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Effects on Flexural Strength of Reinforced Concrete Beam Subjected to Fire

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Abstract

Studies on reinforced concrete members have shown that there is loss of flexural strength of reinforced concrete beam when subjected to elevated temperatures. This is because; there are membrane forces and the redistribution of bending moment which considerably affects the behavior of the reinforced concrete beam. The aim of this study was to use non-linear analytical methods to determine the temperature reached at a given depth of concrete and hence determine the flexural strength at such elevated temperatures and hence give a way forward to develop a procedure in analyzing the reinforced concrete flexural member's subjected to fire. This paper gives the way forward on the effects of fire on flexural strength of a beam at elevated temperature and at a given time. More so, it discusses effect of such beams cooled by quenching with cold water, a practical case which relates to the fire fighting process.It was found that, when reinforced concrete classes C20 is heated at 250°C there is a loss of up to 20.1% when heated for one hour and 24.88% when such member is heated for two hours. However, when heated at a temperature of 600°C for one hour, the loss of flexural strength ranges from 33.1% and 34.36% for members heated for two hours. For a member heated at a temperature of 750°C, the loss of strength ranges from 41.81% when heated for one hour 43.01% for members heated for two hours.When class C25 is heated at a temperature of 250°C and cooled by normal loading, for one hour, the loss of flexural strength is 18.22% and when heated for two hours, the flexural strength loss is 20.84%. For members heated at a temperature of 600°C the strength loss of such member is 24.37% and when heated for duration of two hours, it loses the flexural strength of 27.14%. For members heated and cooled by quenching with cold water, the flexural strength loss is very high compared to those cooled at room temperature.

Keywords: flexural strength, non-linear analytical methods, elevated temperatures, normal loading, quenching

1. Introduction

Concrete has excellent properties in regards of fire resistance compared to other materials and can be used to shield other structural materials such as steel (Khoury, Grainger, Sulivan, 1985).

Effects of high temperatures on the mechanical properties of concrete have been investigated as early as the 1920s (Schneider, Lebeda, 2000). In the 1960s and 1970s fire research was mainly directed to study the behaviour of concrete structural elements (Kordina, 1997).

During fire, the mechanical characteristics of the concrete are changing. During the cooling process concrete is not able to recover its original characteristics

The assessment of the residual load bearing capacity of reinforced concrete member after fire exposure is a complex task. It includes the estimate of the actual strength of both concrete and steel and the subsequent computation of the sections' bearing capacity.

However in most cases the knowledge of materials strength, even after accurate and extensive testing, is not sufficient for the purpose. In fact in-situ testing cannot be extended over all the sections depth, while every single spot of the sections contributes to the overall bearing capacity with a strength that depends on the local maximum temperature reached during the fire.

This research is aimed at giving a further contribution to recognise and understand better this problem, proposing an assessment methodology based on a suitable analytical procedure which will be applied to a model reinforced concrete beam, concrete and steel bars subjected to fire.

2.Literature review

2.1 Reinforced concrete material properties

The rise in temperature affects the strength and modulus of elasticity of both concrete and steel reinforcement. However, the rate at which the strength and modulus of elasticity decrease depends on the rate of increase in the temperature, duration of the fire and the insulating properties of concrete.

2.1.1 Concrete

Concrete is a composite material that consists mainly of mineral aggregates bound by a matrix of hydrated cement paste. The matrix is highly porous and contains a relatively large amount of free water unless artificially dried.

When exposed to high temperatures, concrete undergoes changes in its chemical composition, physical structure and water content. These changes occur primarily in the hardened cement paste in unsealed conditions.

Such changes are reflected by changes in the physical and mechanical properties of concrete that are associated with temperature increase.

Chemical changes can be studied with thermogravimetrical analyses (TG/DTG/DTA).

The following chemical transformations can be observed by increase of temperature:

Around 100 °C the weight loss is caused by water evaporating from the micropores. The decomposition of ettringite ($3CaOAl2O3\cdot3CaSO4\cdot32H2O$) occurs between 50 °C and 110 °C. At 200°C there is further dehydration which causes small weight loss. The weight loss with various moisture contents is different until all the pore water and chemically bound water is gone. Further weight loss is not perceptible around 250-300 °C (Khoury, Grainger, Sullivan, 1985, Schneider, Weiss, 1997).

During heating the endothermic dehydration of Ca(OH)2 occurs between the temperatures of 450 °C and 550 °C ($Ca(OH)2 \rightarrow CaO + H2O\uparrow$) (Schneider, Weiss, 1977). In case of concretes with quartz gravel aggregate another influencing factor is the change of crystal structure of quartz α formation→ β formation at the temperature of 573 °C (Waubke, 1997). This transformation is followed by 5.7% volumetric increase.

Dehydration of calcium-silicate-hydrates is found at the temperature of 700 °C (Hinrichsmeyer, 1989).

3.Methods and Materials

3.1 Aggregates

Aggregates used in this work were crushed, processed natural materials as specified in BS 882 1992. The course aggregates used constituted of 20mm maximum aggregates retained on a 5.0 mm BS410 test sieve and containing no finer materials than is permitted for the various sizes.

Fine aggregates were uncrushed river sand determined in accordance with BS 812-103.1using 0.6 mm sieve determined by sieve analysis test. The amount of material passing the 75µm sieve controlled at 4%.

Water absorption was determined in accordance with BS 882. For fine aggregates

3.2 Water

Water used was for three different purposes as follows:

3.2.1 Mixing water

The mixing water that is the free water encountered in freshly mixed concrete has three main functions i.e. it reacts with water cement powder and thus producing hydration, it acts as a lubricant contributing to the workability of the fresh mixture and it secures necessary space in the paste for the development of hydration.

This is so because waters containing no more impurities than 2000 ppm of common ions (that is, 0.2% of the weight of water) are generally acceptable as mixing waters, whereas for drinking waters 1000 ppm is the permissible upper limit in some specifications. Nevertheless, use of untreated domestic waste water is not advocated as mixing water.

In this work, water used is fresh with approximately 2000 ppm.

3.2.2 Water for curing

Water for curing are less stringent than mixing mainly because, curing water is in contact with the contact with the concrete for relatively short time. Such water may contain more inorganic and organic materials, sulfuric anhydride, acids, chlorides, and so on, than acceptable mixing water; especially discoloration of the concrete surface is not objectionable. Nevertheless, the permissible amounts of the impurities are still restricted.

3.2.3 Water for washing aggregate

Water for washing aggregate should not contain materials in quantities large enough to produce harmful films or on the surface of aggregate particles [Ujhelyi 1973. Essentially the same requirement holds when the water is used for cleaning concrete mixers and other concreting equipment.

Chemical limitations for the impurities in wash water are specified in ASTM C 94-8913.

3.3 Workability

Workability was controlled within the following limits:

3.3.1 Slump

In accordance with BS1881 part 101 the slump was controlled at 45 ±5mm

3.3.2 Compacting factor

Targeted at 0.90 ±0.03

3.4 Cement content

For an equivalent grade the assurance of minimum cement content was used and batched by weight to comply with the specified minimum cement content if the compressive strength results for the equivalent grade are to comply with the requirements of clause 3.1.6.2. of BS5328 Part 4:1990

The samples were heated at varying temperatures of 250°C, 600°C and 750°C for one hour and two hours intervals.

After heating, the colour change was noted weighed the weight loss determined crushing test done by use of compressive strength machine to determine the loss in compressive strength.

3.5 Properties of reinforced concrete materials at elevated temperature

Reinforced concrete is a composite material comprising of steel and concrete. The rise in temperature affects the strength and modulus of elasticity of both concrete and steel reinforcement. However, the rate at which the strength and modulus of elasticity decrease depends on the rate of increase in the temperature and duration of the fire and the insulating properties of concrete

3.5.1 Physical properties of concrete at elevated temperatures

These are properties which attribute to physical changes of the concrete after heating. The temperatures were regulated at 750°C for **one** and **two** hours respectively and physical properties were noted and tabulated as shown below in *table 3.2.*

Temp (°C)	Heating Time (hrs)	Wt. before placing in furnace (kg)	Weight after placing in furnace k(g)	%ge weight loss	Ultimate load (KN)	%ge loss in strength	Average Ultimate strength (KN)
Room temp.	**-**	**33.48**	**33.48**	**0**	**65.34**	**0**	**65.34**
250	1	33.11	31.65	4.42	53.04	18.83	52.94
250	1	33.23	31.75	4.45	52.83	19.14	
250	2	33.17	31.60	4.73	50.28	23.05	50.44
250	2	33.22	31.67	4.68	50.59	22.58	
600	1	33.12	31.35	5.36	47.57	27.19	47.82
600	1	33.28	31.48	5.42	48.06	26.44	
600	2	33.14	31.26	5.68	43.77	33.01	43.88
600	2	33.23	31.34	5.94	43.98	32.69	
750	1	33.17	31.11	6.20	37.67	40.82	38.14
750	1	33.32	31.29	6.10	38.61	40.91	
750	2	33.31	31.20	6.35	38.18	41.57	38.12
750	2	33.26	31.13	6.41	38.07	41.74	

3.5.2 Determine temperature distribution in reinforced concrete beam beam with temperature after quenching with cold water.

Materials method proposed by Wickström (1987) provides ah series of calculated temperature profiles in floor slabs or walls, beams and columns.

NB: This method does not take into account of possible spalling of concrete.

In general, the temperature rise (**θ_x**) in a point at a given distance from the surface **x** is given by

$\theta_x = \eta_x * \eta_w * \theta_f$ …………………………………………………………………………………… i

Where **η_w** is the ratio between the temperature rise of the surface**θ_w** and the fire**θ_f** given by:

$\eta_w = 1 - 0.0616\, t_w^{-0.88}$ …………………………………………………………………………………… ii

η_x is the ratio between the interior point **θ_x** and the surface given by:

$\eta_x = 0.18 \ln u_x - 0.81$ (for constant thermal properties) ………………………………………………… iii

Where $u_x = \square_a * t/x^2$ ……………………………………………………………………… ..iv

$\square_a = {}^{a}/{a_c}$ ……………………………………………………………………… v

$a = {}^{k}/{c\rho}$ ……………………………………………………………………………………vi

Where $k = 1.0 Wm^{-1}K^{-1}$ for constant thermal properties and

$c = 1000\ J\ kg^{-1}K^{-1}$

ρ is the density of concrete given by $2400 kg/m^3$

a_c for normal weight concrete is given by $417 x 10^{-9}\ m^2 s^{-1}$

t = fire duration in hours

x = distance from the surface in metres,

θ_f = temperature in °C

To determine the temperatures reached at several depths in concrete, the following formulae were applied:

3.5.2.1 Temperature rise for cubes heated at 750°C in 1 hour

$\boldsymbol{\theta_x = \acute{\eta}_x . \acute{\eta}_w . \theta_f}$

Where $\acute{\eta}_x = 0.18 \ln u_x - 0.81$

But $u_x = \square_a . {}^{t}/{x2}$

Where ⍰$_a$ is a coefficient between thermal diffusiveness of the actual structure given by:
⍰$_a$ = a/a$_c$
And t = heating time in hours =1
x = distance from the surface to the point of consideration in hours.
$a = \frac{k}{c\rho}$
For constant thermal properties, k = 1.0$Wm^{-1}k^{-1}$
c = specific heat of concrete given by 1000$JKg^{-1}K^{-1}$
ρ is the density of concrete = 2400kg/m^3
Thus,
$a = \frac{1}{1000 \times 2400} = 4.1667 \times 10^{-7}$ W/J
$a_c = 417 \times 10^{-9} m^2 s^{-1}$ (for normal concrete)
⍰$_a$ $= \frac{4.1667 \times 10^{-7}}{417 \times 10^{-9}} = \mathbf{0.9992}$
$u_x = 0.9992 \times \frac{1}{0.01^2} = \mathbf{9992}$
$\acute{\eta}_x = 0.18 \times \ln 9992 - 0.81$
$= \mathbf{0.8477}$
$\acute{\eta}_w = 1 - 0.0616t^{-0.88}$
$= 1 - 0.0616 \times 1^{-0.88}$
$= \mathbf{0.9384}$
θ_f = **750°C**
Therefore, the temperature rise 10mm depth of concrete is given by :
$\theta_x = 0.8477 \times 0.9384 \times 750$
= **<u>596.61°C</u>**

k			$1.0Wm^{-1}k^{-1}$			**u_x**	**n_x**	**n_w**	**θ_f (°C)**	**θ_x (°C)**
ρ			2400kg/m^3							
C			1000$JKg^{-1}K^{-1}$							
a			4.1667×10^{-7} W/J							
a_c			$417 \times 10^{-9} m^2 s^{-1}$							
⍰$_a$ = a/a$_c$			0.9992							
x(m)	0.015	x^2	2.25×10^{-4}	$\frac{1}{x2}$	4444.44	4440.89	0.701	0.938	750	**493.68**
	0.020		4.0×10^{-4}		2500.00	2498.00	0.598	0.938	750	**420.69**
	0.025		6.25×10^{-4}		1600.00	1598.72	0.518	0.938	750	**364.41**
	0.030		9.0×10^{-4}		1111.11	1110.22	0.452	0.938	750	**317.98**

Table 3.2 Summary of temperature rise at different points from the surface at 750°C in 1 hour

3.5.2.2 Temperature rise for cubes heated at 750°C in 2 hours

$\boldsymbol{\theta_x = \acute{\eta}_x \cdot \acute{\eta}_w \cdot \theta_f}$
Where $\acute{\eta}_x = 0.18\ln u_x - 0.81$
But u_x =⍰$_a$. $^t/_{x}2$
Where ⍰$_a$ is a coefficient between thermal diffusiveness of the actual structure given by:
⍰$_a$ = a/a$_c$
And t = heating time in hours =2
x = distance from the surface to the point of consideration in metres = 0.01
$a = \frac{k}{c\rho}$
For constant thermal properties, k = 1.0$Wm^{-1}k^{-1}$
c = specific heat of concrete given by 1000$JKg^{-1}K^{-1}$
ρ is the density of concrete = 2400kg/m^3
Thus,
$a = \frac{1}{1000 \times 2400} = 4.1667 \times 10^{-7}$ W/J
$a_c = 417 \times 10^{-9} m^2 s^{-1}$ (for normal concrete)

$\square_a = \frac{4.1667 \times 10^{-7}}{417 \times 10^{-9}} =$ **0.9992**

$u_x = 0.9992 \times \frac{2}{0.010^2}$ = **19,984**

$ή_x$ = 0.18 x ln 8881.78 - 0.81
= **0.97248**

$ή_w = 1 - 0.0616 \times t^{-0.88}$
$= 1 - 0.0616 \times 2^{-0.88}$
= **0.96653**

θ_f = **750°C**

Therefore, the temperature rise 10mm depth of concrete is given by :

θ_x = 0.97248 x 0.96653 x 750
= **704.95°C**

<table>
<tr><td colspan="2">k</td><td colspan="3">$1.0Wm^{-1}k^{-1}$</td><td rowspan="6">u_x</td><td rowspan="6">n_x</td><td rowspan="6">n_w</td><td rowspan="6">θ_f (°C)</td><td rowspan="6">θ_x (°C)</td></tr>
<tr><td colspan="2">ρ</td><td colspan="3">$2400kg/m^3$</td></tr>
<tr><td colspan="2">C</td><td colspan="3">$1000JKg^{-1}K^{-1}$</td></tr>
<tr><td colspan="2">a</td><td colspan="3">4.1667×10^{-7} W/J</td></tr>
<tr><td colspan="2">a_c</td><td colspan="3">$417 \times 10^{-9}m^2s^{-1}$</td></tr>
<tr><td colspan="2">$\square_a = a/a_c$</td><td colspan="3">0.9992</td></tr>
<tr><td rowspan="4">x(m)</td><td>0.015</td><td rowspan="4">x^2</td><td>$2.25x10^{-4}$</td><td rowspan="4">$\frac{2}{x^2}$</td><td>8,888.9</td><td>8881.18</td><td>0.827</td><td>0.967</td><td>750</td><td>599.78</td></tr>
<tr><td>0.020</td><td>$4.0x10^{-4}$</td><td>5,000.0</td><td>2498.00</td><td>0.598</td><td>0.967</td><td>750</td><td>433.70</td></tr>
<tr><td>0.025</td><td>$6.25x10^{-4}$</td><td>3,200.0</td><td>1598.72</td><td>0.518</td><td>0.967</td><td>750</td><td>375.68</td></tr>
<tr><td>0.030</td><td>$9.0x10^{-4}$</td><td>2,222.2</td><td>1110.22</td><td>0.452</td><td>0.967</td><td>750</td><td>327.81</td></tr>
</table>

Table 3.3 Summary of temperature rise at different points from the surface at 750°C in 2 hours.

Data Analysis , results and discussions

4.1 Introduction

The study involved 56 reinforced concrete beams with which, twenty eight were class 20 while the other twenty eight were of class 25 concrete reinforced with Y12 steel bars. Three samples were taken for each test descriptive examination and laboratory testing.

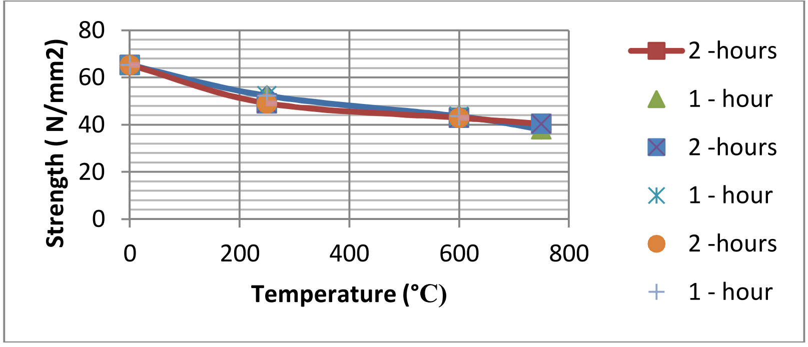

Figure 4.1: Flexural strength variation of class 20 reinforced concrete beam with temperature after cooling at room temperature

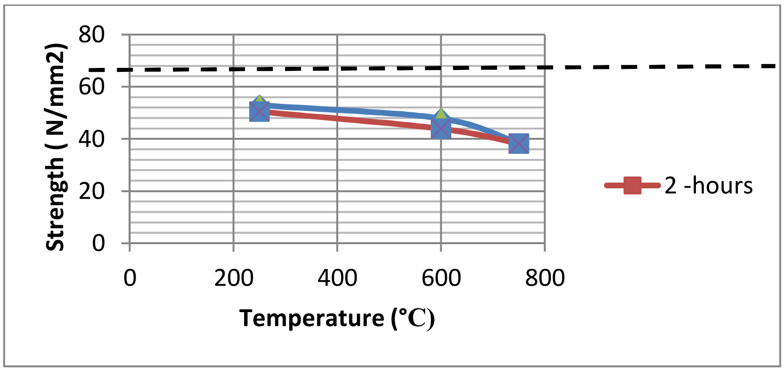

Figure 4.2: Flexural strength variation of class 20 reinforced concrete beam with temperature after heating and quenching with cold water

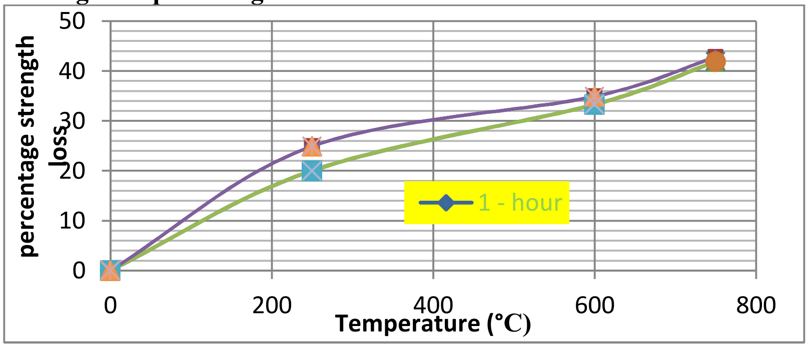

Figure 4.3: Percentage flexural strength loss of class 20 reinforced concrete beam with temperature after heating and cooling at room temperature

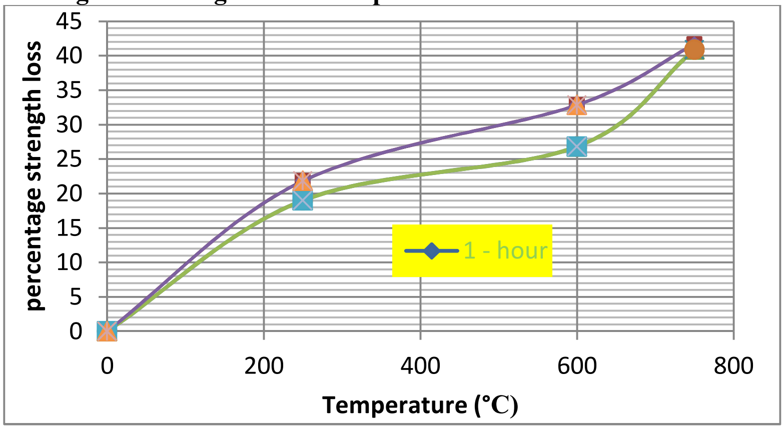

Figure 4.4: Flexural strength loss of class 20 reinforced concrete beam with temperature after heating and quenching with cold water

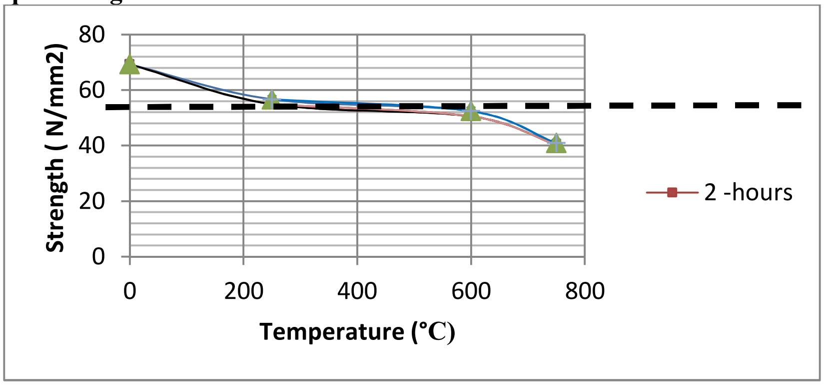

Figure 4.5: Flexural strength variation of class 25 reinforced concrete beam with temperature after heating and cooling at room temperature.

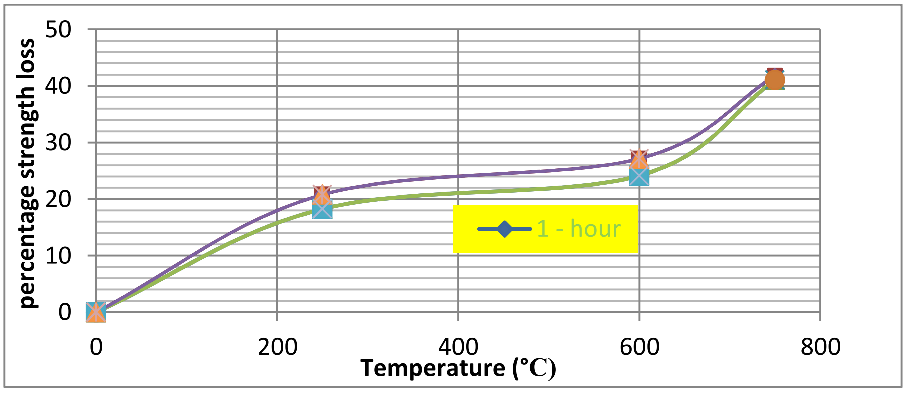

Figure 4.6: Percentage flexural strength loss of class 25 reinforced concrete beam with temperature after heating and cooling at room temperature.

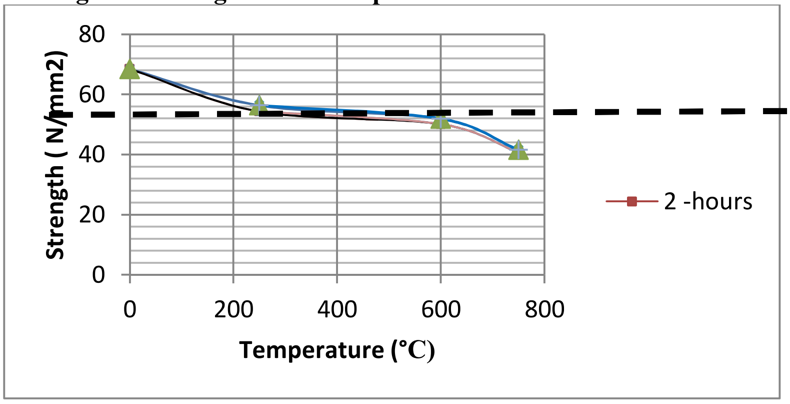

Figure 4.7 Flexural strength variation of class 25 reinforced concrete beam with temperature after heating and quenching with cold water.

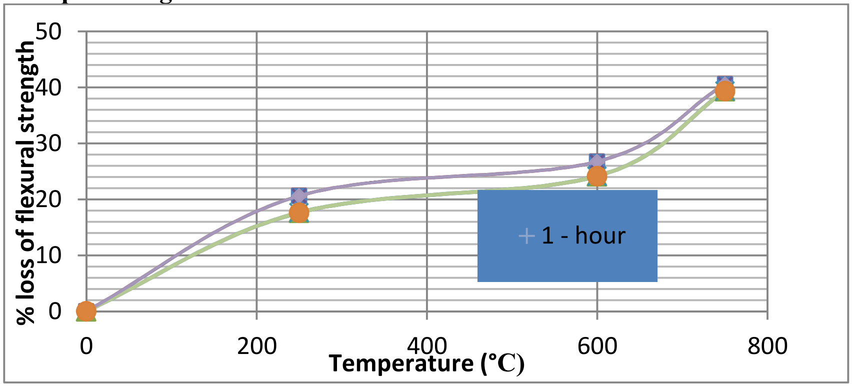

Figure 4.8: Percentage loss of flexural strength of class 25 reinforced concrete beam with temperature after heating and quenching with cold water.

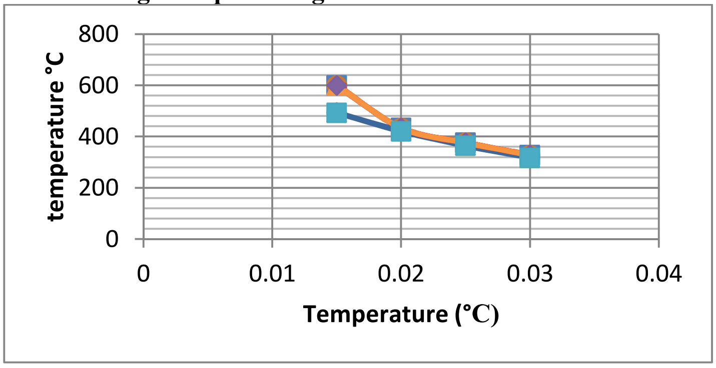

Figure 4.9: Heat penetration after heating concrete block at 750°C in 1and 2 hours

4.2 Results analysis

From the results it can be seen that, when reinforced concrete beam is heated the flexural strength reduces up to 42% depending on the concrete class, heating time, nature of cooling and the maximum temperature reached.

4.2.3 Class 20 reinforced concrete beam heated at 750°C

Flexural strength of class 20 reinforced concrete beams heated at 750°C ranges from 41.81% for members heated in one hour to 43.01% for those heated in 2 hours for members heated and heated and cooled at room temperature. For members heated and quenched with cold water, flexural strength loss range from 40.82% for members heated in one hour and 41.74% for members heated in two hours. The weight loss range between 6.98% for members heated in one hour and 7.12% for members heated for two hours heated and cooled at room temperature. For the members heated and quenched with cold water, the strength loss range from 40.82% for members heated in one hour to 41.74% for those heated for two hours.

4.2.6 Class 25 reinforced concrete beam heated at 750°C

Flexural strength of class 25 reinforced concrete beams heated at 750°C ranges from 40.97% for members heated in one hour to 41.94% for those heated in 2 hours for members heated and cooled at room temperature. Consequently, members heated and quenched with cold water, the strength loss ranges from 39.50% for members heated in one hour to 40.67 for those heated in two hours.

Weight loss ranges from 6.19% for members heated in one hour and 6.46% for members heated for two hours for member heated and cooled at room temperature. For members heated and quenched with cold water, the percentage weight loss ranges from 6.13% to for members heated in one hour and 6.51% for members heated for two hours**.** At this temperature, there is transformation followed by 5.7% volumetric increase.

Dehydration of calcium-silicate-hydrates is found at the temperature this temperature (Hinrichsmeyer, 1989).

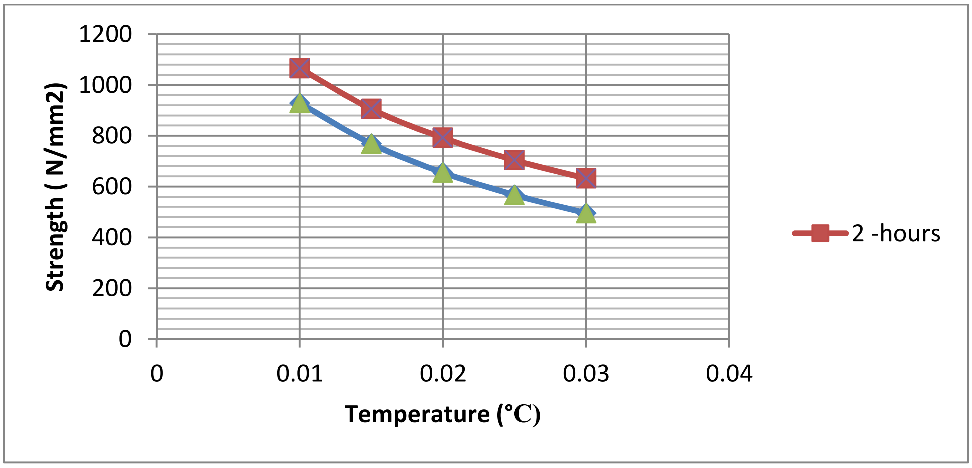

Figure 4.10: Temperature rise in concrete subjected to ISO 834 standard /natural fire

5.0.Conclusions and recommendations

5.1 Conclusions

Based on the results of the research work, the following conclusion can be drawn:

1. High temperature is one of the most important physical deterioration processes that influence the flexural strength of reinforced concrete structures and may result in undesirable structural failures. When exposed to high temperature, flexural strength of a Reinforced concrete beams change considerably regardless of the concrete class. See figures below.

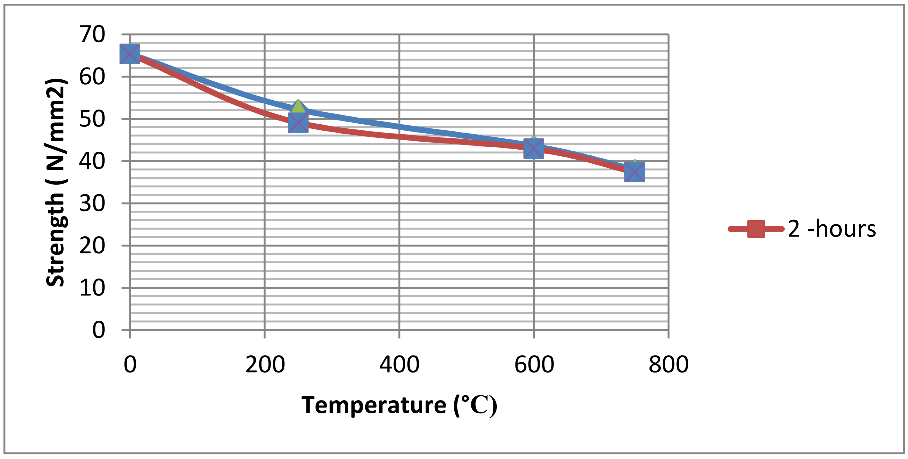

Figure 5.1: Flexural strength variation of class 20 reinforced concrete beam with temperature after cooling at room temperature.

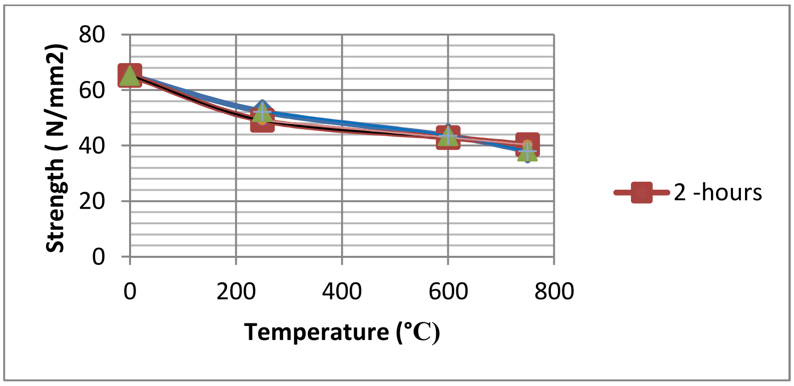

Figure 5.2: Flexural strength variation of class 25 reinforced concrete beam with temperature after cooling at room temperature.

2. The effect of fire on the reinforced concrete beams heated at 750°C cooled rapidly by quenching in water and normally cooled in the atmospheric temperature were studied and it is observed that the of rapidly cooled beams is high.
3. The reductions in flexural strength for beams exposed to fire with a cover thickness of 25mm starts loosing strength beyond 600°C. This is because, at this temperature, concrete will have an endothermic dehydration of Ca(OH)2 and temperature rise at the steel reinforcement will have raised i.e. from the calculations , in one hour, temperature reached will be 291.53°C after heating for one hour and 300.54°C after heating for At this temperature, the softening of reinforcement bars starts and for a loaded beam, it starts to deflect freely.
4. The weight loss of a reinforced concrete beam is negligible and ranges from 3.79% for a beam heated at 250°C to 6.46% for a beam heated at 750°C for class 25 concrete .there is a significant weight loss for class 20 concrete which range from 4.42% a beam heated at 250°C to 6.41% for a beam heated at 750°C
5. After heating, steel regains its strength and even gains more strength after quenching with cold water. Therefore from the result, it can be deduced that, the failure of flexural members due to high temperatures are as a result of the softening of steel during heating process which eventually exceeds the allowable deflection. Otherwise the steel regains most of its strength.
6. Under normal weather conditions concrete heated at standard /natural fire, its temperature rise is high and affects both steel and concrete which starts loosing strength especially for members with covers for up to 25mm. if the fire continues for one hour, it rises from 926.21°C at a depth of 10mm to 495.14°C at a depth of 30mm. when fire continues for two hours, the temperature rise is between 1064.76°C at a depth of 10mm to 631.74°C at a depth of 30mm.

5.2 Future Scope

1. To find the effect on the following temperature ranges 300°C, 450°C 500°C, 550°C, 650°C, 800°C,

850°C, 900°C and 950°C

2. To construct a reinforced concrete structure comprising of all the structural members (beams, columns and slab) and subject it to fire for one and two hours, check the flexural loss and compare the values with the ones obtained in the current work.

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