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Significance of Concrete Cover to Reinforcement in Structural Element at Varying Temperatures

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Abstract— This paper evaluated the significance of concrete cover for reinforcement in structural elements at varying temperatures. Sixty samples of 320 mm x 150 mm x 100 mm concrete beams reinforced with 10 mm main bars and 6 mm nominal reinforcement were cast in the laboratory in four batches. Each batch contains fifteen samples with concrete cover for reinforcement varied at 10 mm, 15 mm, 20 mm and 25 mm respectively. After 28 days of curing, the beam samples were subjected to simulated fire in the laboratory furnace at temperatures ranging from 50 ^{o}C (122 ºF) – 700 ^{o}C (1292 ºF) in steps of 50 ^{o}C. Thereafter, the samples were allowed to cool to room temperature. Subsequently, samples of reinforcement were removed from the beam samples and tested with the universal material testing machine. Results of tensile tests on reinforcements showed that ultimate tensile strength of steel decreased with increasing temperatures. The greatest loss in strengths of steel reinforcements was recorded for beams with 10 mm concrete cover, which reduced from a value of 592.0 N/mm^2 at room temperature to 224.50 N/mm^2 at a terminal temperature of 700^{o}C (1292 ºF), which represented a 62% reduction in strength.

Index Terms— concrete cover, temperature, steel, tensile strength, fire

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1 INTRODUCTION

Steel is widely used in the construction industry to compliment concrete, which is weak in tension. This is usually done by embedding steel within concrete to produce reinforced concrete structural elements. However, unprotected (or exposed) steel reinforcements are likely to suffer serious damage or even collapse, in case of a fire disaster, due to the progressive deterioration in both strength and stiffness of structural steel with increasing temperatures. In order to protect life and reduce fire damage to property and financial loss, a concrete building must be designed to sustain the applied design loads without the occurrence of excessive deflection or even failure in structural members for a spec ified period of time [1].

Narendra et al. [2] revealed that the heat associated with fires may vaporize trapped concrete pore water, and that the lack of continuous voids for pressure relief creates internal tensile stresses that are relieved by cracks and spalls extending to the surface, and also that spalling may be explosive in higher strength concretes.

Additionally, severe heat may cause chemical changes that lead to micro cracking (visible only under magnification) and loss of strength and integrity [3].

2 LITERATURE REVIEW

2.1 Fire Endurance of Concrete

The effects of fire on concrete are significantly influenced by the type of coarse aggregate used to produce it. Siliceous aggregate concrete retains approximately half its capacity at 1200°F (649°C) while carbonate and lightweight aggregate concretes exhibit near full capacity at 1200 °F [4],[5]. The work by Kodur [6] corroborated the findings that carbonate aggregate increases the fire endurance of concrete compared to the siliceous aggregate. In most applications, interest in the behaviour of structural concrete exposed to high-temperatures begins at a lower bound temperature of 100^{o}C (212^{o}F) and immediately above as free water starts to be driven off [7]. Generally speaking, the engineering properties and behaviour of concrete at temperatures slightly above 100 ^{o}C vary by only a few percentage points from those measured at room temperatures. Tests reviewed by Benjamin [8] suggest that the volume and relationship of volume to surface area of the concrete elements also has a significant influence as temperature drop from the exposed surface is steep. Lin et al. [9] found that increasing the cross section size of columns, even in one direction significantly increases fire resistance. Also, according to Hertz [10], the development of distress and a change for the worse in thermal and mechanical properties of concrete that occur with increasing temperature are the result of an uninterrupted series of physical-chemical reactions that are accompanied by shrinkage and micro cracking. It was also noted by Hertz [10] that overlapping, chemically bound water (non evaporable) is released progressively from the complex system of low crystalline order, calcium silicate hydrates, and other hydrates in the cement paste and from the calcium hydroxide crystals formed when cement originally hydrated.

2.2 Effect of Fire on Reinforcement Steel

Suprenant [11] revealed that cold-worked steel subjected to temperatures of less than 450° C (842° F) typically recovers all of its yield strength after cooling. Hot-rolled steel can be exposed to temperatures as high as 600 °C (1112 °F) and recover its yield strength. But higher temperatures may cause significant strength loss in reinforcing steel, and this is usually responsible for any excessive residual deflections of reinforced members. On-site hardness testing also can estimate reinforcement tensile strength and ductility. The hardness of the

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surface, however, may differ from that at the center of the bar due to quenching when putting out the fire. Whenever it is possible, hardness testing should be correlated with the actual strength and ductility of steel specimens removed from the structure [11].

The thermal protection of reinforcing steel is critical; testing indicates that bars heated beyond 500 °C (9320F) lose significant amounts of yield strength and ultimate strength. High strength alloy steels retain approximately 90% of their strength to nearly 316 °C (6000F). Significant dimensional changes and distortions occur at temperatures above 427 °C (8000F). The heat associated with a fire can cause many types of changes to structural steel elements such as member deformation. Besides large deformations, other less obvious changes can occur at higher temperatures such as loss of normalized microstructure; stress relieving or sensitization of stainless steels; high residual stresses; or embrittlement due to rapid cooling associated with firefighting efforts [2].

3 METHOD

3.1 Concrete Mix

Sixty samples of 320 mm x 150 mm x 100 mm reinforced concrete beams were cast at the Structures Laboratory of the Civil Engineering Department of the Federal University of Technology Akure, Ondo State, Nigeria. The beams were cast using crushed granite with nominal maximum size of 10 mm as the coarse aggregate, natural river sand as the fine aggregate, and ordinary Portland cement with potable water as the binder. The water – cement ratio used was 0.45 while four 10 mm bars were used as longitudinal reinforcement for each beam. The shear reinforcement consisted of 6 mm diameter bars. A mix ratio of 1:2:4 by volume of cement, fine aggregate and coarse aggregate was adopted, with the concrete cover for reinforcement being varied. Accordingly, fifteen beam samples each were cast for 10 mm, 15 mm, 20 mm and 25 mm concrete cover. The beams were thereafter cured for a period of 28 days in order to ensure adequate maturity before testing.

3.2 Testing Procedures

After 28 days curing, the beam samples were removed from the water tank and air dried before they were subjected to varying furnace temperatures ranging from 50^{o}C (122 ^{0}F) to 700^{o}C (1292 ^{0}F) at an interval of 50^{o}C (122 ^{0}F) in the Physical Metallurgical Laboratory of the Metallurgical and Material Engineering Department of Federal University of Technology Akure. Figure 1 shows a beam sample removed from the furnace after heating. The beams were allowed to cool and in order to study the significance of concrete cover for reinforcement at varying temperatures; the reinforcement steel bars were removed from the beams and later subjected to ultimate tensile strength test using the SM100 Universal Material Testing Machine. The nominal ultimate tensile strength was calculated according to the following formula:

$$f_y = \frac{F}{A} \qquad (*)$$

where:

f_y is the nominal ultimate tensile strength in N/mm^2
F is the maximum load carried before failure in N, and
A is the original area of the steel sample in mm^2

The tensile strengths of reinforcements were noted at various temperatures with respect to the different concrete covers, and curves of tensile strength versus temperatures were plotted.

4 RESULTS AND DISCUSSION

The results of the ultimate tensile tests on the reinforcement bars removed from the burnt concrete beam samples with concrete cover of 10 mm, 15 mm, 20 mm and 25 mm tested under laboratory condition is presented in the Fig. 2. This Fig. 2 shows the variation of ultimate tensile strength of reinforcement with temperature for beam samples with 10 mm, 15 mm, 20 mm and 25 mm concrete cover for reinforcements.

The result for beams with 10 mm cover to reinforcement showed that, the average ultimate tensile strength decreased from 592.0 N/mm^2 at 30 ^{o}C (86 ^{0}F) to 224.50 N/mm^2 at 700 ^{o}C (1292 ^{0}F). This represents a loss in average ultimate strength of the steel by 62.0%. The decrease in average tensile strength of the steel with increase in temperature were strongly correlated, $R^2 = 0.992$ (n = 15). The R^2 value is found to be 99.2%, which indicates a strong correlation. A 62.0.0 % loss in residual strength was observed at the terminal temperature of 700 ^{o}C (1292 ^{0}F).

For beams with 15 mm cover to reinforcement, the average ultimate tensile strength decreased from 592.0 N/mm^2 at 30 ^{o}C (86 ^{0}F) to 272.04 N/mm^2 at 700 ^{o}C (1292 ^{0}F); representing a loss in strength of the steel by 54.0%. Similarly, the decrease in average tensile strength of the steel with increase in temperature were strongly correlated, R^2=0.989 (n=15).

Also for beams with 20 mm cover to reinforcement, the average ultimate tensile strength decreased from 592.0 N/mm^2 at 30 ^{o}C (86 ^{0}F) to 300.97 N/mm^2 at 700 ^{o}C (1292 ^{0}F); representing a loss in strength of the steel by 49.2%. The decrease in average tensile strength of the steel with increase in temperature were strongly correlated, R^2=0.980 (n=15). Finally for the beams with 25 mm cover to reinforcement, the average ultimate tensile strength decreased from 592.0 N/mm^2 at 30 ^{o}C (86 ^{0}F) to 313.96 N/mm^2 at 700 ^{o}C (1292 ^{0}F); representing a loss in strength of the steel by 47.0%. The decrease in average tensile strength of the steel with increase in temperature were strongly correlated, R^2=0.980 (n=15).

The decrease in strength observed as the temperature was increased could be attributed to the recrystallization of grains, thereby making the material less hard but more ductile.

Fig. 1: Beam sample removed from the furnace after cooling

The variation of average ultimate tensile strength with the cover to reinforcement, at various temperature, is presented in Fig. 3. It shows that for each of the temperatures to which the reinforced concrete was heated, the average tensile test increased with increasing cover to reinforcement.

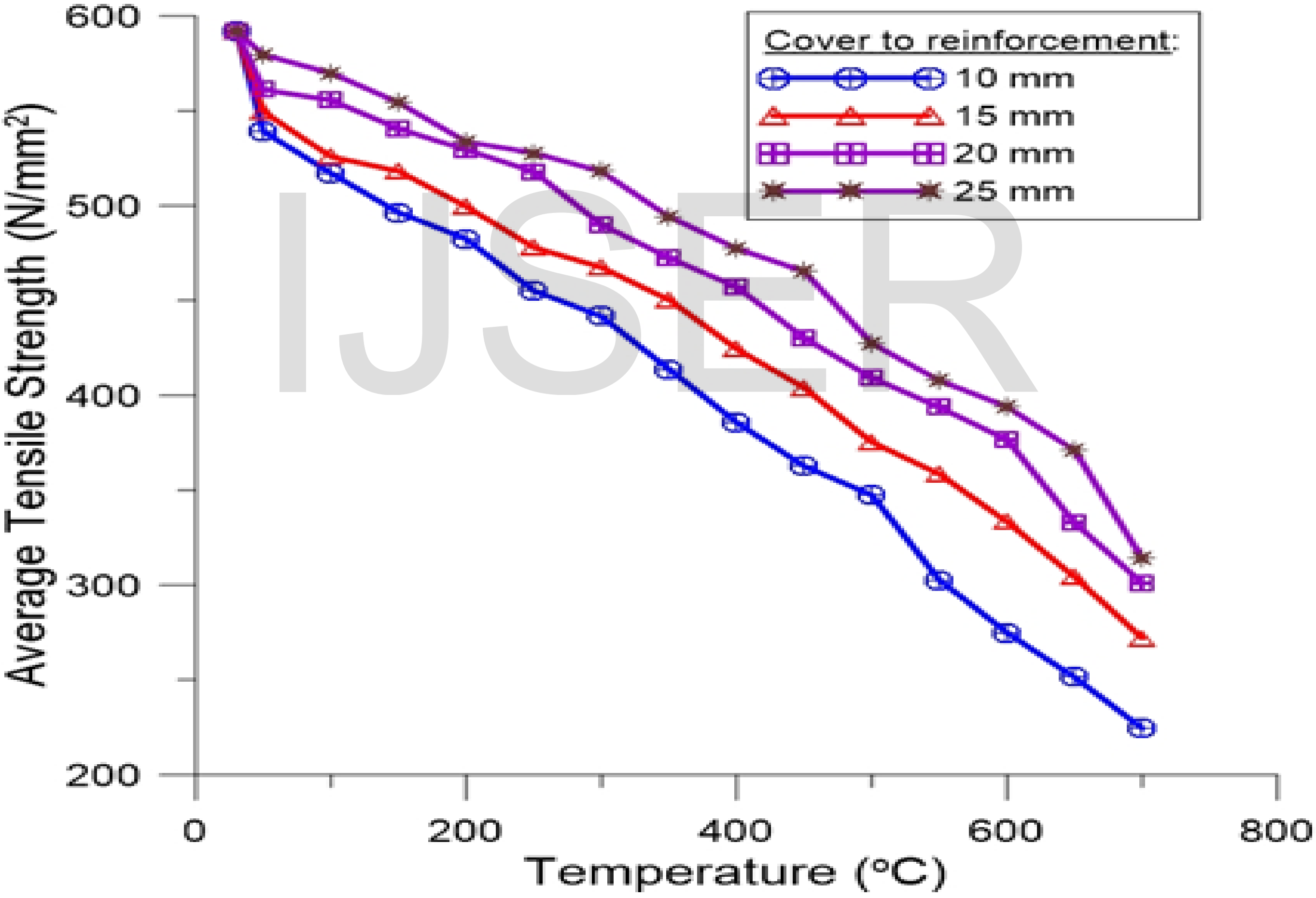

Fig. 2: Variation of average tensile strength with temperature

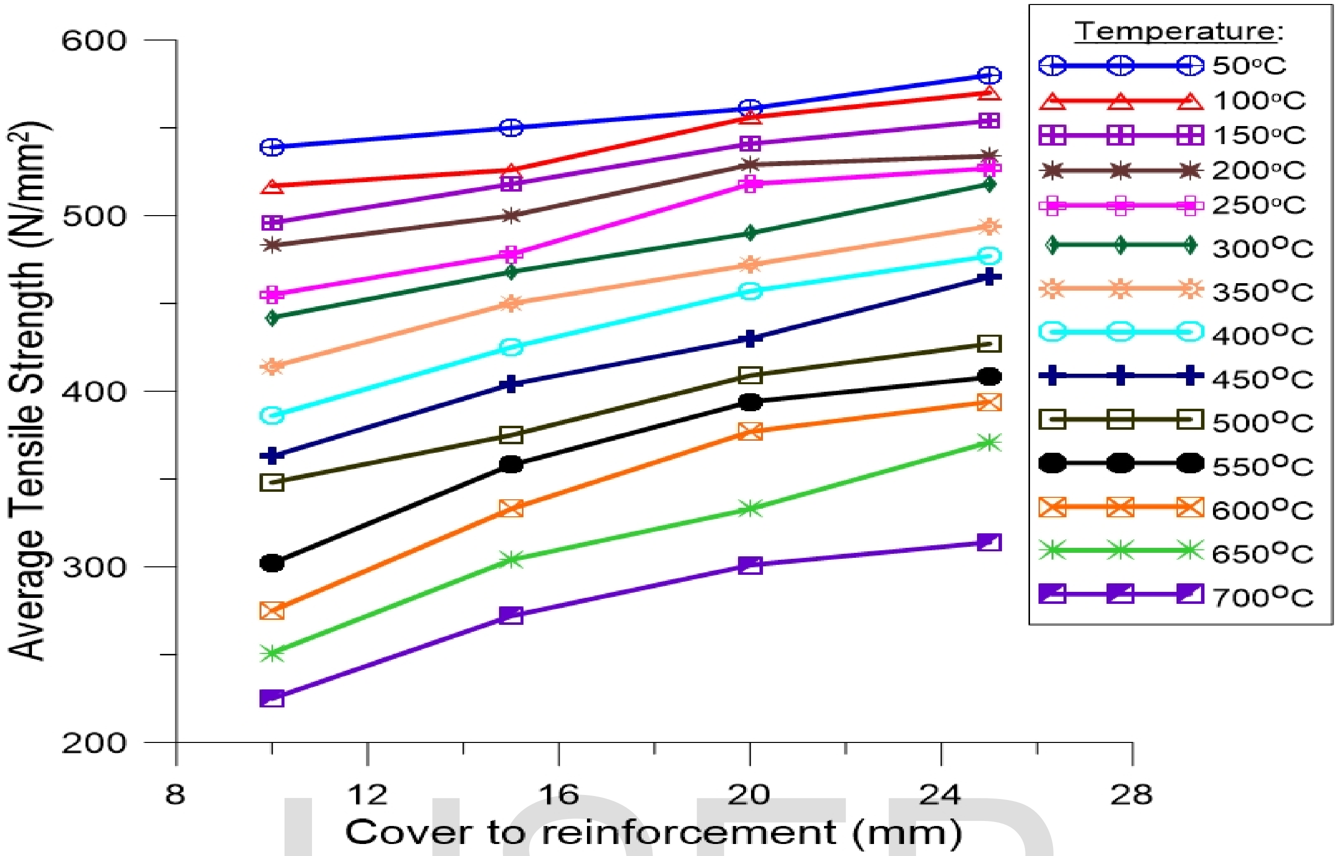

Fig.3: Variation of average tensile strength with cover to reinforcement

5 CONCLUSION

From the results obtained, it has been established that the thicker the cover to reinforcement of a reinforced concrete structural element subjected to fire (at a constant temperature), the greater the residual strength of the steel reinforcement after the fire. It was also established that the higher the temperature of reinforced concrete subjected to fire (given that the cover to reinforcement is constant), the lower the residual strength of the steel reinforcement.

Consequently, Construction Engineers are admonished to strictly adhere to design specifications relating to concrete cover to reinforcement.

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