Journal of Multidisciplinary Engineering Science Studies (JMESS)
ISSN: 2458-925X
Vol. 7 Issue 12, December - 2021

Experimental Verification Of Numerical Models On The Structural Behaviour Of Concretes At Elevated Temperatures

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***Abstract*—This paper presents an experimental investigation to verify the accuracy and validate most commonly cites prediction models for compressive and tensile strength of concrete after exposure to elevated temperature. To achieve this objective, the concrete specimens were cast, cured in water for 28 days and heated in an electric oven to the varying temperatures 100°C, 200°C, 300°C and 400°C at a fixed duration of 45 minutes which accounted for the average waiting time for fire service to arrive at the scenes of fire hazards. The concretes were then tested for the residual compressive and split tensile strengths. The experimental results were then utilized to verify the accuracy of and subsequently validate the prediction models for post-fire compression and tension properties of concrete. The experimental data yielded a change in compressive strength with temperature of -0.0193 where models of Chang et al [22], Li & Purkiss [23] and Jau & Chang [24] yielded -0.046 MPa/ °C, -0.040 MPa/ °C and -0.054 MPa/ °C respectively. A change in split tensile strength with temperature was found to be -0.0031 MPa/ °C by experimental data whereas constitutive models of Chang et al [22] and EN 1992 [25] yielded -0.0034 MPa/ °C and -0.0047 MPa/ °C respectively. Based on the comparisons between the experimental results and the numerical models, it was observed that the investigated models are in good agreement to predict tensile strengths for the studied elevated temperature values. A slight gap was observed between the experimental results on compressive strength and prediction models. This could be attributed to the pattern of heating and cooling effects, the duration of exposure and the size of the specimen which the models did not consider. More reliable models that consider the size effects and geometric parameters of the concrete should be considered for more precise prediction.**

***Keywords*—Compressive strength, tensile strength, elevated temperature, prediction model, residual strength**

I. INTRODUCTION

Concrete is a commonly used building material that consists of mixed cement, fine and coarse aggregates and water to properly set and bind the mix [1]. It is more robust as it can withstand wear and tear and also has a two to three times longer lifetime than any other construction system.

Concrete, however, has a very low tensile strength, which makes stress unstable and appears to be brittle. Tension stresses and shrinkage during the curing stage contribute to the creation of cracks that allow moisture to enter and concrete loss of strength, resulting in cracks when subjected to tensile stresses. Therefore, in the stress zones, reinforcements are provided to hold tensile forces and to restrict crack widths [2].

The most common component of structural engineering is reinforced concrete structures because it has proven to be a very good construction material with desirable characteristics such as toughness, strength, rigidity, fire-resistant properties, low cost, excellent environmental insulation and the ability to form into any given shape. Reinforced concrete structures are now widely used not only in different civil and public buildings, single and multi-story industrial buildings, high-rise and large-span buildings, but also in bridges, communication facilities, and hydraulic and underground engineering [3].

Temperature is typically responsible for three forms of transition. The first one is cracking in the surface zone and microcracking. Cracks usually form along the aggregate surface, possibly representing the variations between cement paste and aggregate in the linear expansion coefficient. In particular, larger cracks will occur where the rise in temperature has affected reinforcement [4]. The phases in aggregate and paste are modified and oxidation and dehydration are related to the key changes occurring in aggregate and paste. Moisture loss can be rapid and probably affect the development of cracks. In general, the paste changes color and different color zones can grow. At about 300 °C and from pink to whitish grey at about 600 °C, a change from buff or cream to pink appears to occur. Finally, the dehydration of the hydrated cement steps in where cementitious paste becomes friable, very brittle and quickly broken down at a temperature greater than 600 °C with significant shrinkage cracking, honeycombing and usually concrete [5].

Depending on the severity of the fire and the high temperature levels reached, concrete will sustain varying degrees of damage. The effects of high temperature fire on concrete structures inside the concrete microstructure are such as the loss of compressive strength and micro cracking [6]. In addition, there is decreases in strength, decreases in elasticity modulus, varying degrees of spalling, loss of bond between concrete and steel, and potential loss of residual strength of steel reinforcement and pre-stressing tendon tension are also high-temperature fire effects.

Concrete structures may be subjected to extreme conditions such as earthquakes, floods, volcanic eruptions, and fire breakouts, thereby altering the structure's life and serviceability. In a situation where the concrete structure is exposed to high temperatures due to fire exposure, the relative properties of the concrete following such exposure are of considerable significance in terms of the building's serviceability. Due to the higher temperature, during these exposures, many changes in the mechanical properties of concrete, such as compressive strength, elasticity modulus, tensile strength, volume stability and concrete resilience, are drastically reduced [7].

The failure of fire structural concrete varies depending on the nature of the fire; the mechanism of loading and the form of construction. Loss of bending or tensile strength, loss of bond strength, loss of shear or torsional strength, loss of compressive strength, and concrete spalling may lead to failure [8].

Assessment of fire-exposed concrete helps to understand the severity of the damage and its effect on the design life and serviceability of the structure and post fire sustainability. If the degree of concrete damage is known, it is possible to make a proper decision as to whether the structural feature requires replacement or repair. It also helps to take precautionary steps for the known cause of the damage to avoid the damage in future [9].

The major properties which govern the behaviour of concrete at high temperatures are compressive strength, elastic modulus, tensile strength, creep strain, peak strain, thermal expansion, thermal conductivity and specific heat capacity. To carry out performance – based fire design these properties of concrete at elevated temperatures needs to be determined. There are a lot of models to determine compressive strength, tensile strength and elastic modulus for concrete at ambient temperature. Only a few models for compressive strength, tensile strength, elastic modulus and peak strain of concrete at elevated temperatures have been proposed.

Li et al [10] investigated the effect of temperature exposure on compressive strength, splitting tensile strength and flexural strength of normal and high-strength concrete (HSC). Oil furnace was used in this study for heating the specimens. The time curve for temperature was similar to the standard curve that complied with the Chinese GB/T 9978 to 1999 standard. The mechanical properties of HSC were discovered after being heated to temperatures of 200 °C, 400 °C, 600 °C, 800 °C and 1,000 °C respectively. It addressed the effect of temperature, water content, specimen size, strength and temperature profiles on the mechanical properties of HSC. They concluded that the loss of strength was found to be lower in larger specimens.

The strengths of cube specimens subjected to elevated temperatures ranging from 100 °C to 800 °C were calculated by Yaragal et al. [11] in steps of 100 °C with a retention time of 2h. Weight loss and the residual compressive strength retention characteristics were analyzed after exposure. The results of the test showed that weight and strength decreased significantly with an increase in temperature. The weight loss of the specimen increased above 200 °C as the exposed temperature increased. With an increase in the grade of concrete, there was a decrease in specimen weight loss after elevated temperatures were observed. Overall, there was a significant loss (74 percent) in the strength of concrete grades M20, M25 and M30 when exposed to higher temperatures. However, for grades M35, M40 and M45, the loss of strength was around 80 percent. The minimum residual strength observed was found at 800 °C to be 18 percent for M45. For NSC, equations to estimate the residual compressive strength for two temperature ranges were derived.

Janotka & Nurnbergerova [12] investigated the performance of concrete at elevated temperature in nuclear power plants. The study revealed loss of concrete strength for temperatures ranging from 100 to 200 ^{o}C because of the loss of chemically bound water leading to the formation of air voids. Furthermore, the overheating of concrete may lead to the malfunctioning of the cooling system of the nuclear power plants that might be hazardous. The mechanical properties of concrete are directly affected when concrete is exposed to high temperature [13]. This is primarily due to the cracking concrete at the interface of aggregate and cement paste due to the difference in thermal behaviour of the two materials [14].

A review of literature shows that the variance of compressive and flexural strengths of ordinary and high-performance micro concrete at elevated temperatures was investigated by Husem [15]. Ordinary and high-performance micro-concrete compressive and flexural strengths that were subjected to high temperatures (200 °C, 400 °C, 600 °C, 800 °C and 1,000 °C) and cooled under various cooling conditions (in air and water) were collected. The compressive and flexural strengths of these 27 concrete samples were compared and then compared with the non-heated samples. The curves of strength loss of these concrete samples were compared with the curves of strength loss given in the codes. It was stated that with increases in temperature, the strength of concrete decreased and that the strength of ordinary concrete decreased more than that of high-performance concrete. The residual compressive and flexural strength were found to be influenced by the form of cooling, the effect becoming more pronounced as the temperature increased.

The objective of this paper is to verify the accuracy of common numerical models for compressive and split tensile strength of concrete at elevated temperatures and validate with laboratory experimental data.

II. EXPERIMENTAL PROGRAMME

The experimental methodology consists of mix proportioning, casting of specimens, exposing the specimens to elevated temperature and testing. The methodology has been summarized in the following section.

A. *Materials*

In this investigation, ordinary Portland cement of grade 52.5 with specific gravity of 3.15 conforming to ACI Standard was employed in the study. The sieve analysis for coarse aggregate and fine aggregate was carried out. Coarse aggregate was crushed granite of maximum nominal size of 19 mm with water absorption of 0.26%. Fine aggregate was well-graded crusher sand of maximum nominal size of 4.75 mm and water absorption of 1.55% and fineness modulus of 3.13. The particle size distribution curves of the aggregates are plotted in Fig. 1. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 1.

TABLE 1: PHYSICAL PROPERTIES OF CEMENT

Standard Consistency (%)	30
Specific gravity	3.15
Initial setting time (min)	290
Final setting time (min)	450
Soundness (mm)	1.0
Compressive strength (N/mm^2)	
3 days	24.5
7 days	30.8

The aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 812 [16]. The properties of fine and coarse aggregates are presented in Table 2. It is obvious that the fine and coarse aggregates employed as constituents of the concrete in the study are well-graded. Potable water of pH of 7.1 which conformed to the requirements of BS 3148 [17] was used in mixing the aggregates and cement. The mix was designed for a target compressive strength of 41.9 MPa according to ACI Standard. The concrete mix produced fresh concrete properties of workability (slump value) of 70 mm. The final mix proportions of concrete constituents are summarized in Table 3.

Crushed granite as coarse aggregate

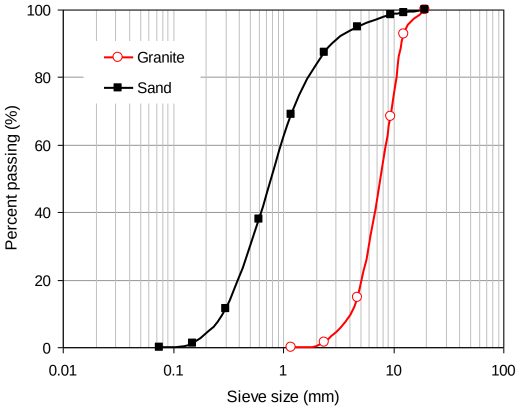

Fig. 1: Samples of particle size distribution of fine and coarse aggregates

TABLE 2: PROPERTIES OF AGGREGATES

Properties	Crusher sand	Crushed granite
Specific Gravity	2.34	2.64
Bulk Density (kg/m^3)	1240	1464
Moisture content (%)	4.24	1.61
Fineness modulus	3.13	2.59
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

TABLE 3: MIX PROPORTION OF CONSTITUENTS FOR A CUBIC METRE OF CONCRETE

Property	Content (kg/m^3)
Cement content	418
Fine aggregate	735
Coarse aggregate	1010
Water	216

B. *Mix proportioning and casting of concrete specimens*

A fixed concrete mix proportions with a fixed water-cement ratio of 0.52 considered for the study. Cement, fine and coarse aggregates were 418 kg/m^3, 735 kg/m^3 and 1010 kg/m^3 respectively which produced a buld density of 2379 kg/m^3. This represented a concrete mix ratio of 1:1.76:2.42 in proportion of cement, fine and coarse aggregates. No plasticizer was added into the mix in this study. Each concrete mix proportion was prepared in a rotating drum mixer. The aggregates and cement were placed in the drum and mixed in parts with water to ensure a better bond between the cement paste and the aggregates. All mixing and sampling of concrete were carried out in accordance with the procedures given in BS 1881[18].

The workability of fresh concrete was determined via slump test in accordance with ASTM C143 [19]. The apparatus used included tamping rod, cone and a measuring rule. The slump test setup is shown in Fig. 2.

Fig. 3: Slump test set-up

Test specimen were prepared and cast into moulds of different sizes. Fifteen (15) cubes of size 100 mm were cast, cured and tested for compressive strengths according to BS 1881 [18] at curing age 28 days. Compression testing machine, employed for crushing of cubes and splitting of cylinders as per the requirements of EN 12390-4[20] as shown in Fig. 4. Compression load was applied without shock and continuously increased at a uniform rate of between 0.3 ± 0.1 MPa/s until the specimen failed. The maximum crushing or spliting load, the appearance of the specimen and any unusual feature in the type of failure was recorded for analysis. The compressive strength was determined by calculating the ratio of the crushing load to the cross-sectional area of the cube specimens.

Fifteen (15) cylinders of 150 mm diameter and 300 mm length were cast, cured and tested at 28 days for the split tensile strength of concrete. The split tensile strength was carried out as per BS EN 12390:6[21]. After curing, water was wiped out from the surface of specimen and diametrical lines were drawn on the two ends of the specimen using a marker to verify that they are on the same axial place. Plywood strips were placed on the lower plate followed by the concrete cylinder specimens and the upper plate was brought down to touch the plywood strip. The load was applied continuously without shock at an approximate rate of 14-21 kg/cm^2/min and the breaking load was recorded for each test specimens.

Fig. 4: Test setup of concrete cubes for compressive strengths.

C. *Post-thermal exposure testing of concrete specimens*

All the specimens were cured for 28 days, and air dried in the laboratory for 24 hrs. Finally, the specimens were subjected to a temperature range from 100 ^{o}C to 400 ^{o}C in an electric oven of 415 volts with a maximum of 400 ^{o}C. The concrete specimens viz cubes, cylinders and beams were presented for testing the compressive strength, split tensile strength and flexural of concrete after exposure to elevated temperature. The specimens were then air cooled and tested. The details of the specimens with type of test, number of specimens tested, cooling method and fire duration are listed in Table 4.

TABLE 4: SPECIMEN DESCRIPTION FOR RESIDUAL STRENGTH AFTER THERMAL EXPOSURE

Specimen	Test on concrete	Number	Cooling method	Fire duration (mins)
Cubes	Compressive strength	15	Air cooling	45
Cylinders	Split tensile strength	15	Air cooling	45

D. *Compressive strength of concrete at elevated temperature*

After curing and heating in an oven for 45 minutes, the cubes were tested for compressive strength by the destructive test method. The tests were conducted in accordance with BS 1881 [18] and the electronically operated digital testing machine was used to test the cube specimens.

To derive a compressive strength temperature relationship for concrete test data from three literatures [22, 23, 24] were used. Regression analysis was performed on the experimental test data and was compared to other models and presented as follows.

The compressive strength model of concrete at elevated temperatures as developed by Chang *et al.* [22] is given in Equation 1.

$$f'_{cT} = f'_{ç}\left(1.008 + \frac{T}{450\ln\left(\frac{T}{5800}\right)}\right) \;.\;.\;.\;.\;.\;.\;.\; (1)$$

The constitutive model developed by Li & Purkiss [23] is given in Equation 2.

$$f'_{cT} = f'_{ç}\left(0.00165\left(\frac{T}{100}\right)^{3} - 0.03\left(\frac{T}{100}\right)^{2} + 0.025\left(\frac{T}{100}\right) + 1.002\right) \quad . \quad . \quad . \quad (2)$$

The third model given as Equation 3 was proposed by Jau (2001)

$$f'_{cT} = f'_{ç}\left(1 - 0.001T\right) \;. \quad . \quad (3)$$

E. Split tensile strength of concrete at elevated temperature

After curing and heating in an oven for 45 minutes, the cylinders were tested for split tensile strength. The tests were conducted and the electronically operated digital testing machine was used to test the cylinder specimens.

To propose a model for split tensile strength, data were collected from two papers [22, 25]. Regression analysis was performed on the experimental data to derive the model for split tensile strength of concrete at elevated temperature. The experimental data was compared with two major models. EN1992 [25] proposed Equation 4 for the residual tensile strength of concrete at elevated temperatures

$$f_{crT} = k_{ck,t}\, f_{cr};\, k_{ck,t} = \begin{pmatrix} 1 \\ T - \frac{100}{500} \end{pmatrix} \cdots \begin{matrix} 20°C \le T \le 100°C \\ 100°C \le T \le 600°C \end{matrix} \quad . \quad . \quad . \quad . \quad (4)$$

Chang *et al*. [22] also proposed Equation 5 given as

$$f_{crT} = f_{cr}\begin{pmatrix} 1.05 - 0.025T \\ 0.80 \\ 1.02 - 0.0011T \ge 0 \end{pmatrix} \cdots \begin{matrix} 20°C \le T \le 100°C \\ 100°C < T \le 200°C \\ 200°C < T \le 800°C \end{matrix} \quad . \quad . \quad . \quad . \quad (5)$$

III. RESULTS AND DISCUSSION

A. Compressive strength of concrete at elevated temperature

The variation of compressive strength of concrete with elevated temperature is illustrated in Fig. 6. The results of the experimental data show a wider variation from the various models, the relationship between the compressive strength and temperature is non-linear with a rate of change of -0.0193 whereas the provisions in the available literatures (Chang et al. (2006), Li and Purkiss (2005), Jau (2001)) show linearity between compressive strength with temperature with larger rates of change of -0.0458 MPa/ ^{o}C, -0.0396 MPa/ ^{o}C and -0.0535 MPa/ ^{o}C respectively. However, a wider variation is observed in the temperature range above 400 ^{o}C.

It was observed that the strength of unheated cubes was greater than the strength of heated cubes at all temperature levels. Based on the experimental data, concrete lost about 6 % of its original compressive strength when heated to 100 ^{o}C and 15 % at 400 ^{o}C. The constitutive models by Chang et al (2006), Li and Purkiss (2005) and Jau (2001) confirmed 1–10% loss of the original compressive strength when heated to 100 ^{o}C and 20 to 40 % at 400 ^{o}C. Moreover, the test results yielded an R^2 of 0.94, while the constitutive models of Chang et al (2006), Li and Purkiss (2005), and Jau (2001) yielded R^2 of 0.99, 0.92, and 1.00, respectively. The models fit well with the experimental data and show good agreement with other models.

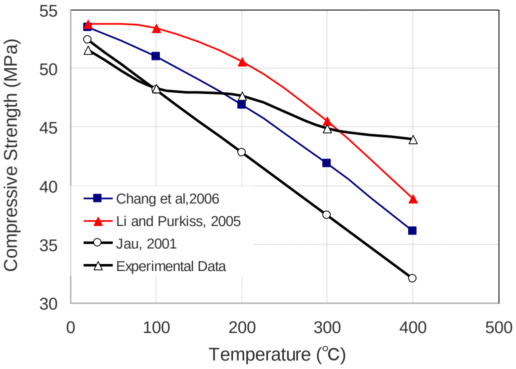

Fig. 6: Residual compressive strength after exposure to varying temperature

The strength loss experienced agrees with the findings of Long & Nicholas [26] that concrete loses about 10 – 20 % of its compressive strength at elevated temperature, although Omer [4] reported a loss of 10 % at 600 ^{o}C. The slight difference could be as a result of the nature of the aggregate used, the grade of concrete as well as the sizes of the specimen. The experimental data was obtained using the 100 mm cube specimens which had a smaller surface area compared to the 150 mm cube specimens used by Long & Nicholas [26] and Omer [4].

Luccioni [27] reported his findings as a function of variations in the intensity of the temperature, but this also depends on the duration of exposure to elevated temperatures. The reductions in compressive strength of concrete when exposed to elevated temperatures can be attributed to the dehydration of concrete by driving out of free water and fraction water of hydration of concrete due to high temperatures [11].

B. Split tensile strength of concrete at elevated temperature

The variation of split tensile strength of concrete with elevated temperature is illustrated in Fig. 7. The results of the experimental data show a wider variation from the various models, the relationship between the split tensile strength and temperature is linear with a rate of change of -0.0031 whereas the provisions in the available literatures [22, 25] show linearity between split tensile strength with temperature with rates of change of -0.0034 and -0.0047 respectively. From the rates of change of the compressive strength with temperature, it is shown that the experimental data is in good agreement with the constitutive models. From Fig. 7, the available literatures trace the same path when concrete is exposed to temperatures of 20 to 200 ^{o}C whereas after 200 ^{o}C, Chang et al [22] and experimental data had a good agreement. However, this small variation is mainly because of the variations from different tests using different heating or loading rates, specimen size and curing, testing conditions (moisture content and age of specimen), and the use of admixtures.

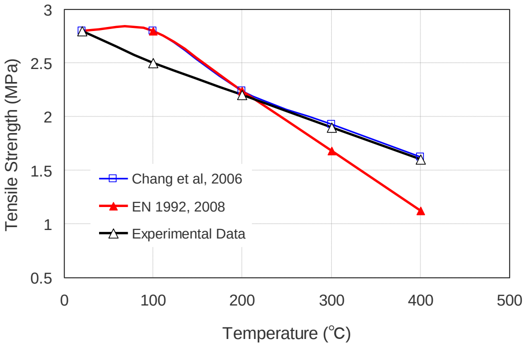

Fig. 7: Residual split tensile strength of concretes after exposure to varying temperature

At all temperature stages, the strength of unheated cylinders was found to be greater than the strength of heated cylinders. Concrete cylinders lost 0–10% of their original splitting tensile strength when heated to 100 °C, and 42–60% when heated to 400 °C, according to the experimental results. The constitutive models by Chang et al [22] and EN 1992 [25] confirmed 0–10% loss of the original split tensile strength when heated to 100 ^{o}C and 40–60% at 400 ^{o}C. Furthermore, the test results yielded an R^2 of 0.998, while the constitutive models of Chang et al [22] and EN 1992 [25] yielded R^2 of 0.962 and 0.959, respectively. The experimental results indicate that the regression fit is closer to 1 hence it is the best fit compared to the constitutive models. The rate of change of the split tensile strength with temperature is -0.0031 MPa/ ^{o}C, -0.0034 MPa/ ^{o}C, and -0.0047 MPa/ ^{o}C, respectively. It can be shown that the splitting tensile strength decreases with temperature for all of the curves [22, 25].

The loss in split tensile strength is very pronounced, which is different from the more gradual loss of compressive strength. This is because the tensile strength is more sensitive to cracks either on a macro- or micro-scale, which are caused by concrete becoming subject to high temperatures.

Li et al. [10] agrees that the decrease in tensile strength of NSC with temperature can be attributed to weak microstructure of NSC allowing initiation of microcracks. At 300 ^{o}C, concrete loses about 20% of its initial tensile strength. Above 300 ^{o}C, the tensile strength of NSC decreases at a rapid rate due to a more pronounced thermal damage in the form of microcracks and reaches to about 20% of its initial strength at 600 ^{o}C. HSC experiences a rapid loss of tensile strength at higher temperatures due to development of pore pressure in dense microstructured HSC [28].

Concrete being a poor conductor of heat, its exposure to high temperature causes thermal gradient between its outer and inner layers, which is responsible for the cracking of concrete at high temperature. The thermal gradient mainly depends on the heating rate, cooling rate, intensity of heat and concrete thermal properties. Further, during exposure to elevated temperature, pore pressure also develops in the concrete, which depends up on the intensity of heat, rate of heating and size of the specimen.

Previous studies have reported the appearance of cracks on concrete specimen surface for exposure temperatures beyond 600^{o}C. It is probable that cracking is initially due to the normal thermal expansion of cement paste causing local breakdown of bond between the cement and the aggregate. As the exposure temperature rises, drying shrinkage eventually becomes much greater than thermal expansion as water is driven off. These two opposing actions progressively weaken and crack the concrete [8, 11, 14]

IV. CONCLUSION

The study was primarily intended to verify the accuracy and validate most commonly cites prediction models for compressive and tensile strength of concrete after exposure to elevated temperature. To achieve this objective, the concrete specimens were cast, cured in water for 28 days and heated in an electric oven to the varying temperatures 100^{o}C, 200^{o}C, 300^{o}C and 400^{o}C at a fixed duration of 45 minutes which accounted for the average waiting time for fire service to arrive at the scenes of fire hazards. The concretes were then tested for the residual compressive and split tensile strengths. The experimental results were then utilized to verify the accuracy of and subsequently validate the prediction models for post-fire compression and tension properties of concrete. The following conclusions can be drawn from the experimental verification of veracity of selected models.

1. In accordance with the aim of study, the experimental data yielded a change in

compressive strength with temperature of -0.0193 where constitutive models of Chang et al [22], Li & Purkiss [23] and Jau [24] yielded -0.046 MPa/ °C, -0.040 MPa/ °C and -0.054 MPa/ °C respectively.

2. A change in split tensile strength with temperature was found to be -0.0031 MPa/ °C by experimental data whereas constitutive models of Chang et al. [22] and EN 1992 [25] yielded -0.0034 MPa/ °C and -0.0047 MPa/ °C respectively.
3. Based on the comparisons between the experimental results and the numerical models, it was observed that the investigated models are in good agreement to predict tensile strengths for the studied elevated temperature values.
4. A slight gap was found between the experimental results on compressive strength and prediction models. This could be attributed to the pattern of heating and cooling effects, the duration of exposure and the size of the specimen which the models did not consider.
5. More reliable models that consider size effects and geometric parameters of the concrete should be considered for more precise prediction.

ACKNOWLEDGMENTS

The authors acknowledge the technical supports provided by the technical staff of Structures and Materials Laboratory of the Department of Civil Engineering at the University of Botswana.

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