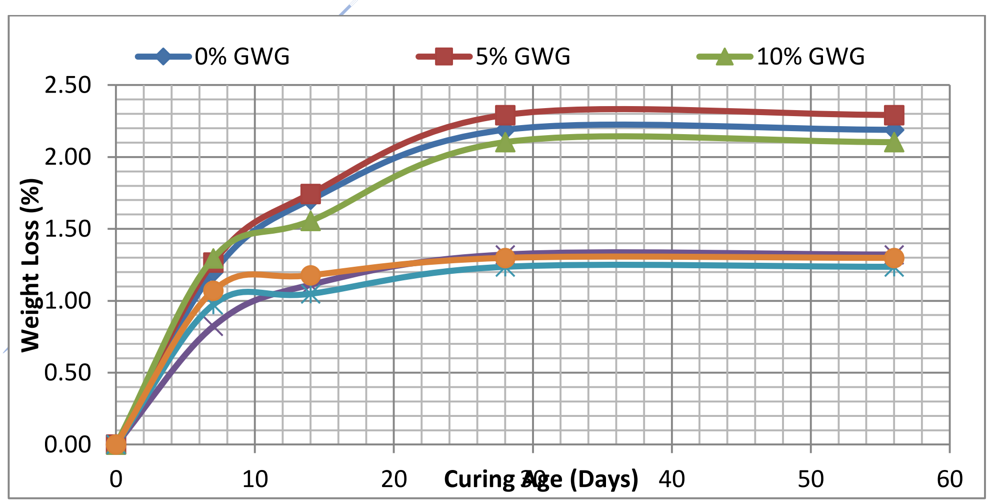

Figure 5: Wight loss of GWG-HPC immersed in $MgSO_4$ medium.

The reason behind the improved durability with increase in GWG content is the filling effects of GWG which make the GWG-HPC dense and prevent the entry of sulphate into it. The HPC containing GWG was more resistant against sulphate attack, reducing the porosity of the GWG-HPC and leaching of calcium salts from the impermeable surface there by increasing the sulphate resistance of HPC.

Resistance of GWG-HPC to Elevated Temperature

Figure 6 shows the effects of elevated temperature on GWG-HPC, the results show that there is loss in weight as the temperature rises as well as the percentage content of

GWG increase. For the control sample the weight loss increases from 0.18% at 100ºC to 3.85% at 500ºC, similarly, 25% GWG content, the weight loss increases from 0.47% at 100ºC to 8.12% at 500ºC. The weight loss could be linked to moisture evaporation, the rapid loss of moisture which prevents long term hydration leading to decreased in weight (Ma *et al.*, 2015).

The effect of heat on GWG-HPC specimen with increase in temperature is not much up to a temperature of about 250°C, but above 300°C the residual-free water in the interior has evaporated. This is consistent with the findings of Ellis *et al.,* (2018). The bound water in the cement gel raises as the temperatures continuously increases, leading to the decrease of the weight of the GWG-HPC specimens.

When the temperature is 400°C, the weight loss is higher because that the un-carbonated $Ca(OH)_2$ begins to dehydrate to CaO causing the micro cracks in the interface between the cement gel and the coarse aggregate to expand (Evandro *et al.,* 2002). Mendes *et al.,* (2007) confirmed that 400°C was the critical temperature for performances degradation of concrete. Furthermore, the colour of GWG-HPC changes slightly from grey to yellowish with increases in temperature from 400°C to 500°C. Certain colours correspond with specific temperature range which is an important indicator of the maximum temperature the concrete can be exposed to. This result is consistent with the findings of Abdulwahab and Uche, (2021) works with Cassava Peel Ash (CPA) as SCMs.

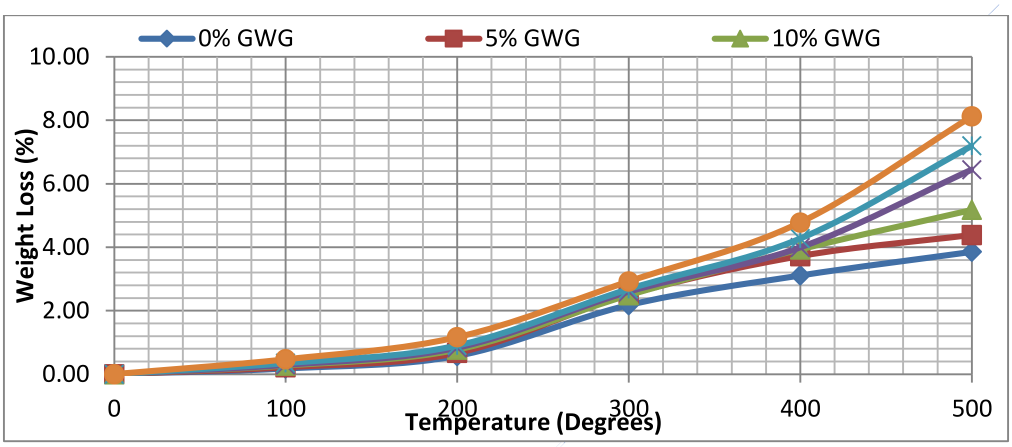

Figure 6: Wight loss of GWG-HPC exposed to elevated Temperature.

Conclusion

In conclusion, it was observed that the soda-lime GWG is suitable material for use as SMCs since it satisfied the minimum requirement for such material by having a reactive SiO_2, Al_2O_3 and Fe_2O_3 of more than 70%. The compressive strength of HPC can be improved by the replacement of OPC with GWG of adequate replacement level. The incorporation of GWG lowers the water absorption and improved the HPC resistance to H_2SO_4 and $MgSO_4$ aggression. Furthermore, at elevated temperature, addition of GWG reduces the performance of HPC.

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