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Behaviour of ground cupola furnace slag blended concrete at elevated temperature

Stephen Adeyemi Alabi *, Jeffrey Mahachi

Department of Civil Engineering Technology, University of Johannesburg, Doorfontein Campus, South Africa

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Fires adversely affect the performance of concrete when expose to extreme temperatures. However, it is important to study the effects of elevated temperature on the concrete properties. Concrete often contains other cementitious materials such as ground granulated blast furnace slag (GGBFS) and this has been successfully used to improve its properties. Hence, little or no study has been carried out on the use of ground cupola furnace slag (GCFS) in concreting. Therefore, this paper investigates the behavior of concrete blended with GCFS at elevated temperatures. A total of 300 samples were prepared with four different GCFS contents. The test specimens were cured for 28-d and 56-d and subjected to elevated temperatures ranging from 200ºC to 800ºC up to 24 h. The slump, residual compressive and tensile strength tests were carried out on fresh and hardened concrete. The results showed that the compressive strength and splitting tensile strengths of concrete generally increased with increasing % GCFS content but decreased as temperature increases. At 28-d and 56-d, the strengths were observed to be maximum at 10% replacement when the temperature is 200ºC compared to other mixes. It can be concluded that the strength drastically decreased at temperature above 200ºC. An analysis of variance (ANOVA) was also carried out to determine the effect of the elevated temperature and percentage replacement of cement with GCFS on the 28-d and 56-d compressive strength of concrete. The results showed that temperature and % GCFS content had a statistically significant effect on the concrete performance. Based on Tukey's honestly significant difference (HSD), the effect of GCFS was found to be statistically non-significant for 4% and 6% GCFS content at 28-d; and 2% and 4% GCFS content at 56-d. The effect of temperature was also found to be statistically non-significant for 600ºC and 800ºC at 28-d; and 27ºC and 600ºC; 200ºC and 400ºC at 56-d.

1 Introduction

Concrete is an essential building construction material but the combination of high cost of its Portland cement component, the negative environmental impact and the high energy demand associated with its production, are averse to principles of sustainability. Measures for reduction of the embodied energy in concrete mitigates the harm to the

* *Corresponding author. Tel.: +2347032605510.*
E-mail address: saalabi@futa.edu.ng

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environment, and when otherwise industrial waste products are incorporated, reduction in unit cost of production is also achieved. Such a measure is therefore, an environmentally-responsible, sustainability-conscious and budget-responsive one. The highlighted problems with the use of Portland cement for concrete production have necessitated the research for the alternative cost effective binding materials that could partially or wholly replace its traditional Portland cement.

Concrete has been the most used construction material around the world, consisting of a hard, chemically inert particulate substance known as an aggregate that is bonded together by cement and water [1]. However, the manufacturing of cement which is the major component of concrete has been found to contribute significantly to greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed and through the use of energy, particularly from the combustion of fossil fuels. Therefore, there is a growing interest in reducing carbon emissions as related to concrete. One of the effort that has been made is the replacement of cement with pozzolanic material that requires little or no emission of CO_2.

Afolayan and Alabi [2] investigated the potentials of cupola furnace slag in concrete. The results of the investigation were satisfactory compared to normal aggregates concrete. Arum and Mark [3] investigated the potentials of cupola slag as a partial replacement option for ordinary Portland cement (OPC) in application requiring low permeability concrete. It was observed that strength of the concrete progressively increased at all curing ages as the replacement of cement increased and attained a maximum strength of 29.8 N/mm^2 at 28-d for 15% cement replacement. Yuvraj et al. [4] replaced coarse aggregates by 16, 33, 50, 66, 83, and 100% with cupola slag and fine aggregate by 100% with quarry dust. Their results show that strength decreases as the replacement level of cupola slag increases. Mohamed and Najm [5] tested several sustainable self-compacting concrete (SCC) mixes with a constant water/binder ratio of 0.36 where Ordinary Portland cement (OPC) was partially replaced with GGBS in the range of 0% to 80%. They noted that the highest 28-day compressive strength was obtained when 35% of the cement was replaced with GGBS as compared with strength obtained for the control mix with 100% OPC. They concluded that replacing cement with more than 35% GGBS in binary OPC-GGBS, results in a reduction of compressive strength compared to the compressive strength corresponding to the optimum replacement ratio, and possibly lower than the control mix.

Bhagat et al. [6] investigated the suitability of concrete using cupola slag as partial replacement of coarse aggregate and foundry sand as partial replacement of fine aggregate. They concluded that the modified concrete has similar compressive strength and flexure strength with normal aggregate concrete but split tensile strength of concrete decreases at higher percentage of cupola slag as coarse aggregate. Ramakrishnan et al. [7] carried out an experimental study on the mechanical and durability properties of concrete based on the combined effect of crushed waste glass powder (GP) and GGBS as a partial replacement of cement from 5% to 45% and 45% to 5% in step of 5%, respectively. The optimum mix was selected from the 3, 7, 28-ds, compressive strengths of different mixes. The combined mix (cement + GP + GGBS) as 50:15:35 and 50:20:30 increased the compressive strength by 44.20% and 43.08% as compared to the control mix. Similarly, the split tensile strength of the combined mix (cement + GP + GGBS) with 50:15:35 and 50:20:30 increased the split tensile strength value over the control mix by 9% and 7.6% respectively. It was found that addition of GP and GGBS reduced the sorptivity rate and water absorption rate. Their results also shown that GP and GGBS can be successfully utilized as an effective mineral admixture in cement concrete with 15% and 35% respectively as an optimal replacement of cement in combined manner.

Dadsetan and Bai [8] carried out an experimental assessment SCC samples with water/binder ratio of 0.45 in which the cement was partially replaced with 10%, 20%, and 30% GGBS, and shows that the compressive strength increased with replacement ratio as compared with the control mix. Their further studies on durability where 50% of OPC was partially replaced with various combinations of glass power (GP) (45% to 5% in decrements of 5%) and GGBS (5% to 45% in increments of 5%), the optimum GGBS replacement for maximum compressive strength was found to be 35% (along with 15% GP) after 3, 7, and 28 days of curing. Mansour et al. [9] revealed that the compressive strength of SCC cubes after 7 and 28-ds of water curing increased with an increase in the replacement percentage of OPC with GGBS from 5% to 25% in steps of 5%. Guoxin et al. [10] studied the ground granulated blast furnace slag (GGBS) effect on the durability of concrete with ternary cement when subjected to 5% NaCl, 5% Na_2SO_4 and 5% NaCl - 5% Na_2SO_4 attack. Their results showed that the partial replacement of ternary cement by GGBS increased bound chloride, enhanced compressive strength, and decreased apparent porosity.

Majhi et al. [11] carried out an experimental investigation on the compressive strength of concrete using recycled coarse aggregate (RCA) and ground granulated blast furnace slag (GGBS) as replacement of natural coarse aggregate

(NCA) and cement for developing sustainable concrete. Concrete mixes are prepared with 0%, 25%, 50% and 100% replacement of NCA by RCA for each 0%, 20%, 40% and 60% replacement of cement by GGBFS. The test results obtained showed that the compressive strength decrease with increase in the percentages of RCA or GGBFS or both. Their results also further show that the use of GGBFS improves the quality of the concrete mixes by improving the internal transition zone (ITZ) and bond between mortar and RCA. The concrete mix with 50% RCA and 40% GGBFS achieves values of these properties closer to those of the concrete mix without RCA and GGBFS. They concluded that, the concrete mix with 50% RCA and 40% GGBFS is considered as the optimum mix which is satisfying the target mean strength of the mix design and producing sustainable concrete by saving 40% of cement and 50% of NCA and utilizing maximum waste products such as GGBFS and RCA. Mohamed and Najm [12] studied the effect of the curing methods on the compressive strength of sustainable self-consolidating concrete. In their study 90% of cement was replaced with recycled combinations of fly ash, silica fume, and GGBS with water/binder ratios of 0.36 and 0.33. Compressive strength test results showed that the curing under direct sun produced the highest strength development after 28 days of curing compared to using a curing compound or using traditional method of submerging concrete samples in water. In addition, using acrylic-based curing compound resulted in a higher strength development compared to traditional curing method submerging concrete samples under water for 28 days. Mohamed, [13] investigated the effect of replacing a large volume of cement with ground granulated blast furnace slag (GGBS), fly ash, and silica fume on the strength development of self-compacting concrete (SCC).

The use of ground granulated blast furnace slag (GGBFS) as a cementitious material has received a greater attention since it generally improves the properties of the blended cement concrete [14 - 20] even at elevated temperatures [21 - 29]. However, the use of ground cupola slag as a partial replacement for cement in concrete when subjected to elevated temperature have received little or no attention. Therefore, in this study, an extensive experimental work was carried to investigate the thermal behaviour of ground cupola furnace slag (GCFS) blended concrete. Also, the findings were subsequently subjected to univariate ANOVA to assess the effect of the factors (percentage replacement of cement with GCFS and the elevated temperatures) on the residual strength of concrete.

2 Materials and Methods

2.1 Materials

Crushed coarse aggregate was used in production of concrete, with maximum size of 20 mm. The overall grading, particle shape as shown in Table 1 and surface texture of this aggregate were found to contribute to lower values of strength properties of concrete produce in Akure. The results of the physical properties of coarse aggregate (granite) used, are presented in Table 2.

Pit-sand is commonly used as fine aggregate. Sieve analysis is shown in Table 1 and it is found not to satisfy the requirement of BS 812 [30]. The overall grading limit as given by BS882, [31] requires percentage mass passing to be between 0 – 15% for sieve size 150 µm. The results show that the soil sample does not satisfy the overall grading limit as given by BS882, [31]. The percentage mass passing is 17.84%, which indicates that the sand contains finer particles than the one recommended by standard. However, from Table 2, coefficient of uniformity, Cu and coefficient of curvature (Cc) were determined to be 2.59 and 1.06 respectively. Since, Cu < 4 and Cc = 1.06 which is between 1 and 3 in the Unified Soil Classification System [32], the soil is classified as poorly graded sand. More than half of the coarse fraction is not retained on the 4.75 mm sieve showing that the aggregate is poorly distributed. According to the unified soil classification system, the sand sample is a fine – grained soil (sand) because more than half of the coarse fraction is between the 4.75 mm and 0.075 mm sieve size.

Cupola furnace slag is quite different from blast furnace slag. This is formed when recycled metal materials such as aluminium, cast iron, brass, bronze or iron pellets, copper, steel, tin, and coke are melted together in a cupola furnace. The cupola furnace slag was obtained from the St. Daniel foundry dump site, Akure, Nigeria, in a large extent. The slag was transported to the Metallurgical and Materials Laboratory, Federal University of Technology, Akure, Nigeria. This was then dusted and isolated to remove visible earth impurities. It was then pulverized to less than 4 mm diameter sizes and was afterward ball milled to achieve the powdered granulated form of the slag. A final process was sieved through 75 µm sieve before it could be used as partial replacement for cement in the production of concrete.

Table 1 – Particle size distribution of sand and granite

Sieve Size(mm)	Sand	Granite
	% Passing	% Passing
20	-	84.87
10	-	13.51
4.75	100	8.50
2.36	99.83	-
1.70	99.70	-
1.18	99	2.10
0.60	87.13	1.24
0.50	64.86	-
0.425	64.13	-
0.300	-	0.43
0.212	25.44	-
0.150	17.84	0.05
0.075	13.99	-
Pan	0.00	0.00

Table 2 - Physical properties of aggregates and cement

Physical property of all materials used	Fine aggregate (sand)	Coarse aggregate (granite)	Cement (ordinary Portland Cement)
Fineness (%)	2.00	5.78%	9.62%.
Uniformity Coefficient (C_u)	2.59	4.33	-
Coefficient of Curvature (C_c)	1.06	2.08	-
Specify Gravity	2.64	2.65	-
Bulk density	1530	1635	-
Shape	-	Rough on all sides	-

The results of the chemical composition of the GCFS and ordinary Portland cement (OPC) used in this investigation is presented in Table 3. From this table, it was observed that the sum of the percentage composition of the oxides in the GCFS is 92.8%. According to ASTM [33], a pozzolan should have 70% minimum value for the sum of those oxides.

Table 3 - Percentage of oxides composition of the GCFS and OPC

Common Name	Oxide	OPC Content (%)	GCFS content (%)
Lime	CaO	61.52	24.40
Silica	SiO_2	21.02	45.35
Alumina	Al_2O_3	5.78	9.94
Iron	Fe_2O_3	3.28	4.32
Magnesia	MgO	2.08	5.82
Alkalis	Na_2O and K_2O	0.78	0.69/2.18
Sulfuric anhydride	SO_3	2.04	0.10

2.2 Concrete mixes

A concrete mix ratio of 1:2:4 by weight of cement, sand and coarse aggregate with water-cement ratio of 0.55 was adopted. Five different concrete mix designs were adopted in this study; one conventional aggregate concrete (CAC) and four concretes with 2%, 4%, 6% and 10% GCFS content. The water-to-cementitious materials ratio was kept the same in order to study the effect of replacing cement with GCFS. A total of 300 test samples were prepared (i.e., 60 specimens for each mix). A standard test cube and cylinder of concrete specimen of size 150 mm x 150 mm x 150 mm and 300 mm x 150 mm diameter) were used for both compressive and tensile strength tests. The mixtures designation and quantities of various materials for each designed concrete mixes are given in Table 4. The quantity of each material constituent used in the concrete production can be measure by dividing the density of each constituent by total volume of concrete.

Table 4 - Concrete batching

Concrete	Materials (kg/m^3)						
	CA	FA	Cement	GCFS	Water	$(w/c)_{ef}$	$(w/c)_{ap}$
CC	844	422	211.17	-	126.67	0.55	0.60
RC-2%	844	422	206.83	4.33	126.67	0.55	0.61
RC-4%	844	422	202.67	8.50	126.67	0.55	0.63
RC-6%	844	422	198.50	12.67	126.67	0.55	0.64
RC-10%	844	422	190.00	21.17	126.67	0.55	0.67

Note: $(w/c)_{ef}$: $(w/c)_{effective}$; $(w/c)_{apparent}$: $(w/c)_{apparent}$; *GCFS: ground cupola furnace slag.*

All the samples were prepared in accordance to BS1881: Part 111, [34]. The samples were placed in the concrete moulds and manually compacted with tapping rod, free of debris and oil. Care was also taken that there were no gaps, so as to avoid the possibility of leakage from the slurry. After 24 hr. at ambient temperature, the concrete cubes were removed from the mould, weigh and kept under water in accordance to BS1881: Part111, [34]. The ambient temperature ~~for~~ was 27±2ºC.

2.3 Test procedures: heating and cooling regimes

At testing ages 28-d and 56-d, samples were removed from the curing tank, air dried and weighed. The specimens were heated in a furnace to different elevated temperatures (i.e., 200°C, 400°C, 600°C, and 800°C). The heating rate was set at 8ºC/min and maintained at respective temperature for 1 hr to achieve steady heating. The samples were allowed to cool at ambient temperature for a few minutes. The mechanical properties tests of strength was carried out on concrete samples in accordance with BS 1881: Part 111, [34] at curing ages of 28-d and 56-d.

3 Results and discussions

3.1 Slump test

Table 5 shows, the slump test result.

Table 5 - Slump test.

% GCFS	Slump (mm)	Degree of workability
0	68	Medium
2	70	Medium
4	68	Medium
6	63	Medium
10	73	Medium

It is observed that there is no significant change in both the slump values of CAC and GCFS blended concrete. True slumps were experienced for all the mixes. However, 10% replacement gave the highest slump of 73 mm while 6% replacement gave the least slump of 63 mm. This is an indication that inclusion of GCFS content in the mix has effect on the cohesiveness of the mix. This decrease and increase in slump value with increase in GCFS content can be attributed to higher water absorption capacity of the GCFS. However, it can be inferred that the consistency of the concrete measured by slump values concrete for the tested concrete mix ratio are in compliance with the recommendation given by BS1881: Part102, [35].

3.2 Effect of temperature on 28-d compressive strength

From Figure 1, it is observed that the compressive strength of the concrete mixture increased with the increase in GCFS content at all elevated temperature than the conventional aggregate concrete (CAC). At ambient temperature, 28-d compressive strength of concrete containing 2%, 4%, 6% and 10% GCFS was respectively 25.77%, 37.11%, 26.80 and 41.24% higher than the conventional aggregate concrete. It is also observed that at 28-d, the residual compressive strength relatively decreased with increase in temperature (i.e., 200°C, 400°C, 600°C, and 800°C) for all percentage of GCFS. However, there is no significant reduction in the compressive strength between temperature of 600ºC and 800ºC for all the mixes. This is could be due to slow hydration of cement and GCFS gel as a result of slow evaporation of free water. At 0% replacement, the compressive strength decreased by 23.71%, 28.87%, 31.96% and 32.99% at 200ºC, 400ºC, 600ºC and 800ºC when compared to residual compressive strength of 9.7 N/mm^2 at ambient temperature. However, the residual compressive strength decreased at all other percentage of GCFS with increase in temperature. Also, the same trend of loss of strength was observed at 2% replacement with reduction of about 16.80%, 20.49%, 31.15% and 31.15% at varying between 200ºC and 800ºC. At 4% replacement with reduction of about 5.26%, 18.80%, 23.31% and 27.07% at 200ºC, 400ºC, 600ºC and 800ºC. At 6% replacement with reduction of about 1.63%, 5.69%, 14.63% and 17.89% at 200ºC, 400ºC, 600ºC and 800ºC. At 10% replacement with reduction of about 2.92%, 7.307%, 16.79% and 20.44% at 200ºC, 400ºC, 600ºC and 800ºC. Generally, at temperature between 200ºC and 400ºC: There was a loss of concrete strength and steady drop occurred again as it approached 600ºC. Surface cracks were observed in the cubes.

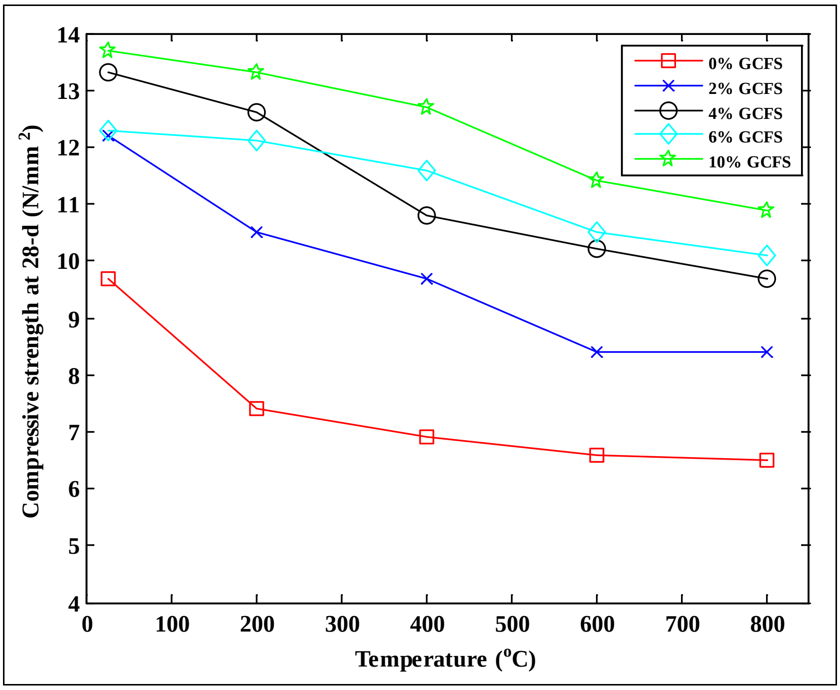

Fig. 1 - Residual compressive strength under varying temperature and grounded cupola slag at 28-d.

3.3 Effect of temperature on 56-d compressive strength

Figure 2 shows the compressive strength at varying elevated temperature and percentage GCFS. It is observed from the figure that for 0% GCFS, the compressive strength at 200ºC decreased by 23.78% as compared with the concrete strength of 14.3 N/mm^2 at ambient temperature. Olanitori and Olotuah [36] achieved a concrete of compressive strength between 8 N/mm2 and 12 N/mm^2. This gives a reduction in strength of about 40% to 60%. Based on the observation by Siddique and Kaur [27], the reduction could be as a result of stresses developed at the interface between the aggregate and the hardened concrete paste when exposed to the elevated temperatures. This could as well result into micro-cracking and disruption of the cement-aggregate bond with a consequent reduction in compressive strength. As the temperature increased to 400ºC, the compressive strength increased a little but still lower than the compressive strength at ambient temperature. It is observed that there was a continuous reduction in the compressive strength at temperature of 400ºC beyond. This could be that as temperature increased from 400ºC to 800ºC, there was a substantial loss of water which result into loss of free water and subsequently reduce the concrete strength.

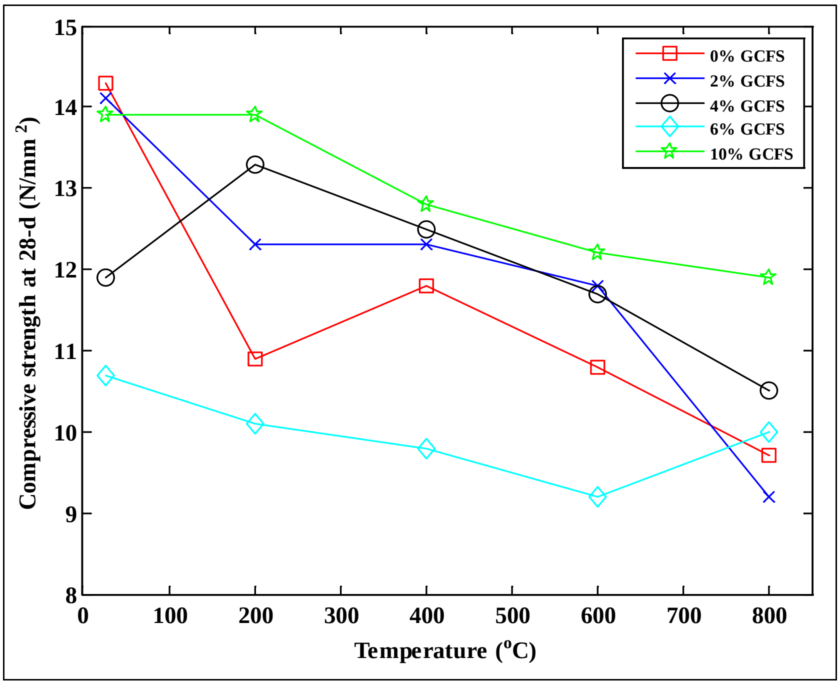

Fig. 2 - Residual compressive strength under varying temperature and grounded cupola slag at 56-d.

A decrease in the residual compressive strength with similar trend to 0% GCFS was observed with 2% replacement of cement with GCFS at 56-d. At 200ºC a reduction in strength by 12.77% was observed. Then, a constant in the strength at 400ºC and thereafter a steady decrease in strength was noticed up to 800ºC compared with the strength at ambient temperature. This may be due to the relative weak interfacial bond between aggregates and hardened paste within the concrete matrix. But at 4% GCFS, an increase in the residual compressive strength was noticed by 11.76% at 200ºC as compared with the strength of 11.9 N/mm^2 at ambient temperature. After the temperature of 200ºC a slow reduction in the strength was observed up to 600ºC, afterwards a drastic reduction in the strength was observed. It is suspected that there was thermal expansion and dehydration of concrete in this temperature regime (i.e, 200ºC to 600ºC).

For 6% and 10% replacement of cement with GCFS at 56-d, a very slow reduction in the residual compressive strength was observed. This could be that the addition of GCFS contributes significantly to the residual compressive strength of concrete at elevated temperatures. In fact, a sudden increase in the residual compressive strength was observed for the concrete produced with 10% GCFS by 2.52% at 800ºC.

3.4 Effect of temperature on residual splitting tensile strength

The 28-d and 56-d splitting tensile strength values for the CAC and GCFS blended concretes at elevated temperature are shown in Figures 3 and 4. From the figures, it is observed that for all the GCFS blended concretes with varying percentage replacement (i.e., 2%, 4%, 6% and 10%) have splitting tensile strength higher than the conventional concrete (CC) at different elevated temperature. It is observed from Figure 3 that the splitting tensile strength at ambient temperature decreased with increasing temperature. The residual splitting tensile strength of concrete containing 2%, 4%, 6% and 10%

GCFS content respectively 8.33%, 25%, 41.67% and 58.33% was higher than the splitting tensile strength, 1.2 N/mm^2 of conventional concrete at ambient temperature with 0% GCFS.

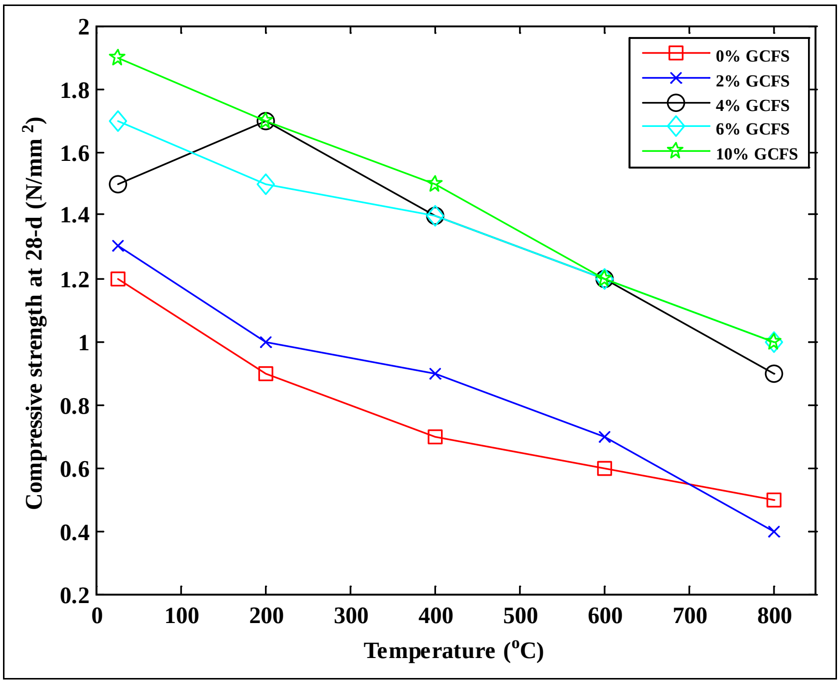

Fig. 3 - Residual splitting tensile strength under varying temperature and grounded cupola slag at 28-d.

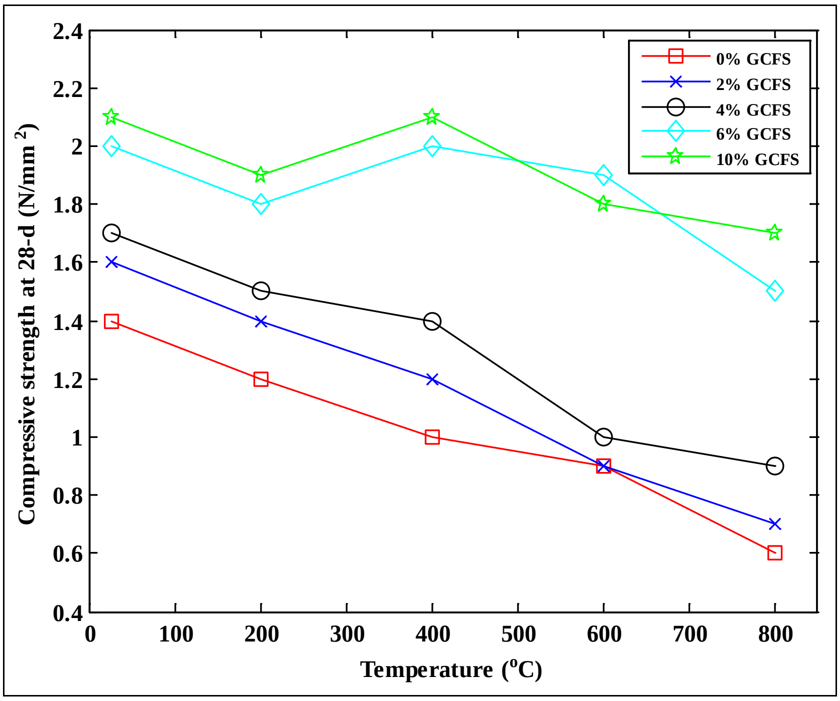

Fig. 4 - Residual splitting tensile strength under varying temperature and grounded cupola slag at 56-d.

From Figures 3 and 4, it is observed that the splitting tensile of concrete decreased with the increase in the elevated temperature. At 28-d, the splitting tensile strength of concrete containing 6% (11.76%, 17.65%, 29.42% and 41.18%) and 10% (10.53%, 21.05%, 36.84% and 47.37%) GCFS content at 200°C, 400°C, 600°C and 800°C respectively were higher than concrete strength (1.7 N/mm^2 and 1.9 N/mm^2) at ambient temperature. At 4% replacement, the residual splitting tensile strength of concrete increased by 13.33% at 200°C when compared to the strength at ambient temperature (1.5

N/mm^2). After wards a steady decrease in the splitting tensile strength is experienced` as the temperature increases. It is observed the concrete blended with the 2% GCFS at 400^{o}C, 600^{o}C and 800^{o}C was 16.67%, 0% and 25% higher than the concrete strength, 1.2 N/mm^2 at ambient temperature. Splitting tensile strength of concrete containing 2% GCFS content at 200^{o}C, 400^{o}C, 600^{o}C and 800^{o}C respectively 16.67%, 25%, 41.67% and 66.67% was lower than the concrete strength at ambient temperature (1.2 N/mm^2). However, similar trend was observed at 56-d splitting tensile strength of concrete.

The behaviour of concrete blended with 6% and 10% GCFS content at temperature ranging between 27^{o}C and 200^{o}C, at 56-d, was characterized with distinct pattern of strength loss. The initial drop in strength may be due to the relative weak interfacial bond between aggregates and the cementitious paste. However, the conventional concrete decreased steadily from 27^{o}C up to 800^{o}C. Considering the temperature range between 200^{o}C and 400^{o}C, a continuous gain in strength was observed. Also, at the temperature between 400 C and 800^{o}C, a subsequent loss of concrete strength and steady drop occurred. This reduction in strength may be due to surface cracks.

3.5 Statistical analysis of 28-d and 56-d compressive strength

A two-way ANOVA was carried out to study the interaction and main effects of the % GCFS content and elevated temperatures on the 28-d and 56-d compressive of the concrete. Tukey's honestly significant difference (HSD) also carried out to established groups within which the differences in the effect of the % GCFS content and elevated temperatures was not statistically significant. All the tests were carried out for a confidence level of 95%, equivalent to a p-value of 0.05.

3.5.1 28-d compressive strength

The normality test carried on the compressive strength for 28-d, shows that their *p*-values greater than 0.05 (i.e. *p*-value > 0.05). This implies that there is no significant deviation from a normal distribution. Based on statistics textbooks like [37], the "rule-of-thumb" minimum number of data points for estimating a decent statistic were suggested be to 30. The 75 compressive strength data points from direct measurement were used in this study.

Figure 1 provides a good understanding on the thermal behaviour of GCFS blended concrete, which shows that there is statistically significant interaction between the % GCFS content and elevated temperature. This implies that the compressive strength of the concrete at elevated temperatures with 4% and 6% GCFS content are random (i.e., uncertain). From the figure, it is observed that the line 0%, 2%, and 10% are parallel i.e., they do not overlap or cross. Therefore, it is not likely to find statistically significant interaction effect between percentage replacement of cement with GCFS and elevated temperature. From Table 6, the *p*-value for the elevated temperature effect is less than 0.05 (i.e. *p*-value = 0.00 < 0.05) with significant partial η^2 of about 95%. The *p*-value for the % GCFS content is also less than 0.05 (i.e. *p*-value = 0.00 < 0.05) with significant partial η^2 of about 97%. This implies that there is statistically significant difference. It can be concluded that, the effect of the elevated temperature on the compressive does not depend on the % GCFS content. Also, the effect of the % GCFS content compressive strength can be said not to depend on the elevated temperature. The *p*-value for the interaction between % GCFS content and elevated temperature is less than 0.05 (i.e. *p*-value = 0.00 < 0.05) with significant partial η^2 of 61.1%. This support the observation from Figure 1 that interaction effect between the % GCFS content and elevated temperature is statistically significant. However, there is sufficient evidence not to reject the interaction effect null hypothesis. It can be concluded that in spite of weak interfacial bond or cracking and the different thermal properties of the matrix-aggregate interface of concrete, the incorporation of GCFS does influence the thermal response of the concrete.

From Table 6, it is observed that the effect of temperatures only explains about 95% of the total variability in the compressive strength of the concrete. The effect of % GCFS content explains about 97% of the variance in the compressive strength. The interaction between the elevated temperature and % GCFS content accounts for about 61% in the variability in the compressive strength of the concrete. These findings further support, the fact that effect of % GCFS content is more significant than the presence of the elevated temperature on the compressive strength of the concrete.

Based on the Tukey HSD outcomes for 28-d compressive strength, there were no significant differences for the concretes containing 4% and 6% GCFS content and also there were statistically non-significant difference at elevated temperature of 600^{o}C and 800^{o}C respectively. This may be due to relatively weak interfacial bond between the aggregates and hardened paste within the matrix. Two groups with equal variances were identified: group A (*p*-value = 0.97 > 0.05) for % GCFS content; and group B (*p*-value = 0.92 > 0.05).

3.5.2 56-d compressive strength

Figure 2 also provide the same information as whether or not there is a statistically significant interaction between the % GCFS content and temperature effects. From the figure, it is observed that the line 0%, 2%, and 4% are not parallel i.e., they overlap or cross each other. Therefore, it is likely to find statistically significant interaction effect between the percentage replacement and temperature at 56-d.

Table 6 present the two-way ANOVA results for 56-d compressive strength based on the interaction effect between the % GCFS content and temperature. It is observed that there is statistically significant difference between % GCFS content and temperature. Based on the Tukey HSD outcomes for 56-d compressive strength, there were no significant differences for the concretes containing 2% and 4% GCFS content and also there were statistically non-significant difference at temperature (i.e., 27ºC and 600ºC; 200ºC and 400ºC respectively). Three groups with equal variances were identified: group C (*p*-value = 0.132 > 0.05) for % GCFS content; group D (*p*-value = 0.998 > 0.05) and group E (*p*-value = 1 > 0.05) for temperatures.

Table 6 - Summary of two-way univariate ANOVA results

Property		Effect	Mean square	F-value	P-value	Partial η^2
Compressive strength	28-d	Temperature	29.20	240.64	0.00	0.95
		% GCFS content	56.83	468.36	0.00	0.97
		Interaction between variables	0.60	4.91	0.00	0.61
	56-d	Temperature	5.46	29.04	0.00	0.70
		% GCFS content	18.53	98.57	0.00	0.89
		Interaction between variables	1.98	10.51	0.00	0.77

Note: *variables are temperature and percentage replacement of cement with GCFS*

4 Conclusion

This paper has presented a study on the effect of elevated temperature on the properties of concrete blended with GCFS. It was observed that, 10% replacement gave the highest slump while 6% replacement gave the least slump. At 28-d, it was observed that the compressive strength of the concrete mixture increased with the increase in GCFS content at all elevated temperature than the conventional concrete (CC). Again, at 0% GCFS content, 56-d compressive strength at 200ºC decreased by 23.78% as compared with the concrete strength of 14.3 N/mm^2 at ambient temperature. Similar trend to 0% GCFS content was observed at 2% replacement of cement with GCFS. At 200ºC, a reduction in strength by 12.77% was observed. Afterwards, a constant in the strength at 400ºC and thereafter a steady decrease in strength was noticed up to 800ºC compared with the strength at ambient temperature. For 28-d and 56-d splitting tensile strength, it was observed that for all the GCFS blended concretes with varying percentage replacement have splitting tensile strength higher than the conventional concrete (CC) at different elevated temperature. It can be concluded that the splitting tensile strength at ambient temperature decreased with increasing temperature. Based on the analysis of variance conducted on the compressive strength, the result showed that the effect of GCFS was found to be statistically non-significant for 4% and 6% GCFS content at 28-d; and 2% and 4% GCFS content at 56-d, but statistically significant for 2% and 10% GCFS content. It can be concluded that, the effect of the elevated temperature on the compressive does not depend on the % GCFS content. Also, the effect of the % GCFS content compressive strength can be said not to depend on the elevated temperature.

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