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Structural failures from high temperature effect and remedial measures in the Nigerian environment.

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Abstract

Three conventional normal strength concrete grades 20, 25, and 30 were investigated, under very high temperatures which ranged from 250^{0}C and 1000^{0}C. Sample cubes were made from cement, sand and coarse aggregates [20mm diameter granite chippings], with water/cement ratio equals 0.62. After 90 days curing, the specimens were subjected to heat in a regulated oven, which temperature varied between 250^{0}C and 1000^{0}C. The results obtained show that the concrete grade 20 exhibited higher resistance to heat than concrete grades 25 and 30. Although, at 1000^{0}C, none of these concrete cubes was of structural importance any more as the compressive strengths fell below 5N/mm^2.

1. Introduction.

In recent times, it has been observed that the rate at which buildings of structural importance are gutted by fire is becoming very high. Soon after the disasters, the structural elements such as beams, columns slabs/decks, begin to crumble and subsequently the buildings collapse.

This, no doubt has led to colossal financial losses, loss of lives among others. Within the last three decades a good number of corporate institutions and markets have incurred monumental financial and structural losses to fire disasters. Virtually, all the markets in the thirty six [36] states of the nation have suffered this fate. The proprietors/owners are usually faced with the problem of knowing the extent to which their property have been affected by the inferno. Secondly, they also contend with the problem of demolishing and rebuilding, either partially or wholly. From the foregoing therefore, there is an urgent need to look into this problem and to find possible ways of averting total disintegration of buildings gutted by fire, by using the appropriate concrete grades or fire resistant concretes in the execution of load bearing structural elements, which hitherto disintegrate below acceptable levels during and after fire disaster.

Furthermore, it is essential to ascertain temperature levels on these buildings, by determining independently the state of each structural element. Sequel to this, the research had gone further to examine the effects on, and behaviour of concrete grades 20, 25 and 30, when subjected to heat at very high temperatures and to determine which concrete grade is best suited to resist inferno. These concretes were allowed to cool normally simulating a real life situation without fire fighting services.

2. Materials and methods

The thermal properties of concrete are more complex than of most other materials, because not only is concrete a composite material whose components have different thermal properties, but also its properties depend on moisture content and porosity.

From earlier work done by Nwokike and Onyeyili [2004], it was clear that after 7 days curing concrete grade 20 had attained its full compressive strength, while 25 and 30 had an average compressive strengths of about 80% of their design strengths. At 28 days the strengths of concrete grades 25 and 30 had slowly gone up to between 88-90% of the design strengths. However, at 90 days they had all attained their full design strengths.

From the foregoing therefore, concrete grade 20 hydrates faster than the other concretes, for these reasons.

a) The specific surface area of the coarse aggregate in concrete grade 20 is higher than those of concrete grades 25 and 30.

b) Though the volume of its concrete paste is comparatively less than those of other concrete grades, it has a higher bonded surface area with coarse aggregates.

Compressive strengths and elastic modulus are significantly influenced by the mineralogical characteristics of the aggregates. Crushed aggregates from fine diabase and limestone gave best results. Concrete made from river gravel and crushed granite that contained inclusions of soft minerals were found to be relatively weaker in strength. This can be examined through stress and strain curves and loading and unloading hysteresis loops for concrete mixtures, calculated, using the expression earlier reported by Chang and Su, [1996].

$$\sigma = \frac{Ph}{V} \, [N/mm^2]$$

σ - Compressive strength of aggregate.
V - Volume of single aggregate determined, using Archimedes principles after the over dried aggregate is measured.
P - Maximum load on single aggregate.
H - Distance between the two opposite load points of P.
A large number of aggregate should be tested to obtain a meaningful result.

Aggregate size affects strength. For large aggregate, cement paste bond strength is less, and the compressive strength is reduced; [Cook, 1989] affirmed this through his test.

Although, cement paste in practice will never completely hydrate, the aim of curing is to ensure sufficient hydration in pastes, with lower water/cement ratio, self desiccation can occur during hydration and this prevents further hydration, unless water is supplied externally. An adequate amount of moisture is necessary to attain desired strength. Thus, the need to immerse the cube specimens in a pooling tank.

2.1. Experimental analysis

At various stages of heating other essential characteristics – compressive strengths, modulus of elasticity, permeability and other durability indices are observed. This is not done without ensuring that at each interval of 250^{0}C, in increasing order, the cube specimens of 150mm x 150mm x 150mm are soaked in heat for two hours after attaining the expected temperatures to ensure proper permeation into the cubes. Heat flow factor had been reported by Brewer, [1967].

2.1.1. Compressive strength

Eighteen [18] cube specimens of various mixes were investigated at different temperatures as shown in the table 3.1. The individual compressive strength is determined by subjecting it to compression, using hydraulic testing machine. At room temperature the average compressive strength of two cube specimens is determined, the values can be seen in table 3.1 and appendix 1.

2.1.2. Modulus of elasticity

In this case, Alfes [1992] hypothesis is considered with the expression:
$E_c = 0.2w^{1.09}f_{cu}^{0.84}$ at 28 days.
Where,
E_c – Modulus of Elasticity [N/mm^2].
f_{cu} – Concrete Strength [N/mm^2]
w - Unit weight of concrete [kg/m^3]

The modulus of elasticity is measured in relation to the unit weight and concrete strength. These parameters are employed because deformation is very small.

2.1.3. Permeability and durability

Darcy's formula for falling head:

$$K = \frac{\left[\frac{d_b}{D_s}\right]^2 \times L \times \log \frac{H_1}{H_2}}{t}$$

Where,
K – Permeability [mm/s]
d_b – Diameter of burette [mm] = 50mm
D_s – Diameter of specimens [mm] = 150mm
L - Thickness of specimen [mm] = 150mm
H_1- Initial level of water [ml] = 500ml
H_2 – Final level of water [ml]
t - Time of percolation [sec]

This formula is applied to determine the permeability of the concrete specimens at different temperatures, noting the different degrees of loss of humidity through its weight.

2.2. Analytical method

Compressive strengths in relation to temperatures can be analyzed graphically and mathematically as shown in the Appendix 1 and table 3.1.

2.2.1. Graphical representation

The graphical behaviour of each of these concretes at various temperatures is illustrated and can be seen in Appendix 1.

2.2.2. Mathematical analysis

Compressive Strength-Temperature relationship is expressed by applying the equation of gradient. This gives rise to the following expressions, peculiar to each concrete grade with temperatures between 500^0C and 1000^0C. The values are thus:

[x, y] and x_2, y_2]

[500, 23] and [1000, 5]

Equation of gradient:

$$y = mx + c$$

where,

$y = \sigma$ - Compressive strength [N/mm2]

$x = T$ – Temperature [^{0}C]

c - Constant

Thus,

$$\sigma = mT + c$$

3. Results and discussion

After attaining the curing age of 90 days, the concrete specimens were subjected to heating in a regulated industrial oven at temperatures varying between 250^0C and 1000^0C. At intervals of 250^0C, the physical appearances of some of these concretes were studied.

Below 500^0C, the colours of all the concretes are still the same both externally and internally, as observed when the concrete cubes were crushed. This implies that the cement paste-aggregate bond does not suffer much stress even when the cube is restrained and it is relatively intact within that temperature range.

Micro cracks are not visible with the ordinary eyes, if they existed, they could not be above 0.01mm in size.

Slight reductions in weights are noticed as a result of loss of water from concrete.

Between 500^0C and 750^0C, the colour of the concrete changes from light sea green to dirty white, forming flakes around it.

Few micro cracks are seen on the concrete specimens which dimensions are between 0.01- 0.1mm.

Expulsion of water due to heating reduces their weights, while the dislocation of cement paste-aggregate bond due to excessive heating, increase the volume of specimen. The colour of the granite chippings turns light brown.

Between 750^0C and 1000^0C, in addition to a change in colour to dirty cream, crumbs form due to large cracks and the coarse aggregate completely turns dark brown. The weights reduce by 2.3% of its original weight. In this case, the cement paste-aggregate bond has suffered much stress while restrained and thus become loosely packed, crumbling at the slightest pressure. [Zoldners, 1960] reported on the effects of high temperature concrete applying different aggregates.

Table 3.1

Fire test results of concrete grades 20, 25 and 30 at 90 days. Compressive strengths (N/mm^2)

Mix proportion ratio	*Water/Cement Ratio*	*Room Temp. 27.5°C*	*At 250⁰C*	*At 500⁰C*	*At 750⁰C*	*At 1000⁰C*
1:2:4	0.62	[1&2] 23.30	[3] 24.0	[4] 22.67	[5] 13.0	[6] 5.0
1:11/2:3	0.62	[7&8] 22.0	[9] 22.67	[10] 20.0	[11] 11.0	[12] 4.0
1:1:2	0.62	[14] 28.50	[15] 26.67	[16] 24.0	[17] 13.0	[18] 4.0

The equation of a gradient is applied considering the values of the compressive strength with respect to temperature, between 500^0C and 1000^0C. Therefore, the following expressions hold for concrete grades 20, 25 and 30. From table 3.1, the number of specimens is in bracket.

For $500 \geq T \leq 1000^0C$

$$\boxed{\sigma = -0.036T + c;\ \text{where } c=41 \quad C_{20}\text{[Concrete grade 20]}}$$

$$\boxed{\sigma = -0.032T + c;\ \text{where } c=36 \quad C_{25}\text{[Concrete grade 25]}}$$

$$\boxed{\sigma = -0.04T + c;\ \text{where } c=44 \quad C_{30}\text{[Concrete grade 30]}}$$

Table 3.2
Modulus of elasticity of concrete cubes(N/mm^2)

	Room Temp. 27.5^{0}C				*At 250^{0}C*		*At 500^{0}C*		*At 750^{0}C*		*At 1000^{0}C*	
Mix proportion	Design	Ratio	Acquired	Ratio	Acquired	Ratio	Acquired	Ratio	Acquired	Ratio	Acquired	Ratio
1:2:4	$1.22x10^4$	1.0	[19] $1.38x10^4$	1.12	[20] $1.31x10^4$	1.06	[21] $1.34x10^4$	1.10	[22] $8.25x10^3$	0.67	[23] $3.18x10^3$	0.26
1:11/2:3	$1.48x10^4$	1.0	[24] $1.30x10^4$	0.88	[25] $1.23x10^4$	0.83	[26] $1.23x10^4$	0.83	[27] $6.74x10^3$	0.46	[28] $1.90x10^3$	0.13
1:1:2	$1.73x10^4$	1.0	[29] $1.50x10^4$	0.87	[30] $1.45x10^4$	0.84	[31] $1.37x10^4$	0.79	[32] $7.50x10^3$	0.43	[33] $2.27x10^3$	0.13

From table 3.2, it is observed that up to the temperature of 500^{0}C the values of the modulus of elasticity are between 1.0 -1.30 $x10^4$ N/mm^2 and above [Neville,1990] and are therefore within the acceptable values, while above 500^{0}C , the modulus of elasticity has gone below the acceptable range of values. Reports by Harada et al.[1990] revealed further on this. Appendices IIa – IIc show the graphical representations of the above indices.

Table 3.3
Permeability of concrete at different temperature after 90 days

Mix proportion	*K[mm/s] At room temp.*	*Final weight Initial Weight [Kg]*	*K[mm/s] At 250^{0}C*	*Final weight Initial Weight [Kg]*	*K[mm/s] At 500^{0}C*	*Final weight Initial Weight [K g]*	*K[mm/s] At 750^{0}C*	*Final weight Initial Weight [K g]*	*K[mm/s] At 1000^{0}C*	*Final weight Initial Weight [K g]*
1:2:4	[34] $1.12x10^{-4}$	8.20 8,20	[35] $1.77x10^{-4}$	8.11 8.30	[36] $1.60x10^{-3}$	7.04 8.20	[37] $6.30x10^{-2}$	7.04 8.50	[38] $3.89x10^{-2}$	6.50 8.20
1:11/2:3	[39] $8.35x10^{-5}$	8.50 8.50	[40] $1.41x10^{-4}$	8.16 8.50	[41] $1.50x10^{-3}$	7.86 8.40	[42] $7.72x10^{-2}$	7.50 8.40	[43] $3.0x10^{-2}$	6.80 8.40
1:1:2	[44] $5.54x10^{-5}$	8.50 8.50	[45] $1.05x10^{-4}$	8.04 8.60	[46] $1.20x10^{-3}$	8.10 8.60	[47] $6.62x10^{-2}$	7.44 8.60	[48] $2.44x10^{-2}$	7.23 8.50

Table 3.3 shows that, from room temperature to 250^{0}C, concrete grade 20 has its permeability values increasing from 1.12 – $1.77x10^{-4}$mm/s which fall below the acceptable range of values and are still fairly impermeable, while above 500^{0}C, the permeability is increased beyond $1.0x10^{-3}$ mm/s and has become porous. The specimens are numbered, as can be seen in the brackets

Similarly, concrete grades 25 and 30 increase in permeability hence their values move from $8.35x10^{-5}$to $1.50x10^{-4}$ mm/s as they are heated up to 500^{0}C, but they deteriorate even faster at temperatures above 500^{0}C, increasing beyond the acceptable value of $1.0x10^{-3}$ mm/s,[Neville and Brook, 1992].

Below 500^{0}C, as shown in the table 3.1, the compressive strengths of these concretes do not drop below 10% of their design strengths. [This can also be seen in Appendix I].

On the other hand, above 500^{0}C the gradients of their compressive strengths with respect to the increase in temperature are between 0.03-0.035.

At 1000^{0}C , all the concrete specimens are no more of structural importance, as the compressive strengths have fallen below 5.0N/mm^2.

Through heating, the expulsion of water contributes to the relaxation of cement paste aggregate bond, which gives rise to a progressive decrease of modulus of elasticity. This characteristic feature of concrete is directly proportional to its compressive strength. Concrete grade 20 at 500^{0}C, has a higher modulus of elasticity owing to its volume of aggregates, which is more than the volume of aggregates in other mixes. Above 500^{0}C, the chemical compositions of cement are rendered inert and this affects the cement paste aggregate bond in all the mixes. [Castillo and Durani, 1990] researched into the effect of transient high temperature using high strength concrete.

Even though, concrete grade 20 has a higher permeability rate when compared to concrete grades 25 and 30, it yields more slowly to heat than the others. Below 250^0C the ratios of deterioration in permeability in relation to temperature are 1.6, 1.7 and 1.9, respectively, with the values ranging between $1.0x10^{-3}$ – $1.0x10^{-4}$mm/s [Neville and Brook, 1992].

The durability of these concretes is dependent on their permeability rates that could protect them from external agents, especially when they are impervious.

The ingress of moisture and air will result in the corrosion of steel, cracking and spalling may well follow. It is observed that the increase in temperature resulted in the internal gradient of moisture and the osmotic pressure in the cube specimens. [Cagregra et al. 1989] reported on permeability and durability in their research works.

4. Conclusion/recommendation

Much of this paper has been devoted to the problems encountered presently by fire out-breaks on buildings of structural importance, [Shopping Malls, Airports, Residential buildings, Warehouses, Office buildings etc.] in this country.

Since concrete grades 20, 25 and 30 are the conventional concretes, quite often used in construction industry, whereby structural elements which are designed to carry loads are therefore made from these concretes.

At 250^0C properties of these concretes still remain intact. Although, concrete does not obey Hooke's law, its characteristics curve [stress-strain curve] is continuous without distinctive sections of separation as in steel and other materials. The introduction of micro-cracks, loss of weight and increase in osmotic pressure, point to the fact that it may have attained its elastic limit, [Mocanu, 1980]. These features become noticeable above 500^0C, strain energy resulting from either sudden or impact loading on the structural elements can cause a permanent deformation /damage or collapse having entered into the plastic region.

From the foregoing therefore, between 250^0C and 500^0C reconstruction/maintenance of the affected elements is advised. Above 500^0C it is advised that total demolition should be undertaken, if strategically located elements are affected. The most resistant concrete to fire amongst the three conventional concrete is concrete grade 20.

It is therefore recommended that concrete grade 20 should be employed in building houses, airports, markets and other structures posited on dry lands which are vulnerable to fire disaster. Other fire resistant construction materials that can be used are engineering bricks, which strength increase, even as temperature rises to as much as 2000^0C, and laminated glasses.

The researcher chose a crime free route to treat this problem because, if he had chosen to deal with a real structure on ground, he would have been in detention awaiting trial for arson by now, and his proposal to publish this article would have been null and void. There is actually no difference between the concrete specimens prepared and those used in construction works. This research application is therefore used to simulate the real situation on ground.

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