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Experimental Investigation on the Effect of Elevated Temperature on Compressive Strength of Concrete Containing Waste Glass Powder

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Abstract

This study examines the effect of elevated temperature on the strength of concrete containing glass powder (GWP) as Ordinary Portland cement replacement. The cement was partially replaced by 0, 15, 18, 21, 24, 27 and 30 % of GWP and samples were prepared at constant water-binder ratio of 0.5. The cube samples after curing in water for 90 days were exposed to 60, 150, 300 and 500°C temperatures increased at a heating rate of 10°C/min. Compressive strength values were measured on unheated samples and after air-cooling period of the heated samples. A scanning electron microscope (SEM) analysis was carried out on selected samples to examine alterations in the matrix and interface. The results indicate a decrease in the compressive strength with increasing temperature, and significant alteration was observed in the concrete matrix and interface from the SEM analyses. However, the results indicate that concrete samples containing 21% GWP exhibit higher strength compared to control.

Keywords: waste glass powder (GWP), compressive strength, SEM, elevated temperature, sustainability

1. Introduction

Sustainable development can simply be referred to as the prudent use of resources; a major key feature of sustainable development is creating sustainable ways of preserving the environment with focus on reducing greenhouse gas (GHG) emissions, energy saving and preserving the natural resources [1]. In addition, it was emphasized by [1] that the construction industry is one of the major user of the natural resources and contributes a large part of worldwide CO_2 emissions. For example, cement production is highly energy consuming and a major producer of carbon dioxide emissions to the atmosphere. However, [2] opined that utilizing industrial byproducts and solid wastes by the construction industry can help sustain the environment in two ways; first, reusing waste materials that could have been a major concern to the environment by occupying scarce land spaces; and secondly, minimizing environmental degradation through depletion of the natural resources.

This is necessary in view of the rapid population growth, increasing urbanization, resource scarcity, and rising standards of living due to technological improvement, which means; recycling and reusing of waste provides an attractive option that could be used to promotes waste reduction, lower greenhouse gas (GHG) emissions and conserving of natural resources from further depletion hence creating a sustainable green environment [3].

Waste glass in broken forms constitutes a major part of waste byproducts from both the industry and domestic, and [4] in their study mentioned that waste glass represents an urgent environmental challenge all over the world due to the non-biodegradable nature of the glass materials resulting in serious environmental pollutions. Hence, an alternative option

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offered to solve the menace of glass wastes on the environment is to reuse or recycle them. Some ways of recycling waste glass for other usage were explained in the studies of [5]. According to [2, 3, 5], waste recycling will help to conserve the earth's natural resources, minimizes the landfill spaces, and saves energy and capital resources. Furthermore, Ankur et al. [6] pointed out that of recent, using waste materials such as finely grounded glass into powder form is interesting for civil engineers to produce eco-friendly concrete in a bid to protect the environment. In addition, the cement and concrete industry provide a viable alternative solution to the menace of waste glass to the environment due to the chemical composition and physical properties of glass which are quite like that of sand and cement [7]. This implies that waste glass can be used in the production of concrete in order to conserves natural resources, save energy, and reduce GHG to the environment [4, 8]. Various studies have investigated the properties and behaviour of concrete containing waste glass aggregates as replacement for natural aggregates and tried to established an optimum percentage of glass aggregate that can be used to produced concrete without compromising the properties of the hardened concrete, and it was observed that particle size of the glass aggregate is vital in limiting the effect of harmful alkali-silica reaction [4, 9].

In addition, studies by [8-11] have also found that the use of glass as aggregate in concrete have negative influence on the strength of hardened concrete. It was reported that as the percentage glass content increases, the compressive and tensile strength decreases. Again, another major drawback influencing the widespread use of glass in concrete or mortar is the effect of Alkali-silica reaction (ASR), but several mitigation techniques have been studies to suppress this reaction [4, 11]. However, Du and Tan [4] noted that some of these mitigation methods also have negative effects on the properties of the concrete such as workability and compressive strength.

From studies conducted by [12, 13], it was reported that one of the reason concrete material is the most widely used construction material is because of its higher resistance to fire compared to other building materials such as wood, aluminum and steel; however, this resistance to fire can be sustained up to a certain level of elevated temperature and duration of exposure. Fire is regarded as one of the main risks of concrete structures [14]. Chang et al. [15] reported that the behaviour of concrete when exposed to sustained fire is dependent on the characteristics of the concrete constituents. The study opined that the performance of the concrete elements when exposed to elevated temperatures is partly based on the thermal and mechanical characteristics of the used concrete [15]. However, under a sustain elevated temperature; the concrete resistance level may be exceeded causing physical and chemical changes to occur in the concrete thereby resulting in complete deterioration of the concrete. Examples of such deterioration include; spalling of the concrete, formation of cracks, and large pores in the concrete expansion and creeping of the concrete, and weakening of the adhesive bond between the aggregate particles and the cementitious materials in the concrete [13]. Thus, this changes result in the decrease of the mechanical properties of the concrete. In addition, the decrease in strength could also be the result of the rate of heating of the concrete [16]. Furthermore, a study by Terro [2] investigated the influence of elevated temperatures on the residual strength properties of hardened concrete containing glass aggregates. The results show a gradual decrease in the strength properties of the concrete containing glass material as the temperature increase. Studies also show that glass can be used as a pozzolanic or a cementitious material in concrete due to the chemical composition of glass having a high percentage of silica and calcium, coupled with the amorphous structure of the glass material. The glass powder reacts with the $Ca(OH)_2$ in the concrete mix to produce C-S-H gels in the main bonding phase of concrete.

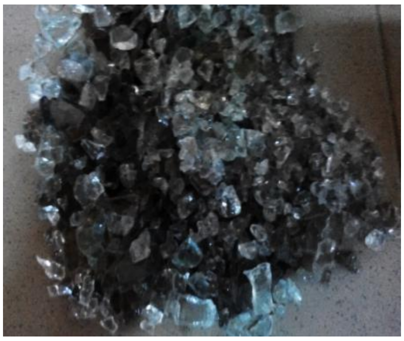
Many studies have investigated the effect of waste glass powder as replacement for cement in concrete [17-20]. Investigations have shown that milled glass with particle sizes less than 75 microns have pozzolanic properties to act as a supplementary cementitious material (SCM), and can be sufficiently compare to other established SCM's such as fly ash and silica fumes [6, 17]. However, the products of the pozzolanic reaction between the pozzolanic properties of glass and cement is still under investigation [17]. Moreover, studies by [6, 14, 18, 20] reported that glass powder can be used to produce high strength concrete (HSC) used extensively in civil engineering projects such as nuclear storage structures, power stations, prestressed concrete members, marine structures, bridges, offshore structures etc. However, studies have shown that HSC deteriorates quicker when exposed to fire than normal concrete [15, 25-26], but Ali et al. [14], reported an efficient resistance of HSC to heating when waste glass powder is added as inert powder in concrete.

This study examines the behaviour of heated low strength normal concrete in terms of the residual compressive strength and the effects of waste glass powder in improving the strength of the concrete under elevated temperature. In addition, changes in the microstructural properties of bonding matrix and interfacial zone between the aggregate particles and bonding materials were also examined using the scanning electron microscope (SEM).

2. Experimental Program

2.1. Binder materials

The cement used for this study is the ordinary Portland cement CEM I 42.5 grade, conforming to the BS EN 197-2000 [27]. The cement was commercially sourced and the Table 1 below gives the chemical composition of the cement determine using the X-ray fluorescence (XRF). The ground glass powder (GWP) used in this study was obtained from waste mixed colour glass sourced from dumpsites and waste collection centres within Ota, Ogun state, Nigeria. Before crushing, the waste glasses were thoroughly washed with water and air dried to remove every form of impurities and dirt as shown in Fig. 1(a). To activate the pozzolanic behaviour and suppressed the alkali-silica reaction, the waste glass was crushed and ground to required degree of fineness using a mill crusher and sieved through a 0.075 mm sieve openings to achieve a consistent particle sizes as shown in Fig. 1(b). The chemical compositions of the ground glass powder were determined using the XRF as presented in Table 1 and the results obtained was compare with the results reported by [11]. Sieve analysis on the cement and GWP material was carried out to determine the particle size distribution of both materials and presented in Fig. 2.



(a) Crushed waste glass

(b) Ground glass powder

Fig. 1 Waste glass material used for this study

Table 1 Chemical composition of the waste glass and cement

Chemical Constituents	Cement (% mass)	Glass (% mass)	*Clear Glass (% mass)	*Coloured Glass (% mass)
SiO_2	**15.38**	**71.35**	**72.14**	**71.22**
Al_2O_3	**4.14**	**1.01**	**1.56**	**1.63**
Fe_2O_3	**3.19**	**0.67**	**0.06**	**0.32**
CaO	**56.92**	**8.74**	**10.93**	**10.79**
MgO	**2.44**	**3.55**	**1.48**	**1.57**
SO_3	**1.59**	**0.25**	**-**	**-**
K_2O	**0.21**	**0.37**	**0.62**	**0.64**
Na_2O	**0.04**	**11.76**	**13.04**	**13.12**
TiO_2	**0.21**	**0.05**	**0.05**	**0.07**
P_2O_5	**0.28**	**0.01**	**-**	**-**
Mn_2O_5	**0.04**	**0.01**	**-**	**-**
Cr_2O_3	**0.02**	**0.03**	**-**	**0.22**

Loss on ignition	-	**1.47**	-	-

*XRF results of Tan and Du [11]

2.2. *Aggregate material*

The river sand and gravel aggregate used for this study were sourced commercially. River sand having its particles size ranging from 0.075 to 4.75 mm and gravel having a maximum size of 20 mm were used for production of the concrete used for this study. The physical properties and the particle size distribution for aggregate materials are presented in Table 2 and Fig. 2, respectively.

Table 2 Physical properties of the natural aggregate and glass materials

Physical Properties	**Natural aggregate**		**Waste glass**
	Sand	**Gravel**	**Glass**
Fineness Modulus	2.69	5.30	-
Specific gravity	2.62	2.70	2.50
Water absorption (%)	0.42	0.25	0.40
Aggregate Impact value (AIV) %	-	10	
Aggregate Crushing value (ACV) %	-	24	

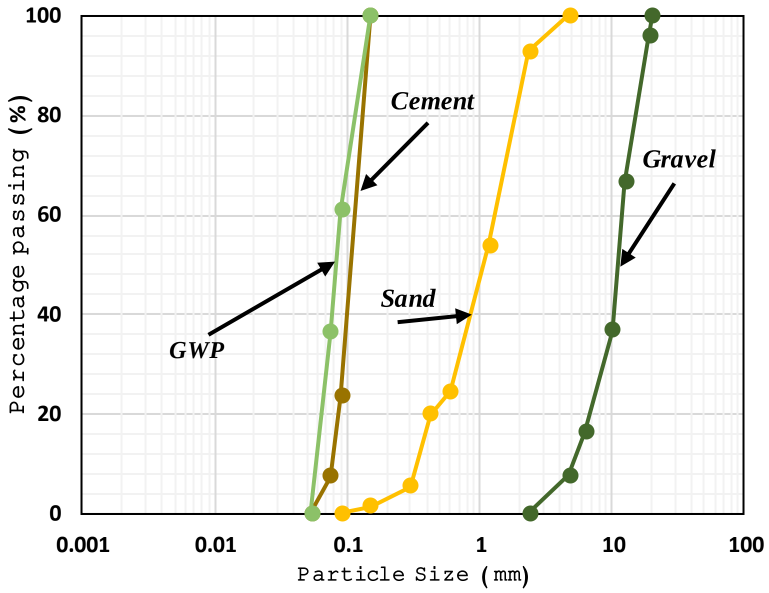


Fig. 2 Particle size of Portland cement, ground glass powder (GWP), sand and gravel

2.3. *Methods*

For the preparation of the control mixes, river sand and coarse aggregate (gravel) combined with ordinary Portland cement were used to produce the concrete used in this study. The particle size distributions and fineness modulus of the sand and coarse aggregate materials was determined using the sieve analysis (Fig. 2). Concrete cubes with dimensions of 150 x 150 x 150 mm were cast in mould at room temperature and removed after 24 hours. The cubes were cured in water by immersion at room temperature at 27-28°C for 90 days and were tested for their compressive strength in accordance with BS EN 12390-3 [28] at four (4) elevated temperatures: 60, 150, 300 and 500°C. The design mixture for the control concrete was batched by weight, using a mix proportion of 1:2:4 (cement: sand: gravel) and a water – cement ratio of 0.5. The mixes were proportioned targeting a 28-day strength of 25 MPa. Ground waste glass powder was used to partially substitute cement by the proportions: 15%, 18%, 21%, 24%, 27% and 30%. The types of concrete mixes used in this study are presented in the Table 3 below.

Table 3 Type of Mixes used in this study.

Mix I	Control mix proportion produced with natural fine and coarse aggregates and 100% cement - CEM100%

Mix II	GWP - Cement binder replacement with finely grounded waste glass powder (GWP) with percentages of 15%, 18%, 21%, 24%, 27%, 30% (using the same natural fine and coarse aggregates)

The mixes were thoroughly mixed to ensure good mix of all concrete constituents and each casted specimen was appropriately labelled for identification purpose. Readings were taken as average of three (3) tests on the cube samples. The blending of the glass powder with cement was first carried out separately in a bowl container based on the quantity required by weight for about 5 minutes. The blended glass powder and cement mixture was then thoroughly mixed with the fine aggregate (sand) materials for another 5 minutes. Then, the coarse aggregate (gravel) was later incorporated into the mix, after which the whole mixture constituents were mixed together for another 5 minutes. Measured quantity of water by weight was added to the mixture and thoroughly mixed for 5 more minutes to form fresh concrete. The process was repeated for all the mixes and the workability of the various mixes including the control mix was determined by slump test in accordance with BS EN 12350-2 [29]. The batching of the concrete constituents for the different mixes and identification for each mix are presented in Table 4.

Table 4 Batching of Concrete Constituents

Mixtures		**Binder Materials (kg/m^3)**		**Aggregate (kg/m^3)**		**Water (kg/m^3)**	**Water to Binder ratio (w/b)**
		Cement	**Glass Powder (GWP)**	**Gravel**	**Sand**		
Control	100% CEM	275	-	1100	550	138	0.5
Glass Powder GWP - CEM	15%GWP	233.75	41.25	1100	550	138	0.5
	18%GWP	225.50	49.50	1100	550	138	0.5
	21%GWP	217.25	57.75	1100	550	138	0.5
	24%GWP	209	66	1100	550	138	0.5
	27%GWP	200.75	74.25	1100	550	138	0.5
	30%GWP	192.50	82.50	1100	550	138	0.5

Heating of the concrete samples was carried out using a muffle furnace that can reach temperatures up to 1500°C. Fig. 3 depicts the heating of the cubes using the muffle furnace. A constant heating rate of 10°C/min was maintained in the furnace regulated by an in-built thermostat that automatically regulate the heating. The range of heating temperatures adopted in this study conforms to the range of temperatures adopted by [2] in the study of concrete residual strength at elevated temperatures. The concrete samples were left in the furnace, after reaching the desired temperatures, for 2 hours to achieve a uniform temperature distribution around the concrete cube samples. The temperature heating curve template in Fig. 4 was adopted. Because the concrete samples will be very hot and to eliminate any form of thermal stresses that might affect the strength, the samples were passed through a slow cooling process as recommended by [2] by allowing them to cool in the furnace and in the open air before testing for their residual compressive strength. Small pieces of the concrete were subjected to microstructural examination using the scanning electron microscope (SEM). The SEM analyses were performed on concrete samples mounted on the SEM brass stubs using Phenom ProX type SEM. The SEM tests were carried out concrete on specimen without glass powder and specimens containing glass powder at ambient temperature and at elevated temperature.

Fig. 3 Concrete samples in the muffle furnace

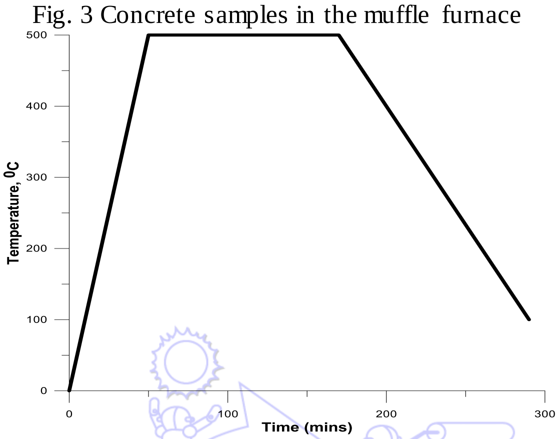


Fig. 4 Used furnace temperature for this study

3. Results and Discussion

3.1. Properties of fresh concrete containing glass powder-workability

The effect of the percentage of glass powder (GWP) content on the slump of concrete mix containing glass powder as cement replacement is shown in Fig. 5. The plot clearly depicts the workability behaviour of the freshly prepared concrete mixes measured by the slump test. The results show that the slump value was kept approximately constant between 15% and 21% cement replacement but slightly lower than the control. The slight difference is about 5 %, compare to the initial slump value of 40 mm recorded for the control at a constant water-binder ratio. However, the slump seems to decrease with higher content of waste glass powder (GWP) at 24%-30% replacement of cement. A decrease of about 50 % in the slump value was observed as the glass powder content increases from 24 % to 30 % cement replacement. This implies that the workability of the concrete mix reduce as the percentage content of the glass powder increases at a constant water - binder ratio. This may be attributed to the increase in the surface area of the glass powder and the flaky angular shape of the glass particles as reported by [30].

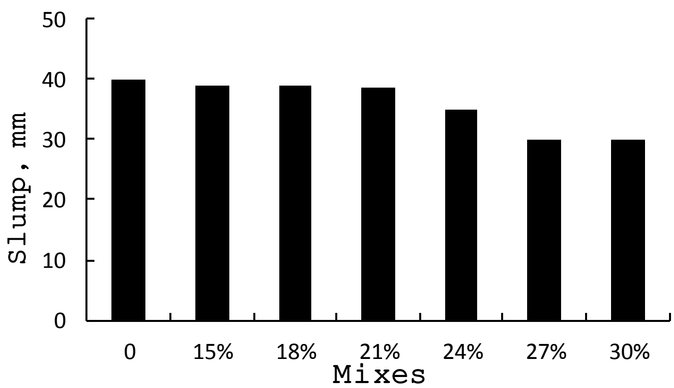
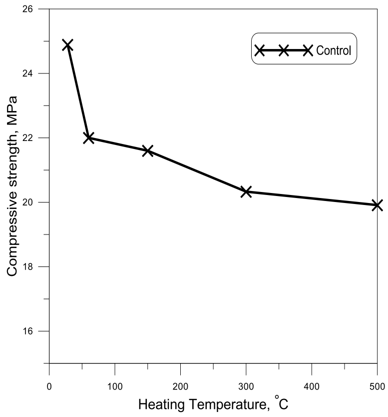


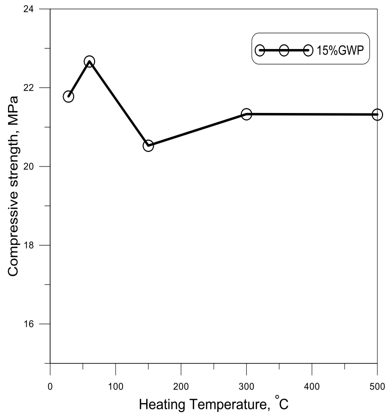
Fig. 5 Results of Slump test

3.2. Properties of hardened concrete -residual compressive strength

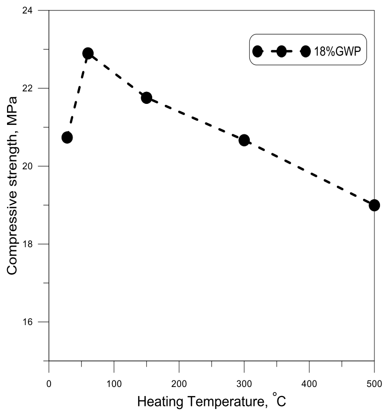
The effect of the heating temperature on the strength of concrete produced without glass powder (GWP) as control and concretes containing glass powder (GWP) content as cement replacement in proportions of 15, 18, 21, 24, 27 and 30% are shown in Figs. 6(a)-(g), respectively. The results show clearly a decrease in the compressive strength of the concrete as the temperatures increases, as reported by previous studies on the performance of concrete containing glass subjected to elevated temperatures [2, 20-22]. However, at 21% replacement of cement with glass powder (GWP) content, the residual compressive strength of the hardened concrete is higher than that of the control mix and mixes made with glass powder content up to the heating temperature of 500°C except at 15% glass content which shows a higher residual strength at 500°C. Although, at room temperature, the control concrete possesses a higher compressive strength than every other concrete samples containing glass powder materials.



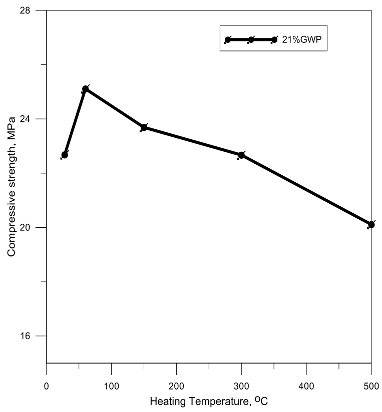
(a) Effect of temperature on the strength of concrete for control



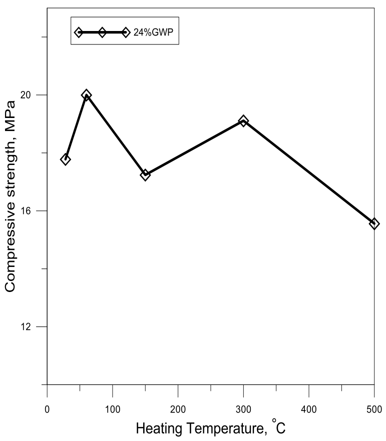
(b) Effect of temperature on the strength of concrete containing 15% GWP as cement replacement



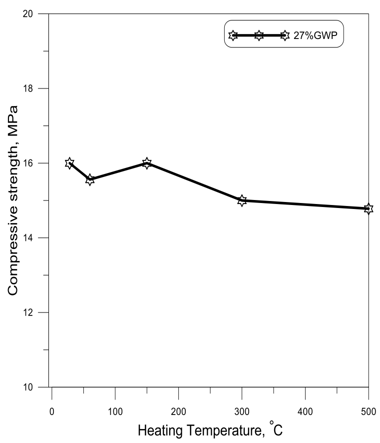
(c) Effect of temperature on the strength of concrete containing GWP as cement replacement for 18%



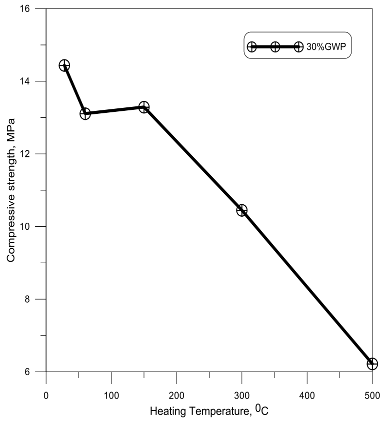
(d) Effect of temperature on the strength of concrete containing GWP as cement replacement for 21%



(e) Effect of temperature on the strength of concrete containing glass powder (GWP) for 24%

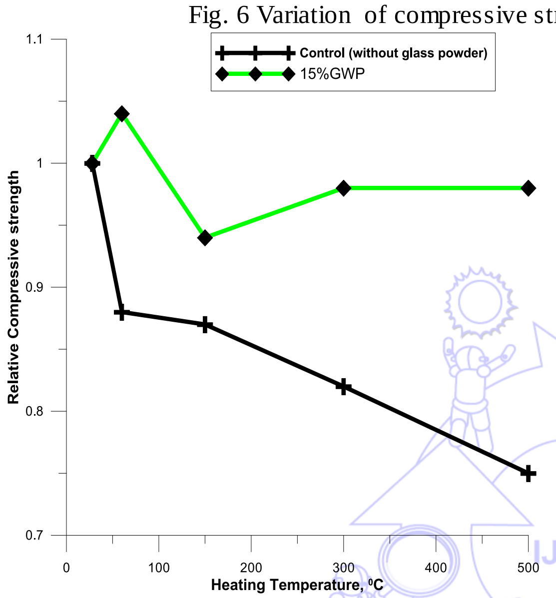


(f) Effect of temperature on the strength of concrete containing glass powder (GWP) for 27%

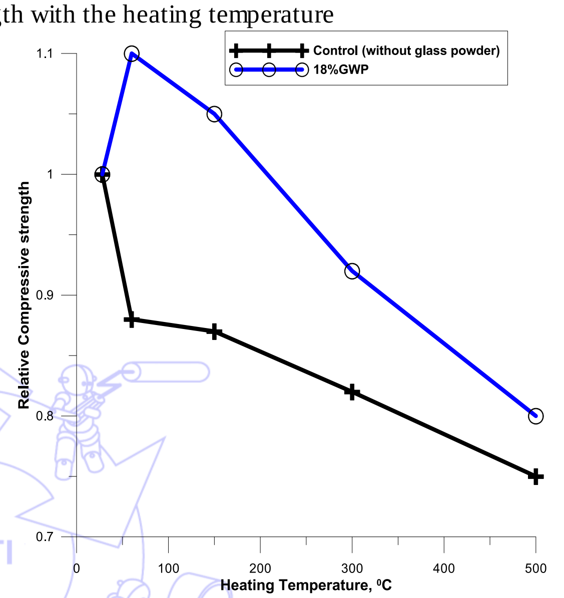


(g) Effect of temperature on the strength of concrete containing 30% glass powder (GWP)

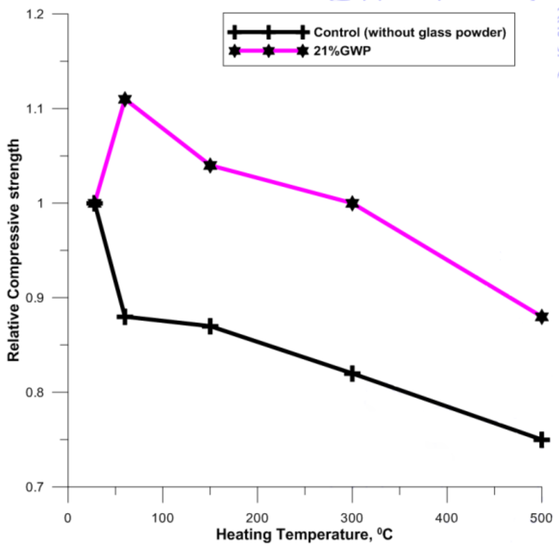
Fig. 6 Variation of compressive strength with the heating temperature



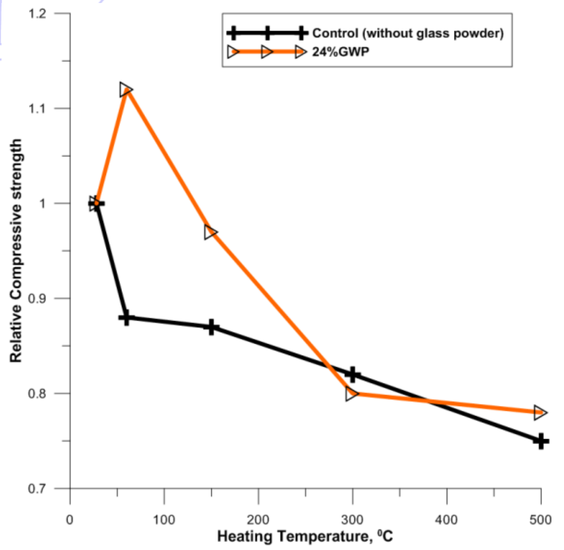
(a) Variation of relative compressive strength with temperature for control concrete and 15%GWP



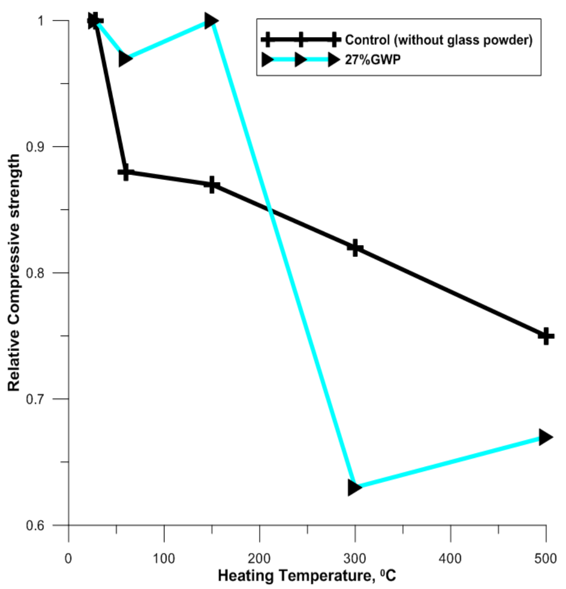
(b) Variation of relative compressive strength with temperature for control concrete and 18%GWP



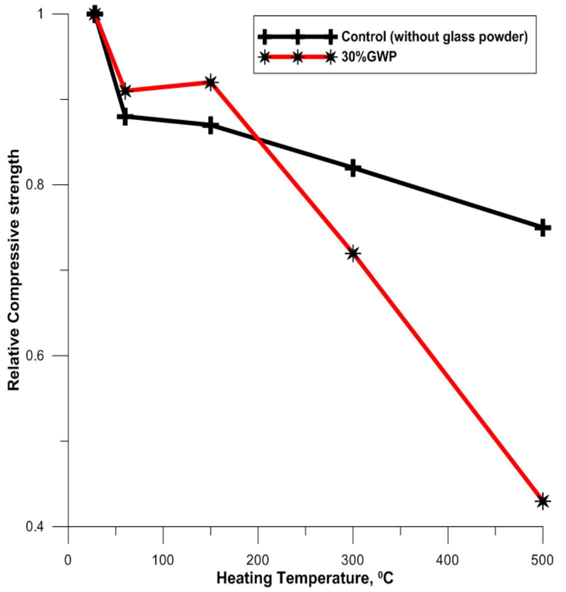
(c) Variation of relative compressive strength with temperature for control concrete and 21% GWP



(d) Variation of relative compressive strength with temperature for control concrete and 24% GWP



(e) Variation of relative compressive strength with temperature for control concrete and 27% GWP



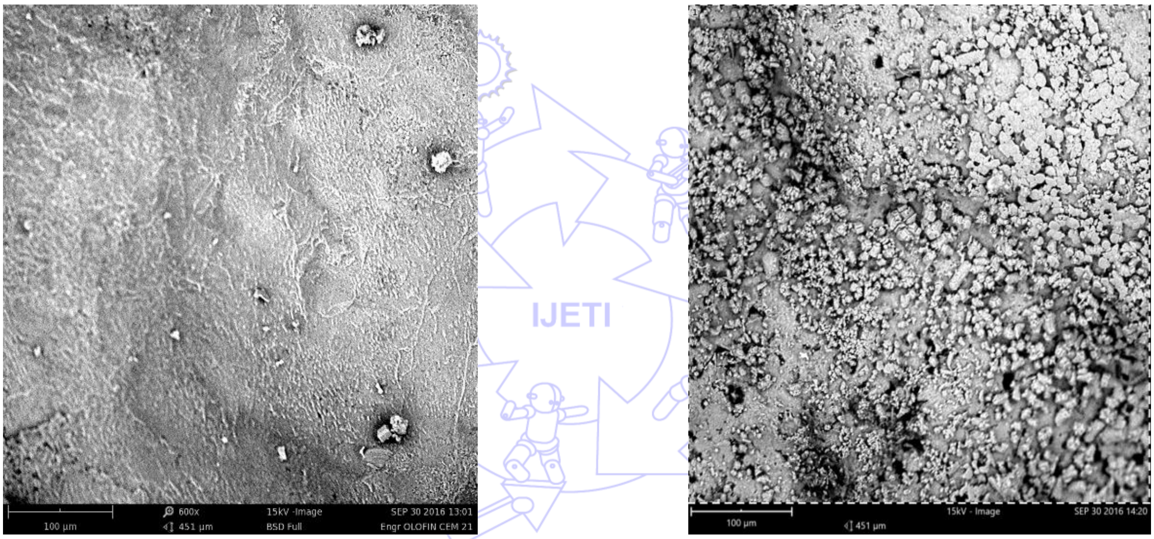
(f) Variation of relative compressive strength with temperature for control concrete and 30% GWP

Fig. 7 Relative compressive strength with heating temperature

Furthermore, the characteristics residual strength of concrete presented in terms of mechanical strength ratio, estimated from the relative property of concrete specimens at elevated temperature to the property of control specimen without heating was illustrated in Figs. 7(a)-(f). The results depict clearly the influence of the glass powder on the compressive strength of concretes when exposed to increasing temperature. It is obvious from the results that normal concrete made with glass powder at percentage replacement of 15-21% shows significant residual strength at increased temperature compare to the control. However, at higher percentage replacement of 24-30%, a significant loss of strength can be observed. Ali et al [14] attributed the decrease in strength to the pozzolanic activity of the glass powder and formation of micro-cracks in the concrete. The loss of strength in the concrete increased substantially when the temperature reaches 500°C due to the disintegration of C-S-H gel and increase of the macro cracks as reported by [13,14, 24]. The percentage loss of compressive strength value for 0, 15, 18, 21, 24, 27 and 30% glass content was 20%, 9%, 17%, 20%, 22%, 33% and 68% respectively. However, the highest compressive strength was observed at 21% glass content, but concrete samples containing 15% glass content exhibit the minimum loss of strength as seen from the results. The obtained results clearly show that the glass powder material content in the concrete mix as cement replacement has a significant influence on the performance of the concrete when exposed to elevated temperatures. This can be attributed to the improved mechanical strength of the concrete with the addition of the glass powder as a pozzolan. As the percentage glass powder (GWP) content increases from beyond 21%, the concrete samples exhibit a lower compressive strength at higher heating temperature. This can be attributed to the significantly slower compressive strength development of the concrete samples even at ambient temperature. Again, changes in the physical colour of the hardened concrete was observed as the temperature increases. Spalling of the concrete can be observed, caused by the dehydration of the C-S-H gel and expansion of the concrete due to the heating. Severity of the spalling and even cracks depends on the duration of exposure to heating and at higher temperature from 300-500°C [23]. Generally, a decrease in compressive strength of the concrete specimens were observed when the concrete specimens were exposed to temperatures beyond 300°C and more. This reduction in strength can be attributed to the changes in the concrete morphology, the formation of micro-cracks and gradual weakening of the interfacial zone of the concrete.

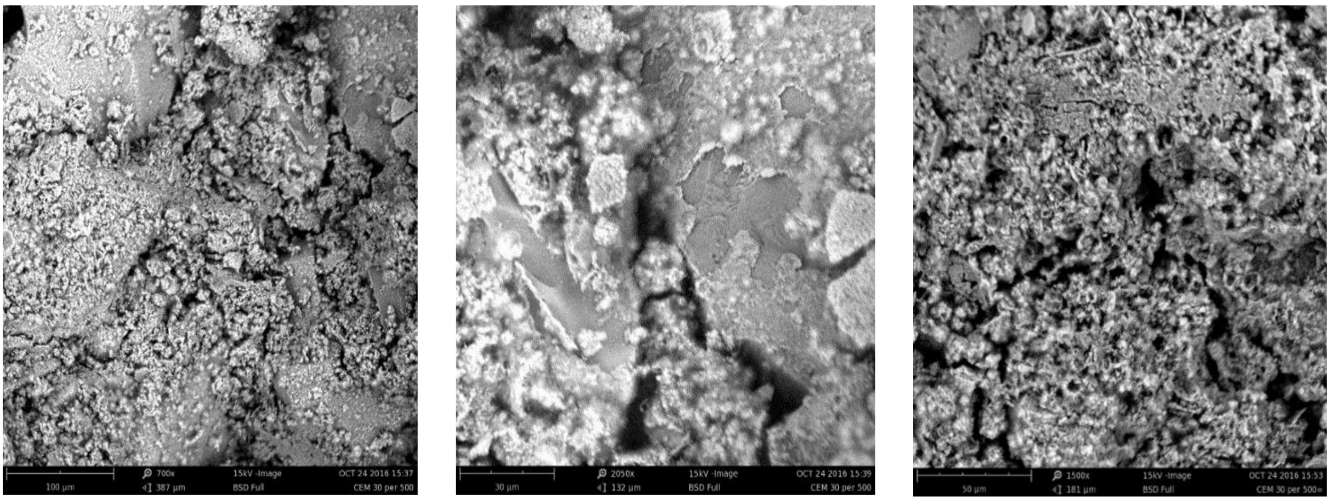
3.3. *Microstructural examination after elevated temperatures*

Microstructural analyses were carried out selected concrete specimens using the scanning electron microscope (SEM) to further assess the microstructure and bond between the paste and aggregate at the interfacial zone before and after heating the concrete. The microstructure and interface between the aggregate and binder materials of the control concrete and concrete specimens containing 21% and 30% GWP content exposed to 28°C, 300°C and 500°C were examined on the crushed specimen surfaces. As observed in Fig. 8 and Fig. 9, changes could be seen in the microstructure, bond paste and interface due to the elevated temperature. At 28°C temperature, the SEM micrographs as seen in Fig. 8 (a) and (b), the microstructure of the concrete specimens containing 21% and 30% GWP is compact, with a good bond at the interfacial zone. When the concretes were exposed to temperature up to 500℃, the SEM micrographs as seen in Fig. 9 (a)-(c), clearly show the loss of strong bond between the paste and aggregates, and weakening of the interfacial zone which may have resulted in the low compressive strength measured values for the concretes especially at higher level of heating temperature of 500°C. This can be attributed to the change in the moisture condition of the concrete resulting in progressive deterioration of the paste-aggregate bond especially at the interfacial zone. Formation of large pores, spalling and cracks can also be seen in the matrix with increasing temperature, particularly at 500°C which contribute to the decrease in the compressive strength of the concretes. Saridemir et al. [24] opined that cracks and pores in the cement matrix and interface of concrete doubled with increasing temperature causing a decrease in the mechanical strength of the concrete. And, it was concluded that reduction in compressive strength is as a result of deterioration, large pores, and crack formation in the concrete specimens due to elevated temperature. Similar comments were made by [13].



(a) Containing no glass powder material (b) Containing 21% GWP (c) 30% GWP

Fig. 8 SEM micrographs on concrete samples before heating containing no glass powder material and containing 21% GWP



(a) Magnification of 100 µm (b) Magnification of 50 µm (c) Magnification of 30 µm

Fig. 9 SEM micrographs on concrete after heating at 500°C at 30% containing glass powder showing the altered bonding at the interface zone at different magnification of 100 µm, 50 µm, 30 µm

4. Conclusions

Based on the experimental work and microstructural analyses using SEM presented in this study, the following conclusions can be drawn:

(1) Concretes produced with 21% glass powder possesses higher compressive strength both at ambient and increase temperatures not beyond 150 °C than normal concrete. However, at higher percentages of cement replacement, concretes containing higher amounts of glass powder possessed the least strength at higher temperature.

(2) The SEM examination conducted on the concrete specimens clearly show deterioration of the C-S-H and $Ca(OH)_2$ gels as the temperature increased.

(3) Waste glass powder can be efficiently used as inert powder to produce normal strength concrete with better resistance to exposed high temperature.

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