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Compressive Behaviour of Sisal Fibre Reinforced Ternary Concrete at Elevated Temperatures

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ABSTRACT

The utilization of pozzolanic materials such as fly ash (Fa) and calcined waste crushed clay bricks (CWCCB) as binders in ternary mixtures and the application of sisal fibre as reinforcing agent in ordinary Portland cement (OPC) concrete has received attention in recent years. Little is known about the mechanical behaviour of these new composites when exposed to elevated temperatures. In this study, the compressive performance of four categories of 150mm concrete cube specimens were considered comprising; (1) Control mix consisting of plain OPC concrete of 1:2:4 mix ratio (one part OPC, two parts fine aggregate and four parts coarse aggregate). (2) Concrete specimens as in (1), but reinforced with 3% volume fraction of 40mm length sisal fibre. (3) Ternary mixtures of OPC, Fa and CWCCB at ratios of 50%, 30% and 20% of total binders respectively, with same fine, coarse aggregate and sisal fibre content. (4) Ternary mixtures of OPC, Fa and CWCCB at ratios of 50%, 20% and 30% of total binders respectively, also with same fine, coarse aggregate and sisal fibre content. Water/binder ratio for all mixtures was fixed at 0.6. The 150mm concrete cube specimens were cured, dried and subjected to varying elevated temperatures of 100, 150, 200, 300, 400 and 600ºC for exposure duration of 2 hours each. The results revealed that between temperatures of 100ºC and 600ºC, the ternary concrete specimen with 30%Fa and 20%CWCCB showed good thermal stability but recorded a 24% reduction in compressive strength at elevated temperatures of 600ºC compared with all the specimens. The ternary concrete with 30%Fa and 20%CWCCB is recommended for structural elements requiring thermal stability.

Key words: Compressive Strength, Elevated Temperatures, Ternary Concrete, Sisal Fibre, Fly Ash, Calcined Waste Crushed Clay Bricks.

1. INTRODUCTION

Concrete as a conventional construction material has been continuously modified and developed to perform better in all situations, especially on exposition to elevated temperature fires. Modifications to the matrix composition such as lower water content, use of super plasticizers, optimization of grain size distribution, use of particles possessing pozzolanic activity, inclusion of vegetal fibres, etc have resulted in striking improvements in many properties such as strength, rheology of fresh concrete, ductility and compactness. However concrete is a fundamentally complex material whose mechanical behaviour including the compressive strengths, Poisson's ratio and modulus of elasticity etc can dramatically alter upon exposure "to elevated temperatures". "To elevated temperatures" according to Neville (1981) [1] is to increase markedly the degree of temperature which occurs when there is a fire disaster. Elevated temperatures as considered by Neville (1981) are temperatures above 250ºC. The consequences of thermal and mechanical stresses on concrete are spalling and loss of compressive strength. Spalling is the explosive or non-explosive breaking off of layers or parts of concrete from the surface of a structural element as a result of exposure to elevated and rapidly rising temperatures as experienced in fires [2].

Experimental studies have reported that plain normal concrete behave differently compared with high strength concrete under elevated temperatures. The high strength concrete inconsistently displayed a sudden catastrophic failure mechanism usually termed explosive spalling when exposed to elevated temperatures [3, 4]. Regardless of the true failure mechanism, explosive spalling was believed to be the result of significant pore pressure build-up within the hardened cement matrix. In an effort to study the influence of the compressive strength stress-strain relationship (stiffness) and energy absorption capacities (toughness) of elevated temperatures on high-performance modified concrete, Poon, Shui and Lam (2004) [5] prepared three series of samples with different pozzolanic modification to the plain ordinary Portland cement. The pozzolanas used for the modifications included, metakaolin (MK) and silica fume (SF) as binary and ternary matrices. Each series of samples comprised concrete mix incorporating either, steel or polypropylene fibres or both. The results showed that after subjecting the samples to temperatures of 600ºC and 800ºC, they retained 45% and 23% of their compressive strength respectively. The results also showed that the loss in stiffness of the concrete specimens were faster than that of the compressive strength but the loss of energy absorption capacity was slower after exposure to elevated temperatures.

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The study observed that binary replacement of cement with 20% metakaolin resulted in higher compressive strength and lower specific toughness in comparison with samples containing 10% of silica fume. Samples containing metalaolin exhibited quicker loss of compressive strength, elastic modulus and energy absorption capacity after exposure to elevated temperatures. The energy absorption capacity of concrete specimens reinforced with steel fibres and exposed to elevated temperatures doubled that of unheated concrete specimens. When concrete samples were reinforced with polypropylene fibres and exposed to elevated temperatures of 800ºC the energy absorption capacity was reduced in comparison with the unheated control sample.

Suhaendia and Horiguchia, (2006)a [6] investigated the residual properties of polypropylene and steel fibre reinforced high-strength concrete under elevated temperatures. The research focused on some variables which included fibre volume fraction, fibre length and fibre material. The residual properties under observation were the compressive strength, splitting tensile strength, modulus of elasticity and water permeability coefficient. Results from the tests showed that residual properties of polypropylene fibre-reinforced high-strength concrete was significantly reduced compared with steel fibre reinforced high-strength concrete, especially in terms of permeability performance, even though polypropylene fibre was found to be more effective in mitigating explosive spalling.

Lau and Anson (2006) [7] studied the effect of high temperatures on compressive strength, flexural strength, elastic modulus and porosity of high performance steel fibre reinforced concrete. The concrete specimens were reinforced with 1% steel fibres and exposed to different elevated temperatures ranging from 105ºC and 1200ºC. The results show a loss of concrete strength with increased maximum heating temperature. For maximum exposure temperatures below 400ºC, the loss in compressive strength was relatively small. As the maximum temperatures exceed 400ºC, significant reductions in compressive strength was observed for both high performance and normal concrete. The study reports that high performance concrete start to suffer a greater compressive strength loss than normal concrete at maximum exposure temperature of 600ºC. It is suggested that pore-restructuring and chemical decomposition of the hardened calcium silicate hydrates were responsible for the strength reduction of high performance concrete at this high temperatures. The study concluded that the mechanical strength of steel fibre reinforced concrete performs better than unreinforced concrete at maximum exposure temperature below 1000ºC.

The mechanical and permeability performance of fibre reinforced high strength concrete after exposure to elevated temperatures was studied by Suhaendia and Horiguchia, (2006)b [8]. Santos et al. (2009) [9] studied high strength concrete reinforced with polypropylene, steel and glass fibres and subjected to elevated temperatures of 300ºC, 500ºC and 600ºC. In the research study, the results indicated that polypropylene fibres prevent concrete spalling.

A number of researches have been conducted on high performance/strength and normal concrete reinforced with a variety of polymeric fibres and subjected to elevated temperatures. However limited studies have been undertaken on the mechanical behaviour of ternary concrete reinforced with vegetal fibres such as sisal fibre at elevated temperatures. The thermal degradation of sisal fibre reinforced concrete and its mechanical properties at elevated temperatures are a crucial aspect in the development of sisal fibre reinforced concrete composites. In this study, the compressive behaviour of concrete modified with fly ash and calcined waste crushed clay bricks reinforced with sisal fibre and exposed to varying elevated temperatures are investigated.

2. MATERIALS AND METHODS

2.1 Materials

The method of extraction and preparation of the locally sourced sisal fibre have been discussed elsewhere (Nwankwo, 2013) [10]. The ternary concrete consisted of (a) the "BUA" brand grade 43 ordinary Portland cement, (b) Class F fly ash, sourced from the Oji River thermal power plant in Oji River local government Area of Enugu State in Nigeria, (c) Calcined waste crushed clay bricks, sourced from a brick factory in Minna, Niger State in Nigeria and ground with the aid of porcelain ball mill for 90 minutes, (d) River sand sourced from River Gumo in Bauchi State in Nigeria was used as fine aggregate (FA), (e) 19mm machine crushed granite sourced from Jos in Jos North, Plateau State in Nigeria was used as coarse aggregate (CA). The properties of the constitutive materials used in the preparation of the concrete samples in this study have been discussed in [10].

2.2 Preparation of Specimens

The concrete specimens are in four categories. The first category are the control mix specimens of plain concrete with a design compressive strength of 20N/mm^2 at 28 days in accordance with "Design of Normal Concrete Mixes" [11] and consisted of one part OPC (100% of binder), two parts FA and four parts CA. This mix proportion is referred to as 1:2:4 mix ratio. The second category of specimens is plain concrete of 1:2:4 mix ratio but reinforced with 3% volume fraction of 40mm average length sisal fibres. The third category is ternary concrete specimens with the same quantities of FA and CA (2:4), reinforced with 3% volume fraction of 40mm average length sisal fibre but with OPC content fixed at 50% of the binders with 20%Fa and 30%CWCCB (20Fa + 30CWCCB). The fourth category of ternary concrete specimens is the same as the third, except that the percentages of the pozzolanas were reversed i.e. (30Fa + 20CWCCB). The water/binder ratio was kept constant at 0.6. The blending ratios and batching of materials for the preparation of the concrete specimens per cubic meter have been discussed in [10] and are presented in Table 1.

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The materials for all specimens were hand mixed, cast and compacted with a steel tamping rod into 150mm cube steel moulds in accordance with the recommendations of B.S 1881: Part 116 (1983) [12]. The specimen concrete cubes were de-moulded after 24 hours and cured by immersion in a water tank kept at 20 ± 1ºC for a duration of 90 days. At the end of 90 days curing, the concrete cube samples were brought out of water and allowed to dry before subjecting them to various elevated temperature ranges. Three concrete cubes from each category were subjected a range of elevated temperatures of 100, 150, 200, 300, 400 and 600ºC in an oven. The three concrete specimens were exposed for duration of 2 hours for each elevated temperature range. The oven is heated by an electric coil with capacity to attain 1200ºC. The required temperature are set and maintained on the oven's panel without fluctuations. The test temperature range is maintained constantly for 2 hours as the heat reaches the testing temperature. After exposure to required temperature range, the oven was switched off and the concrete specimens allowed cooling to ambient temperatures before crushing in the compressive strength testing machine. The compressive strength test of all concrete specimens were performed in an electrically operated universal testing machine housed in the Materials and Concrete Testing Laboratory of the Department of Building of the University of Jos in Nigeria, and shown in Plate 1. The compressive strength is taken as the maximum compressive load the concrete cube specimen can carry per unit area and calculated as follows:

$$f_{cu} = P_{max}/_{A}$$

Where: f_{cu} = compressive strength (N/mm²)
P_{max} = magnitude of the load at failure (N)
A = cross-sectional area of the concrete cube specimen (mm²)

Table 3 Concrete Mix Proportions

Percentage Replacement	OPC (kg.)	Fa (kg.)	CWCCB (kg.)	FA (kg.)	CA (kg.)	SF (kg.)	W (kg.)	w/b
0 (Control)	321	-	-	696	1331	-	250	0.6
0(Control with 3% SF)	312	-	-	696	1331	27	250	0.6
20Fa + 30CWCCB	156	62.2	93.3	696	1331	27	250	0.6
30Fa + 20CWCCB	156	93.3	62.2	696	1331	27	250	0.6

FA: Fine Aggregate

CA: Coarse Aggregate

SF: Sisal Fibre

W: Water

w/b: Water/Binder Ratio

Plate 1. Determination of Compressive Strength of Concrete with Testing Machine.

3. RESULTS AND DISCUSSION

Figure 1 shows the compressive strength of plain concrete specimens, concrete specimens incorporating 3% volume fraction of sisal fibres and concrete specimens with ternary blends of Fa and CWCCB subjected to varying elevated temperatures. Figure 2 shows variation of densities of the concrete specimens with varying elevated temperatures. The results show that the thermal degradation of the specimen containing 3% volume fraction of sisal fibre is a two-stage process. From Figure 1, it can be seen that the first stage started in the temperature range 20°C-300°C. The low temperature degradation process is associated with degradation of hemicelluloses whereas the high temperature process is due to lignin, when the degree of polymerization of cellulose is damaged and the lignin portion starts to soften loosing its binding property. This phenomenon is in agreement with other researchers [13, 14].

However, when the sisal fibre reinforced concrete composite contained a ternary blend of 20% fly ash and 30% calcined waste crushed clay bricks, the two-stage thermal degradation achieved slight stability without a reduction in compressive strength at high temperatures of 600°C. It could be observed from Figure 35 that the plot for this ternary blend became less erratic. From Figure 1, it could be observed that at a ternary blend of 30% fly ash and 20% calcined waste crushed clay bricks, the composite achieved thermal stability, but with a 24% reduction in compressive strength at 600°C, compared with the specimens with 20/30 Fa/CWCCB blend. This suggests that the higher content of fly ash was responsible for the thermal stability of the composite. It is suggested that the physical properties (fineness and the spherical structure), rather than the chemical properties of fly ash may have been responsible for the less coarsening of the pore structure of the matrix, consequently resulting in the observed thermal stability of the composite. The 24% reduction in compressive strength of the 30/20 Fa/CWCCB blend at elevated temperature of 600ºC may be attributed to the chemical decomposition of the already depleted calcium silicate hydrates (CSH) in the blend. Figure 2 showed that at temperatures of 200°C-400°C, the specimens with the ternary blend of fly ash and calcined waste crushed clay bricks recorded lower densities and recovered at 600°C.

It is therefore safe to conclude that thermal stability of sisal fibre reinforced concrete composite could be achieved with the ternary blend of 30% fly ash and 20% calcined waste crushed clay bricks.

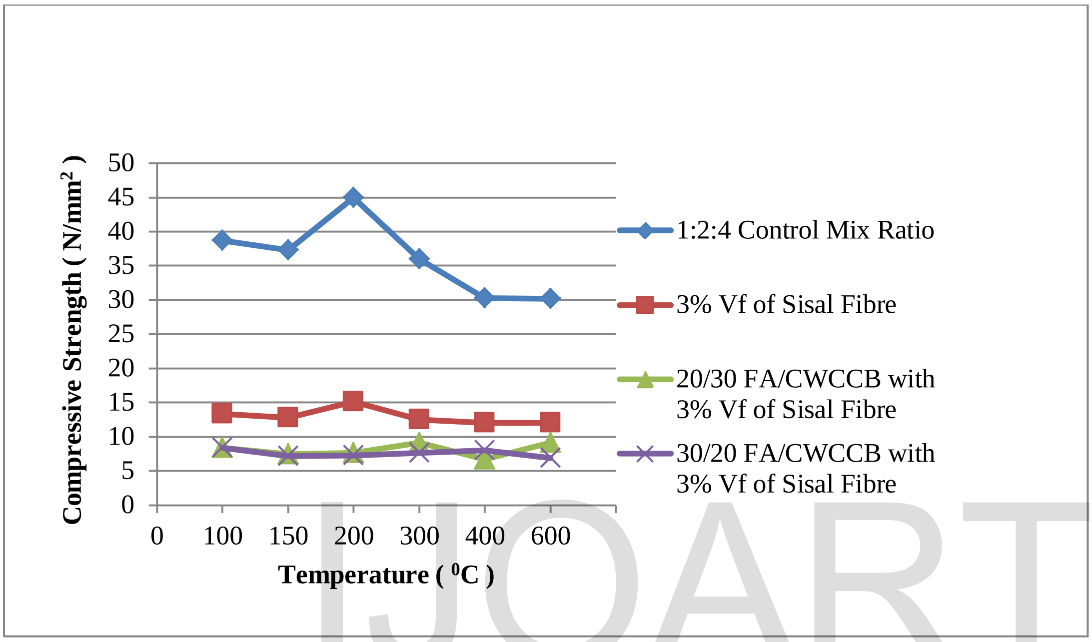

Figure 1. Compressive Strength for Control Mix, 20/30, and 30/20 Ternary Blend of FA/CWCCB at Varying Temperatures.

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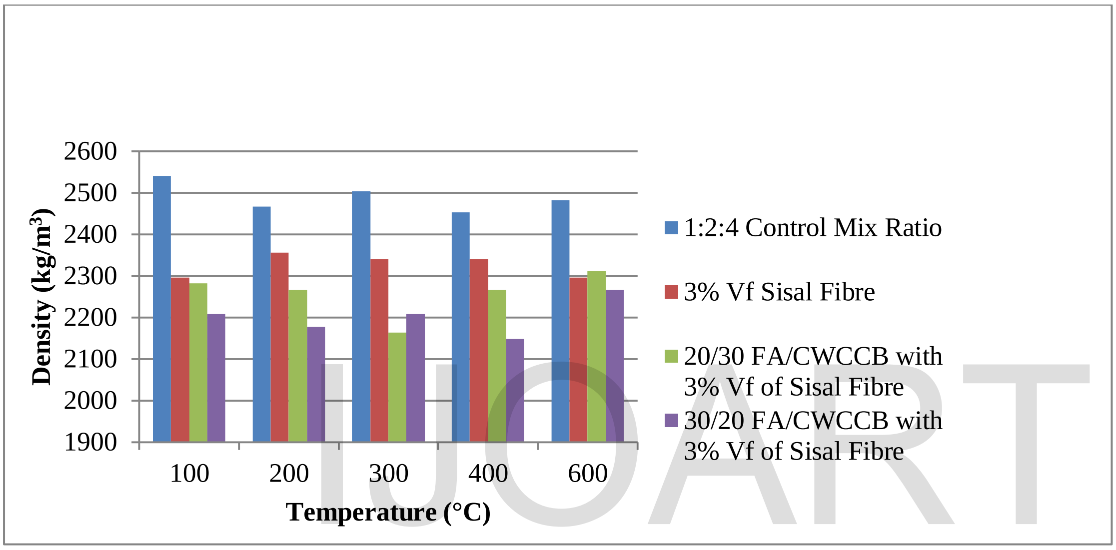

Figure 2. Variation in Density of Composite with Temperature.

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