World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:9, No:4, 2015

# Heating and Cooling Scenario of Blended Concrete Subjected to 780 Degrees Celsius

J. E. Oti, J. M. Kinuthia, R. Robinson, P. Davies



***Abstract*—**In this study, the Compressive strength of concretes made with Ground Granulated Blast furnace Slag (GGBS), Pulverised Fuel Ash (PFA), Rice Husk Ash (RHA) and Waste Glass Powder (WGP) after they were exposed 780$^0$C (exposure duration of around 60 minutes) and then allowed to cool down gradually in the furnace for about 280 minutes at water binder ratio of 0.50 was investigated. GGBS, PFA, RHA and WGP were used to replace up to 20% Portland cement in the control concrete. Test for the determination of workability, compressive strength and tensile splitting strength of the concretes were carried out and the results were compared with control concrete. The test results showed that the compressive strength decreased by an average of around 30% after the concretes were exposed to the heating and cooling scenario.

***Keywords*—**Pulverised Fuel Ash, Rice Husk Ash, heating and cooling, concrete.

## I. Introduction

CONCRETE is a very durable material and when exposed to heating and cooling regime, the extent of the effects have to be assessed in order to determine if the structure can be reused. In some cases depending upon the intensity of the fire, the concrete will have no defects, it is only at elevated temperatures that the concrete may change state, the greater the intensity of the heating the greater the impact upon the concrete [1]. High temperature draws the moisture out of the pores of the concrete structure causing cracking, crumbling and peeling of the concrete [2], [3]. The cement used, type of aggregate used, and the thermal conductivity and heat capacity of the concrete are all properties that can determine the fire resistance [4]. The reasoning for the change in colour of concrete after the effect of fire is due to chemical reactions that take place and form crystals [5], [6]. When a concrete is subjected to fire, temperature rise causes water to transform from water to steam vapour, which increases the pressure in the concrete voids. In denser concrete such as radiation shielding concrete, trapped water vapour causes the internal pressure development [7]. Continuation of steam development in the concrete increases the internal pressure of the matrix until the pressure exceeded the tensile capacity of the concrete causing pieces of concrete to be violently dispersed [8], [7].

Kakali et al. [9] studied the effect of high temperature up to 1000$^0$C on blended cement paste. Natural pozzolan such as Ground Granulated Blast furnace Slag (GGBS), Pulverised Fuel Ash (PFA), metakaolin and limestone were used in the study as main cement substitution replacing part of ordinary Portland cement (OPC) with 10–20%. The test results showed that the used of pozzolanic material especially metakaolin has higher fire resistance whereas samples with limestone showed the worst behaviour. Savva et al. [10] work was on the Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates. When conventional concrete is exposed to an elevated temperature, its physical and mechanical properties are adversely affected [11], in general, the initial degradation for the compressive strength of conventional concrete is experienced between 200 and 250$^0$C, while at 300$^0$C strength reduction is in the range of 15–40% [12] was observed. Papayianni and Valiasis [13] conducted a study on normal strength concrete containing lime stone aggregates with 30–40% FFA. At 400$^0$C, the OPC concrete lost 50% of its strength while the PFA concrete lost 65 % of its strength. The result showed PFA additions to lime stone aggregates concrete were more sensitive to elevated temperatures than conventional concrete.

The effect of high temperatures on the mechanical properties and durability of concrete have been investigated by many researchers, many of the paper in literature deals with the influence of different heating rates on the behaviours of concrete [3], [14], [15]. In spite that the heating and cooling phases is an inevitable stages after any fire, there is no sufficient reliable experimental data which measures the performance of different types of concrete during this phases, using varied cement replacement materials, for examples, there is little research about the effect of heating and cooling on the properties of concrete made with GGBS, PFA, Rice Husk Ash (RHA) and Waste Glass Powder (WGP). This shows that there is a genuine need and real niche to conduct a well-designed experimental investigation into the heating and cooling properties of concrete made with these materials (GGBS, RHA, PFA and WGP) to provide high quality test data to the research field.

## II. Methodology

### A. Materials

The materials used in the research consisted of Portland cement (PC), Ground Granulated Blast furnace Slag (GGBS), Pulverised Fuel Ash (PFA), Rice Husk Ash (RHA), Glass Powder (GP), limestone aggregate, and natural sea-dredged sand.

J. E. Oti is from the Department of Engineering, Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd, CF37 1DL, UK (Tel: +44 1443 483452; Fax: +44 1443 48345; w-mail: jonathan.oti@southwales.ac.uk).

J. M. Kinuthia, R Robinson, and P. Davies are with the Department of Engineering, Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd, CF37 1DL, UK..

1) Portland Cement

Portland Cement (PC), manufactured in accordance with BS EN 197-1 [16], supplied by Lafarge Cement UK, was used throughout this research programme. Some physical properties of the PC, its oxide and some chemical composition can be seen in Table I.

TABLE I
THE OXIDE COMPOSITION AND SOME PHYSICAL PROPERTIES OF PC, GGBS, PFA, RHA AND WGP

| Oxide | PC | GGBS | PFA | RHA | WGP |
|---|---|---|---|---|---|
| $SiO_2$ | 20.00 | 35.35 | 47.60 | 86.80 | 70.59 |
| $TiO_2$ | – | – | 1.03 | 0.02 | – |
| $Al_2O_3$ | 6.00 | 11.59 | 26.20 | – | 2.03 |
| $Fe_2O_3$ | 3.00 | 0.35 | 9.40 | 0.10 | 0.53 |
| MgO | 4.21 | 8.04 | 1.42 | – | 0.94 |
| MnO | 1.11 | 0.45 | – | 0.48 | 0.02 |
| CaO | 63.00 | 41.99 | 2.40 | 1.47 | 10.52 |
| $Na_2O$ | – | – | 3.09 | – | 13.37 |
| $K_2O$ | – | – | 3.02 | 4.98 | 0.52 |
| $P_2O_5$ | – | – | – | 5.04 | 0.02 |
| $SO_3$ | 2.30 | 0.23 | 0.86 | – | – |
| $N_2O$ | – | – | – | – | – |
| $S^{3-}$ | | 1.18 | – | – | – |
| $CaCO_3$ | – | – | – | – | – |
| Loss on Ignition | 0.8 | – | 0.55 | – | 1.23 |
| **Chemical (%)** | | | | – | |
| Cl | 0.03 | – | – | – | – |
| Free lime | 1.32 | – | – | – | – |
| **Bogue's composition** | | | | – | |
| Tricalcium aluminate ($C_3A$) | 6.48 | – | – | – | – |
| Tricalcium silicate ($C_3S$) | 70.58 | – | – | – | – |
| Dicalcium silicate ($C_2S$) | 6.09 | – | – | – | – |
| Tetracalcium alumunate-ferrite ($C_4AF$) | 6.45 | – | – | – | – |
| **Properties** | | | | | |
| Insoluble Residue | 0.5 | 0.3 | – | – | – |
| Bulk Density (kg/m³) | 1400 | 1200 | – | – | – |
| Relative Density | 3.1 | 2.9 | 2.45 | – | 2.68 |
| Blaine fineness ($m^2$/kg) | 365 | 450 | – | – | 433 |
| Colour | Grey | White | – | – | – |
| Glass Content | – | 90 | – | – | – |

PC = Portland Cement, GGBS = Ground Granulated Blastfurnace Slag, PFA = Pulverised Fuel Ash, RHS = Rice Husk Ashe, WGP = Wastes Glass Powder

2) Ground Granulated Blastfurnace Slag (GGBS)

Ground Granulated Blastfurnace Slag (GGBS) used in this study was in compliance with BS EN, 15167–1 [17] and was supplied by Civil and Marine Ltd, Llanwern, Newport, UK. Some physical properties of GBBS and its oxide composition are presented in Table I.

3) Pulverised Fuel Ash (PFA)

The Pulverised Fuel Ash (PFA) used in this study was supplied by a local contractor. The oxide composition and some physical properties of the PFA are also presented in Table I.

4) Rice Husk Ash (RHA*)*

The Rice Husk Ash (RHA) used in this study was supplied by a local contractor. The oxide composition is presented in Table I.

5) Waste Glass Powder (WGP)

The waste Glass Powder (WGP) used in this study was also supplied by a local contractor. Some physical properties of the WGP and its oxide composition is also presented in Table I.

6) Limestone Aggregates

The limestone aggregates used throughout this investigation, were divided into two groups: one was size 20/10 and the other 10/4. The aggregates were supplied by a local quarry and complied with the requirements of PD 6682-1 [18] and BS EN 12620 [19]. The results of sieve analysis of the limestone aggregate performed in accordance with BS EN 12620 [19] and BS EN 933-1 [20] are given in Table II. Some geometrical, mechanical and physical properties of the limestone aggregate in compliance with BS EN 1097-6 [21], BS EN 933-4 [22] and BS 812-112 [23] are shown in Table III.

TABLE II
THE SIEVE ANALYSIS OF THE COARSE AND FINE AGGREGATES

| Sieve Sizs (mm) | Sand | Limestone 10/4. | Limestone 20/10. |
|---|---|---|---|
| **31.5** | 100 | 100 | 100 |
| **16** | 100 | 100 | 84.5 |
| **8** | 100 | 77 | 2 |
| **4** | 100 | 2 | 0.18 |
| **2** | 83 | 0.3 | 0.15 |
| **1** | 54 | 0.28 | 0.14 |
| **0.5** | 21.8 | 0.19 | 0.13 |
| **0.25** | 6 | 0.14 | 0.12 |
| **0.125** | 1.2 | 0.1 | 0.1 |

TABLE III
SOME GEOMETRICAL, MECHANICAL AND PHYSICAL PROPERTIES OF THE COARSE AND FINE AGGREGATES

| Property | Sand | Limestone 10/4. | Limestone 20/10. |
|---|---|---|---|
| Water absorption (%) | 0.85 | 1.5 | 1.1 |
| Saturated density (Mg/m³) | 2.82 | 2.68 | 2.65 |
| Dry density (Mg/m³) | 2.71 | 2.57 | 2.54 |
| Shape index (%) | – | 12 | 7 |
| Impact value (%) | – | 23 | 15 |
| Flakiness index (%) | – | | |

7) Sand

The sand used throughout this study was natural sea-dredged sand from the Bristol Channel. The results of sieve analysis of the limestone aggregate performed in accordance with BS EN 12620 [19] and BS EN 933-1 [20] are given in Table II. Some geometrical, mechanical and physical properties of the sand in compliance with BS EN 1097-6 [21], BS EN 933-4 [22] and BS 812-112 [23] are also are also given in Table III.

*B. Mix design, Sample Preparation and Testing*

The control mix for the concrete in the current research work adopted a mix used on various occasions in previous studies by the authors. This mix had been used to assess the strength and consistency of concrete incorporating slate waste [24]. The mix used a binder: sand: aggregate proportion of 1 : 1.85 : 2.64, using limestone aggregate and a Portland cement content of 390 kg/m$^3$. The water/binder ratio was 0.5, with a slump of 70 mm. Based on this control mix for the concrete, the current investigation used Ground Granulated Blast furnace Slag (GGBS), Pulverised Fuel Ash (PFA), Rice Husk Ash (RHA) and Waste Glass Powder (WGP) to replace the Portland Cement PC in the control mix. The intention was not to maintain a specified consistency but to obtain usable concrete, irrespective of consistency, using GGBS, PFA, RHA and WGP and, if possible, without using superplasticisers, for cost-effectiveness, the various combinations as shown in Table IV. The first mix was referred as JO1 which is the control mix with 100% PC. For the second mix (JO2), 20% of the PC in the control concrete mix was replaced with 20% GGBS. The third mix was designated JO3 and the mix was produced by replacing 20% of the PC in the control concrete mix with 20% PFA. The fourth mix was referred as J04 and it was produced by replacing 20% of the PC in the control concrete with 20% RHA. The final mix was designated JO5 and the mix was produced by 20% of the PC in the control concrete mix with 20% GPW

TABLE IV
THE VARIOUS MIX COMBINATIONS

| Mix | PC | GGBS | PFA | RHA | WGP |
|---|---|---|---|---|---|
| | | | (kg/m$^3$) | | |
| JO1 | 390 | 0 | 0 | 0 | 0 |
| JO2 | 312 | 78 | 0 | 0 | 0 |
| JO3 | 312 | 0 | 78 | 0 | 0 |
| JO4 | 312 | 0 | 0 | 78 | 0 |
| JO5 | 312 | 0 | 0 | 0 | 78 |

PC = Portland Cement; GGBS = Ground Granulated Blast furnace Slag; RHA = Rice Husk Ash; PFA = Pulverised Fuel Ash; WGP = Waste Glass Powder

Water = 208 kg/m$^3$; Aggregate 20/10= 677kg/m$^3$,_Aggregate 10/4 = 333kg/m$^3$, Aggregate 4/0= 700kg/m$^3$

Cube (100 mm × 100 mm × 100 mm) and cylinder (150 mm × 300 mm) test specimens were used in the production of all the concrete. For all mix compositions, the test specimens, were prepared in accordance with BS EN 206-1 [25], BS EN 12350-1[26] and BS EN 12390-1 [27]. The consistency of the fresh concrete was measured using the slump test and compaction index test in accordance with BS EN 12350-2 [28] and BS EN 12350-4 [29]. De-moulding of the test specimens was done after 24 hours. The curing of the test specimens were carried out in accordance with BS EN 12390-2 [30]. All the cube specimens were tested for 3, 7, 14, 28, 56 and 90-day compressive strength in accordance with BS EN 12390-3 [31] and BS EN 12390-4 [32]. The concrete cylinders were tested for 28-day tensile splitting strength in accordance with BS EN 12390-6 [33]. For all mix compositions, the results reported are the average obtained from five individual specimens for compressive strength and three for tensile splitting strength. The determination of the heating and cooling behaviour of the concrete was done by means of Wild a Barfield MI354 – DA700 Furnace with a maximum operating temperature of 220$^0$C, the furnace equipped with a computer that has Picolog software and PICO USBTC–08 Thermocouple data logger transducer. The concrete samples were exposed to three temperatures regimes (180$^0$C, 480$^0$C and 780$^0$C) and it was assumed that the fire will remain confined to the compartment where it has originally started. The duration for the exposure of the concrete sampled was around 60 minutes. The concrete samples were then allowed to cool down gradually in the furnace for about 280 minutes to ensure that a reasonable cooling down scenario that can be encountered in real fire situations (see Fig. 1). For all mix compositions, three cube test samples were subjected to heating and cooling scenario after the curing age of 3, 7, 14, 28, 56 and 90 day.

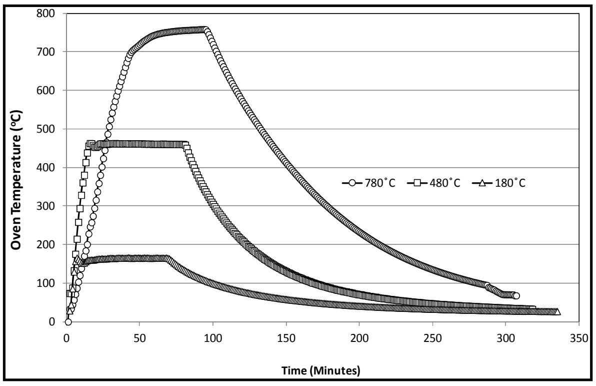


Fig. 1 Heating Temperature and cooling time for the concrete samples

## III. RESULTS

### A. Consistency of Fresh Concrete

The results for Consistency of fresh concrete measured using slump test are presented in Fig. 2. The target slump of 70 mm was only achieved with the control mix (JO1). It was not possible to achieve this target slump for the concrete mixes containing GGBS, PFA, RHA and WGP. Mix JO2, where the PC in the concrete control mix was replaced with 20% GGBS showed a marginally higher slump value of 80mm. The observed slump value for mix JO3 (the mix where 20% of the PC in the control concrete was replaced with 20% PFA) was 62mm. The slump value for the mix JO4 where 20% of the PC in the control concrete was replaced with 20% RHA was significantly lower (15mm). The slump value for mix JO5 was 25mm and this was the mix where 20% of the PC in the control concrete was replaced with 20% WGP. No segregation was observed in these mixes.

Fig. 3 shows the results of the compaction index test for all the concrete mixes. As expected, the control concrete mix show significantly lower compaction index value when compared with the values obtained for the mixes incorporating GGBS, PFA, RHA and WGP. The highest compaction index value was obtained for Mix JO4.

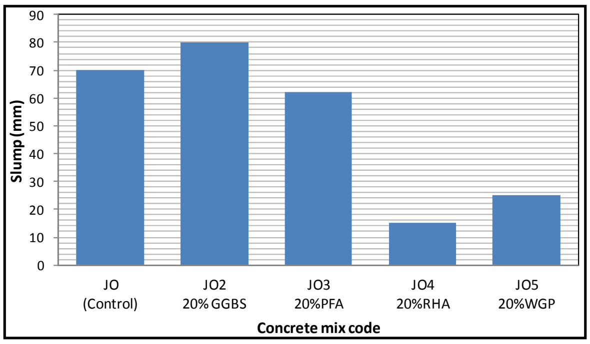


Fig. 2 Consistency of fresh concrete measured by slump test

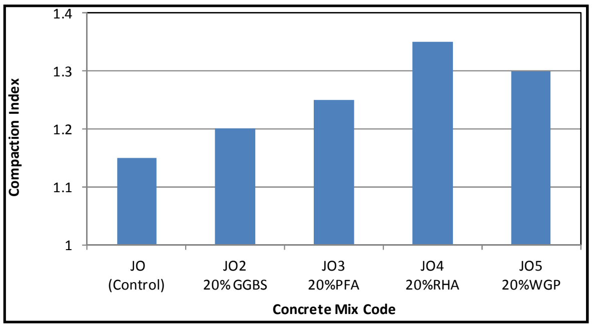


Fig. 3 Consistency of fresh concrete measured by compaction index test

*B. Compressive Strength*

Fig. 4 shows the compressive strength development of the 100 mm × 100 mm × 100 mm test concrete cubes for the control mix (JO1) at normal condition and when subjected to heating at cooling at various ages. It can be seen that increasing the temperature up to 780$^0$C resulted to reduction in the concrete strength. At the end of the 90-day curing period, the highest compressive strength value was obtained with the normal concrete while the lowest strength values was obtained with the concrete was subjected to a temperature up to 780$^0$C. The results in Fig. 4 show that there is little or no effect to the concrete strength when it was subjected to a temperature of 180$^0$C at all ages. When the concrete was subjected to a temperature of 480$^0$C there was a noticeable difference in strength.

Fig. 5 presents the results of the compressive strength of all the concrete mix JO2 (where the PC in the concrete control mix was replaced with 20% GGBS) at normal condition and when subjected to heating at cooling at various ages.

Again like mix JO1, it can be seen that increasing the temperature up to 780$^0$C resulted to reduction in the concrete strength. The effect of heating and cooling scenario is more significant at 780$^0$. The highest strength was observed for the control mix. Fig. 6 presents the results of the compressive strength of all the concrete mix JO3 (where the PC in the concrete control mix was replaced with 20% PFA) at normal condition and when subjected to heating at cooling at various ages. Again like mix JO1 and JO2, it can be seen that increasing the temperature up to 780$^0$C resulted to reduction in the concrete strength. At the end of the 90-day curing period, the highest compressive strength value was obtained with the normal concrete while the lowest strength values was obtained with the concrete was subjected to a temperature up to 780$^0$C.

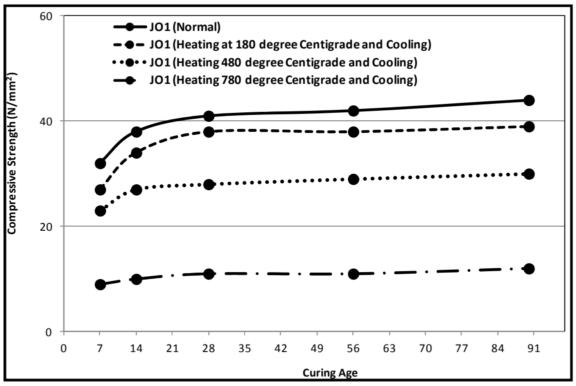


Fig. 4 The compressive strength of the concrete mix JO1 at normal condition and when subjected to heating

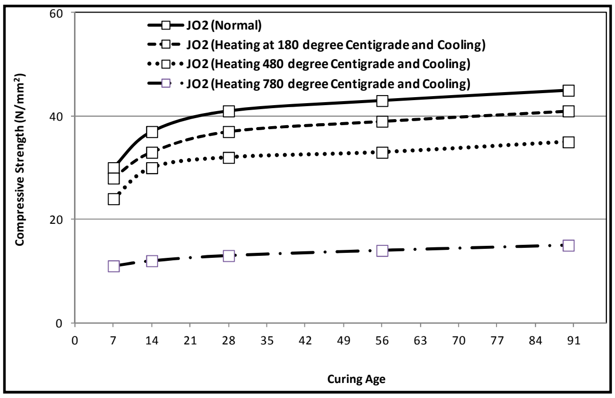


Fig. 5 The compressive strength of the concrete mix JO2 at normal condition and when subjected to heating

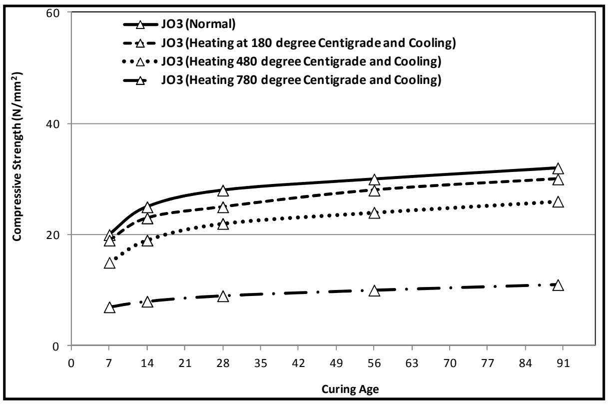


Fig. 6 The compressive strength of the concrete mix JO3 at normal condition and when subjected to heating

Fig. 7 presents the results of the compressive strength of all the concrete mix JO4 (where the PC in the concrete control mix was replaced with 20% RHA) at normal condition and when subjected to heating at cooling at various ages. Again like mix JO1, JO2 and JO3, it can be seen that increasing the temperature up to 780$^0$C resulted to reduction in the concrete strength. After exposing the concrete to heating and cooling, a significant loss in strength was observed for all of the concretes at all temperature.

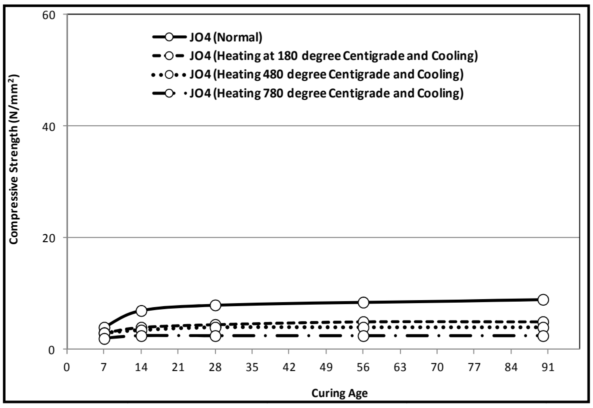


Fig. 7 The compressive strength of the concrete mix JO4 at normal condition and when subjected to heating

Fig. 8 shows the results of the compressive strength of all the concrete mix JO5 (where the PC in the concrete control mix was replaced with 20% WGP) at normal condition and when subjected to heating at cooling at various ages. Again like mix JO1, JO2, JO3 and JO4 it can be seen that increasing the temperature up to $780^0$C resulted to reduction in the concrete strength. The compressive strength at a temperature of $780^0$C decreased more sharply than that of the control mix.

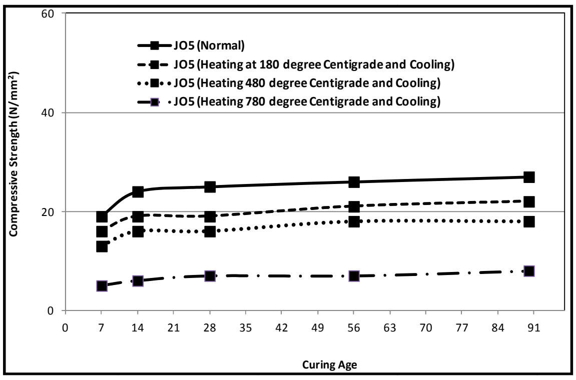


Fig. 8 The compressive strength of the concrete mix JO5 at normal condition and when subjected to heating

Fig. 9 presents the results of the tensile splitting strength of all the concrete mixes at the end of the 28-day curing period. The highest tensile splitting strength of 2.7 N/mm2 was obtained from mix JO1 (control). The lowest tensile splitting strength was obtained from mix PKSC-4; this was where 20% of the PC in the control concrete was replaced with 20% RHA.

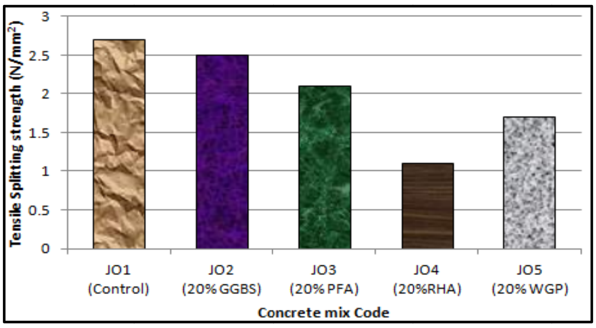


Fig 9 The Tensile Splitting strength for all the concrete mix

## IV. Discussion

The consistency of all mixes were found to be different but with a noticeable pattern. When 20% of the PC in the control concrete was replaced with 20% GGBS resulted to a noticeable the slump increase. This clearly shows that by supplementing GGBS in to a concrete mix it makes the mix stiffer and the slump increased by 14%. When 20% of the PC in the control concrete was replaced with 20% RHA, the slump value of the concrete decreased to around 85%. However, when analysing the compactability differences between the mixes, a much difference trend between the mixes were observed, the mix with 20% RHA tend to have a higher compaction index value.

The results of the tensile splitting strength showed that the control mix has the highest tensile strength value while the presence of RHA resulted to a drastic reduction in the tensile splitting strength value. A significant decrease in the compressive strength was observed in all of the mixtures (JO1, JO2, JO3, JO4 and JO5) after heating to $780^0$C. Some researchers reported that this strength loss is largely attributed to decomposition of calcium hydroxide, which is known to occur at elevated temperatures [34]-[36]. Furthermore, at high temperatures lower strength values were observed because the bond between the aggregate and the paste is weakened, the cement paste contracts following loss of water while the aggregate expands. However, some slight increase in concrete strength associated with a further increase in temperature between $100^0$C-$200^0$C has been reported [37]; this is attributed to the general stiffening of the cement gel due to the removal of absorbed moisture [37]. When the temperature of the concrete is elevated to $400^0$C, gel-like hydration products are decomposed. Between $600^0$C-$780^0$C, $Ca(OH)_2$ is dehydroxylated and $CaCO_3$ dissociation to CaO and $CO_2$ accompanied with the re-crystallisation of non-binding phases from hydrated cement under re-combustion are dominant, at this stage, the concrete is characterized by the collapse of its structural integrity, and loss in compressive strength, colour change of the concrete to or brownish/ yellowish grey/ pinkish red was observed [37]-[39].

Generally, the reaction of concrete materials to heating is complex; degradation in physical properties of concrete varies strongly depending on the concrete matrix [5], [6], [3], [14], [15]. Heat damaged concrete; unlike the other forms of deteriorations and damages on concrete is mostly either intentional (arson) or unintentional (accidental) which triggers flame and heat [6], [3], [14]. The heating associated with fire may cause evaporation of trapped concrete pore water, but due to lack of continuous voids, pressure relief creates internal stresses that are relieved by cracks and spalls extending to the surface of concrete [14], [15]. Exposing a concrete specimen to a higher level of temperature, 800$^{o}$C, generally causes more physic – chemical transformation to take place. These physical and chemical changes in concrete will have the effect of reducing compressive strength of material. In practice, the critical temperature for significant strength reduction depends strongly on aggregate type.

## V. Conclusions

The investigation carried out in the current study has demonstrated the heating and cooling scenario of blended concrete made with Ground Granulated Blast furnace Slag (GGBS), Pulverised Fuel Ash (PFA), Rice Husk Ash (RHA) and Waste Glass Powder (WGP) and expose to a temperature of up to 780$^{0}$C. The key conclusions that can be drawn from this investigation are summarised in the following list.

1. There was variation in the slump values of the concretes, depending on the type of material used in the replacement of PC. The consistency varied from very low with a slump value below 15 mm for the concrete where 20% of the PC in the concrete control mix was replaced with 20% RHA, to marginally higher with a slump value of 80mm for the concrete where 20% of the PC in the concrete control mix was replaced with 20% GGBS.
2. The results of the compressive strength test showed that the highest strength value was obtained for the control mix while the lowest strength was obtained from the concrete where 20% of the PC in the control concrete was replaced with 20% RHA. It was also observed that increasing the temperature up to 780$^{0}$C resulted to reduction in the concrete strength. The effect of heating and cooling scenario is more significant at 780$^{0}$. The results of the tensile splitting strength showed that the control mix has the highest tensile strength value while the presence of RHA resulted to a drastic reduction in the tensile splitting strength value

## References

[1] Kodur V., 2014. Properties of Concrete at Elevated Temperatures," ISRN Civil Engineering, vol. 2014, Article ID 468510, 15 pages, doi:10.1155/2014/468510.
[2] Luo X, Sun W and Chan S.Y.N., 2000. Effect of heating and cooling regimes on residual strength and microstructure of normal strength and high-performance concrete. Cem. Concr. Res, 30, pp. 379–383
[3] Chan Y.N, Peng G.F and Chan K.W., 1996. Comparison between high strength concrete and normal strength concrete subjected to high temperature. Mater Struct, 29, pp. 616–619
[4] Gani M.S.J., 1997. Cement and Concrete. Chapman and Hall. ISBN 9780412790508
[5] Masaki K and Maki I., 2002. Effect of prolonged heating at elevated temperatures on the phase composition and textures of portland cement clinker. Cement Concrete Res., 32 (2002), pp. 931–934
[6] Saad M, Abo-El-Enein S.A Hanna G.B and Kotkata M.F., 1996. Effect of temperature on physical and mechanical properties of concrete containing silica fume. Cement Concrete Res., 26 (1996), pp. 669–675
[7] Vydra V, Vodak V, Kapickova O and Hoskova S., 2001. Effect of temperature on porosity of concrete for nuclear-safety structures. Cement Concrete Res., 301 (2001), pp. 1023–1026
[8] Kim J.K, Han S.H and Park S.K., 2002. Effect of temperature and aging on the mechanical properties of concrete. Part II. Prediction model. Cement Concrete Res., 32 , pp. 1095–1100
[9] Kakali G., Leventi R., Benekis V and Tsivilis S., 2006. Behavior of blended cement paste at elevated temperature. Scientific Paper, Greece.
[10] Savva A., Manita P and Sideris K. K., 2005. Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates. Cem Concr Compos, 27 (2005), pp. 239–248
[11] Arioz O., 2007. Effects of elevated temperatures on properties of concrete. Fire Safety Journal Volume 42, Issue 8, Pages 516–522
[12] Georgali B and Tsakiridis P.E., 2005. Microstructure of Fire-damaged Concrete. A Case Study. Cement & Concrete Composites, Vol.27, pp.255-259.
[13] Papayianni J and Valiasis T., 1991. Residual mechanical properties of heated concrete incorporating different pozzolanic materials. Mater. Struct, 24, pp. 115–121
[14] Felicetti R, Gambarova P., 1998, Effects of high temperature on the residual compressive strength of high-strength siliceous concretes. ACI Mater Journal 95(4), p.395–406.
[15] Chan YN, Luo X, Sun W., 2000. Compressive strength and pore structure of high performance concrete after exposure to high temperature up to 8000C. Cem Concr Res 30(2), p.247–51.
[16] BS EN 197-1:2011. Cement Part 1: Composition, specifications and conformity criteria for common cements.
[17] BS EN 15167–1, 2006. Ground granulated blast furnace slag for use in concrete, mortar and grout - Part 1: Definitions, specifications and conformity criteria
[18] PD 6682-1:2009. Aggregates – Part 1: Aggregates for concrete – Guidance on the use of BS EN 12620
[19] BS EN 12620:2002 +A1:2008. Aggregates for concrete
[20] BS EN 933-1:1997. Tests for geometrical properties of aggregates Part 1: Determination of particle size distribution — Sieving method
[21] BS EN1097-6:2000. Tests for mechanical and physical properties of aggregates — Part 6: Determination of particle density and water absorption
[22] BS EN 933-4:2008. Tests for geometrical properties of aggregates Part 4: Determination of particle shape — Shape index
[23] BS 812-112: 1990. Testing aggregates — Part 112: Methods for determination of aggregate impact value (AIV)
[24] Oti J.E., Kinuthia J.M, Bai J, Delpak R and Snelson D.G., 2010. Engineering properties of concrete made with slate waste. Construction materials 163 (3), p.131-142.
[25] BS EN 206-1:2000. Concrete - Part 1: Specification, performance, production and conformity
[26] BS EN 12350-1:2009. Testing fresh concrete Part 1: Sampling.
[27] BS EN 12390-1:2009.Testing hardened Concrete. Part 1: Shape, dimensions and other requirements of specimens and moulds
[28] BS EN 12350-2:2009. Testing fresh concrete Part 2: Slump-test.
[29] BS EN 12350-4:2009. Testing fresh concrete Part 4: Degree of compactability
[30] BS EN 12390-2:2009. Testing hardened Concrete. Part 2: Making and curing specimens for strength tests.
[31] BS EN 12390-3:2009. Testing hardened Concrete. Part 3: Compressive strength of test specimens.
[32] BS EN 12390-4:2009. Testing hardened Concrete. Part 4: Compressive strength - Specification for testing machines.
[33] BS EN 12390-6:2009. Testing hardened Concrete. Part 6: Tensile splitting strength of test specimens.
[34] Zhang B, Bicanic N., 2002. Residual fracture toughness of normal and high strength gravel concrete after heating to 6000C. ACI Mater Journal 99(3), p.217–26.
[35] Lin W, Lin TD, Couche L.J., 1996. Microstructures of fire-damaged concrete. ACI Mater Journal 93(3), p.199–205.
[36] Bentz DP., 2000. Fibers, percolation, and spalling of high-performance concrete. ACI Mater Journal 97(3), p.351–9.
[37] Cheng F P, Kodur V K R and Wang T C., 2004. Stress-Strain Curves for High Strength Concrete at Elevated Temperatures. Journal of Materials in Civil Engineering 16(1) 84-90.
[38] Lau A and Anson M., 2006. Effect of high temperatures on high performance steel fibre reinforced concrete. Cement and Concrete Research 36(9) 1698-1707

[39] Sideris K K Manita P and Chaniotakis E., 2009. Performance of Thermally damaged Fibre Reinforced Concretes. Construction and Building Materials 23(3) 1232–1239.