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Effect of spalling on normal strength concrete (NSC) at transient high temperature.

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Abstract

Investigation is carried out on the behaviour of some normal strength concrete (NSC) grades 20, 25 and 30, having heated up the specimens in a regulated industrial oven from room temperature of about 28^0C to 1000^0C. The effect of heat flow induces various kinds of stresses that move at cross-lines generating strains and deformation that give rise to the phenomenon referred to as spalling. This is an irreversible destructive or deformable plastic state of concretes. This paper has established that spalling in normal strength concrete (NSC) takes place between 650^0C and 800^0C with concrete grade 20 exhibiting higher resistance to spalling than the other concrete grades. However, concrete grade 30 has the tendency of having explosive spalling due to its range of conflicts of stresses involved, which is shorter than the rest, as can be seen in the graphical representations. The result therefore, is that concrete grade 20 has smaller flexural cracks and deflections at transient high temperature compared to other concretes.

Introduction

Indeed, high temperatures have devastating effects on concretes, as they in no small measure progressively affect their strengths, the remnants of which constitutes the residual strengths, having suffered substantial thermal stresses (Nwokike V.M., Onyeyili I.O., 2004). These residual strengths of concretes have values less than or equal to the original strengths, depending on the intensity of heat and the period of impact on them.

The static system is disrupted as a result, especially when the original strengths of the structural members which are load bearing have reduced, they loose stability. The features that might have preceded such instability or collapse are cracks and deformation, as a result of the increased osmotic pressure which has direct consequence of increased thermal stresses and strains. These members tend to enter into the plastic stage, either gradually or spontaneously.

Concrete grades 25 and 30 are generally recommended in Nigeria for use in the construction of water retaining structures, bridges etc., because of their high strengths and impervious property, while concrete grade 20 is used in the execution of structures on dry land. Once these concretes are attacked by fire they exhibit similar behavior of reduction in strengths but have different magnitudes. This is largely due to the different composition of materials of construction and the bonded surface. At a high temperature of about 1000^0C, spalling is bound to have taken place and at this juncture that damage caused is irreversible.

Spalling is the phenomenon whereby pieces of the hardened concrete surface exposed to fire, break away explosively or fall off during the course of rapid high temperature exposure. Observations from fire tests on concrete specimens indicate that spalling ranges progressively, where minor pieces are dislodged and there is gradual reduction in cross-section, while in explosion, test specimens are suddenly disintegrated into fine fragments, accompanied by a sharp loud bang and the release of sufficient amount of energy which disperses the broken fragments in all directions at high velocity.

2.0 Materials and methods

Over eighteen specimens of the chosen concrete grades with dimension 150 x 150mm x 300mm are investigated. Granite chippings which dimensions are 20mm diameter are used in the mix, with water/cement ratio of 0.6. The specimens are cured in a pooling tank for ninety days, so that they could exhibit long term property devoid of micro-cracks and ensuring that proper hydration has taken place.

The ratios of the coarse aggregate and cement paste to the concretes are calculated, while the volumes of the concrete specimens remain constant.

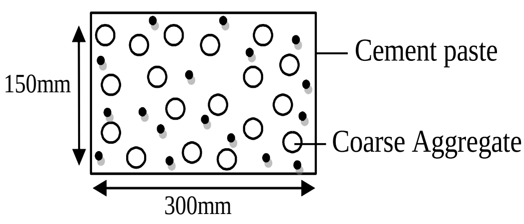
Based on the ratios of the coarse aggregate and cement paste earlier calculated, their accumulated heights are known, as can be seen in the idealized specimen.

In practice, at room temperature, it should be assumed that the properties of concrete are intact and therefore temperature or thermal stress is zero, at this juncture the residual strength is equal to the normal strength.

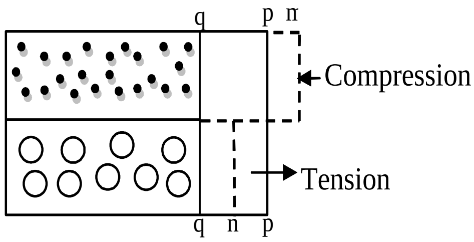
2.1 Numerical Simulation
(Thermal behavior modeling)
Some data are lifted from Mocanu, 1980 and Neville 1975. They are as follows:

$\propto_{aggr} = 5.3 \times 10^{-6}/^0C$
$E_{aggr} = 4.5 \times 10^4 N/mm^2$
$\propto_{cp} = 11 \times 10^{-6}/^0C$
$E_{cp} = 4.5 \times 10^3 N/mm^2$

$\propto_{aggr}$, $\propto_{cp}$. - Coefficients of thermal expansion of coarse aggregate and cement paste respectively.
$E_{aggr.}$, E_{cp} - Modulus of Elasticity for aggregate and cement paste, respectively.
$E_{cp} = E_c$ - is derived using Alfes (1992) hypothetical formula
E_c - Elastic Modulus in N/mm^2
w - Unit weight of concrete in kg/m^3 ($2459kg/m^3$)
f_{cu} - Concrete cube strength in N/mm^2



Concrete



Idealized Concrete Specimen

These specimens are heated up to 1000^0C at intervals of 100^0C, based on the differences in properties as enumerated above, their responses to heat are different, if they are allowed to expand freely along the horizontal axis.

As $\propto_{cp}$ is greater than $\propto_{aggr.}$, therefore the extension of cement paste will be more than the aggregate, but since they are bonded together the former will try to pull the latter, while the latter will try to push the former; finally, however they will become stable at a certain position pp after compromise (Rajput, R.K., 2006) who expressed this with metallic alloys and other materials.

Increase in length of cement paste in mm;

$qm = \propto_{cp} (t_2 - t_1)L$ Eq. 1

t_1 – room temperature in ^0C
t_2 – new temperature in ^0C
L – length of specimen in mm

Increase in length of aggregate in mm;

$qn = \propto_{aggr.}(t_2 - t_1) L$ Eq.2

qp - restrained extension of cement paste due to bonded aggregate (compression induced) or extension of aggregate due to bonded cement paste (tension induced) in mm.
pp - Compromised position of cement paste and aggregate.
Then,

Compressive, strain in cement paste;

$\varepsilon_{cp} = \frac{pm}{L} = \frac{qm - qp}{L} = \frac{qm}{L} - \frac{qp}{L}$

$= \propto_{cp} (t_2 - t_1) - \varepsilon$ Eq.3

Where, $\frac{qp}{L} = \varepsilon$- common strain (concrete strain)

Tensile strain in aggregate

$\varepsilon_{aggr} = \frac{np}{L} = \frac{qp}{L} - \frac{qn}{L}$

$= \varepsilon - \propto_{aggr} (t_2 - t_1)$ Eq.4

Adding Eqs.(3) and (4) we get

$\varepsilon_{cp} - \varepsilon_{aggr} = \propto_{cp} (t_2 - t_1) - \propto_{aggr} (t_2 - t_1)$
$= (\propto_{cp} - \propto_{aggr}) (t_2 - t_1)$ Eq.5

But, $\varepsilon_{cp} = \frac{\sigma_{cp}}{E_{cp}}$; $\varepsilon_{aggr} = \frac{\sigma_{aggr.}}{E_{aggr.}}$ Eq.6

or $\sigma_{cp} + \sigma_{aggr.} = (\propto_{cp} - \propto_{aggr}) (t_2 - t_1)$

Shear force = $\sigma_{aggr} \times A_{aggr} = \sigma_{cp} \times A_{cp}$ Eq.7

Shear Stress = $\frac{\text{Shear Force}}{\text{Shear Area}}$ Eq.8

σ_{cp} - Stress in concrete paste in N/mm^2
σ_{aggr} - Stress in aggregate in N/mm^2
A_{aggr} - Shear Area of aggregate in N/mm^2
A_{cp} - Shear Area of cement paste in N/mm^2

The average concrete thermal stress is obtained by dividing the sum of the thermal stresses on cement paste and coarse aggregate by two.

THEORETICAL

	Thermal stresses, $\sigma_{t.th}$ (N/mm^2)										
	Room temp (28^{0}C)	100^{0}C	200^{0}C	300^{0}C	400^{0}C	500^{0}C	600^{0}C	700^{0}C	800^{0}C	900^{0}C	1000^{0}C
1;2;4	0	1.50	3.58	5.67	7.75	9.23	11.91	13.99	16.08	18.16	20.23
1;1½;3	0	1.56	3.73	5.89	8.06	10.23	12.40	14.56	16.72	18.89	21.05
1;1;2	0	1.68	4.01	6.34	8.67	11.00	13.34	15.67	18.00	20.33	22.67

EXPERIMENTAL

	Normal/Residual Compressive Strength, $\sigma_{r.compr.}$ (N/mm^2)										
	Room temp (28^{0}C)	100^{0}C	200^{0}C	300^{0}C	400^{0}C	500^{0}C	600^{0}C	700^{0}C	800^{0}C	900^{0}C	1000^{0}C
1;2;4	23.65	23.65	22.65	23.25	23.00	22.67	19.25	15.20	11.00	8.00	5.00
1;1½;3	22.34	22.34	22.34	21.85	21.00	20.00	17.00	12.50	9.10	6.50	4.00
1;1;2	28.50	27.50	27.00	26.00	25.00	24.00	20.00	16.00	10.90	7.00	4.00

EXPERIMENTAL

	Expended Strength $\sigma_{r.th.}$ (N/mm^2)										
	Room temp (28^{0}c)	100^{0}C	200^{0}C	300^{0}C	400^{0}C	500^{0}C	600^{0}C	700^{0}C	800^{0}C	900^{0}C	1000^{0}C
1;2;4	0	0	0	0.40	0.65	0.98	4.40	8.45	12.65	15.65	18.65
1;1½;3	0	0	0	0.49	1.34	2.34	5.34	9.84	13.24	15.84	18.34
1;1;2	0	1.0	1.50	2.50	3.50	4.50	8.50	12.50	17.60	21.50	24.50

$\sigma_{t.th}$ - Theoretical thermal stress in N/mm^2
$\sigma_{r.th}$ - Real thermal stress in N/mm^2
$\sigma_{r.compr}$ - Residual compressive strength in N/mm^2

DISCUSSIONS AND RESULTS

From the experimental analysis carried out, it shows that the residual compressive strengths and the expended strengths of the concrete move in the opposite directions as can be seen in the tables and graphs. The gradients of which are below 0.1 between temperatures of 28^{0}C and 300^{0}C. Beyond 500^{0}C the gradients increase steeply. The observation therefore, is that there can not be spalling effect, unless there is a balance between the compressive strength, ($\sigma_{r\cdot compr\cdot}$), which is a stress parameter and the theoretical thermal stress ($\sigma_{t.th.}$), and or the real thermal stress ($\sigma_{r\cdot th,}$) which is directly proportional to the expended strength. The expended strength is also another stress parameter. The points whereby the latter stresses intersect with the residual strength form the spalling region.

The gradients are maximum in the following normal strength concretes (NSC):-

Concrete grade 20: between 720^{0}C - 780^{0}C
Concrete grade 25: between 670^{0}C - 740^{0}C
Concrete grade 30: between 705^{0}C - 730^{0}C

Averagely, it means that spalling in Normal Strength Concretes takes place between 650^{0}C - 800^{0}C. This is a clear indication that spalling takes place at higher temperatures in Normal Strength Concrete (NSC) than in High Strength Concrete (HSC) which is induced between 300^{0}C - 600^{0}C, as ascertained by (Phan et al, 2001). Explosive spalling was not experienced in the specimens, but there is the tendency that concrete grade 30 can be affected by explosive spalling, having recorded a maximum gradient of 0.05 N/mm^2/^{0}C, while concrete grade 20 has 0.046N/mm^2/^{0}C. Since, it has been propounded in earlier research work Nwokike et al., (2004) that concrete compressive strengths fall to as low as 4N/mm^2. In summary though, spalling is an important phenomenon in the construction industry, it could be observed that these normal strength concretes tested had their strengths reduced drastically at the spalling stages and therefore it is not advisable to profer any remedial measures on the concrete structure, since they have lost half of their strengths in the process. Research works on spalling have been carried out by Harmathy, 1993; Crozier and Sanjayan, 2000 on concrete walls. Quite recently, Ongah and Mendis 2006 researched further into the fire performance of high strength reinforced concrete walls.

The researches carried out on High Strength Concrete (HSC) on spalling effect indicate that this type of concrete having been encumbered by this phenomenon, can be reversible at the range of temperatures earlier stipulated. Normal Strength Concrete (NSC) are not reversible at spalling stages highlighted in this paper. However, it is clearly known from the experimental and theoretical exercises on Normal Strength Concrete (NSC) conventionally used in Nigeria, concrete grade 20 (1:2:4mix) has a smaller deflection and flexural cracks compared to the other concrete grades studied in this research.

Conclusion

Concrete grade 20(1:2:4 mix) has actually exhibited higher resistance to transient high temperatures compared to the other concretes. In that case flexural cracks and deflections are hardly noticed in concrete grade 20 at high temperature. This is a reaffirmation of the fact that concrete grade 20 should be used to construct structures vulnerable to fire disasters.

Note: This is an opportunity to suggest that High Strength Concretes (HSC) having encouraging characteristic in spalling should be used in executing structures in the industry in Nigeria, because of the advantages derivable from them.

Spalling also can affect concretes through the rain and ground water, over time due to their chemical compositions. Therefore, structures exposed to such a problem pose a great danger to public lives and property.

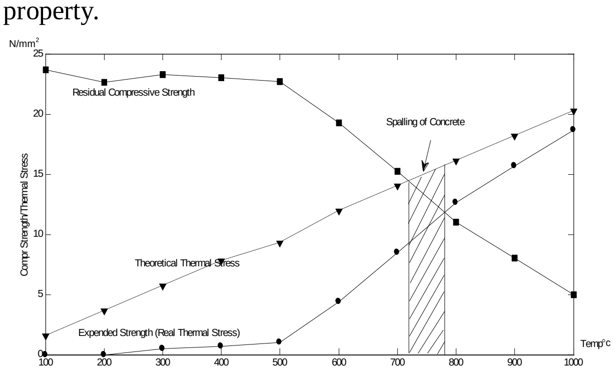


Fig 1:Spalling Effect on 1:2:4 mix

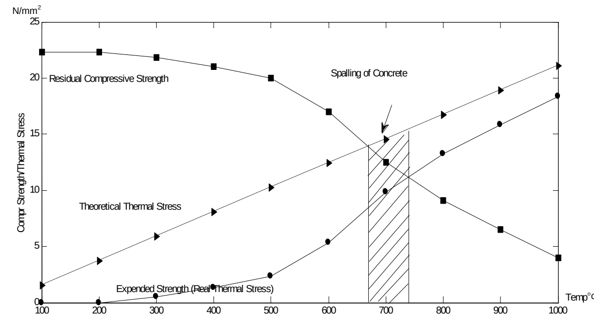


Fig 2:Spalling Effect on 1:1 1/2:3 mix

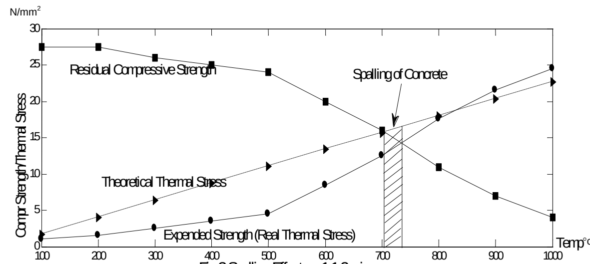


Fig 3:Spalling Effect on 1:1:2 mix

REFERENCES

Alfes, C. 1992. Modulus of Elasticity and Drying Shrinkage of high strength concrete containing Silica fume, Fly Ash Slag and Natural Pozzolans in concrete, Proceeding of Sheffield, Ed by R.N. Swamy; Elsevier Applied Science London pp.293 -301.

Crozier, D.A & Sanjayan, J.G. 2000. Tests of Load-Bearing Slender Reinforced Concrete Walls in Fire ACI Structural Journal 97(2): 243-251.

Hamathy, T.Z. 1993. Fire Safety Design and Concrete UK: Longman Group UK Limited.

Mocanu, D.R. 1980. Resistanta Materialelor Editura Technica, Bucharest pp.23-53.

Neveille, A.M., 1975 Properties of Concrete Romanian Translation pp.357-366.

Nwokike V.M., and I.O Onyeyili, 2004. Thermal Properties of Concrete at High Temperature M.Sc. Thesis Nnamdi Azikiwe University, Awka.

Rajput, R.K. 2006. Strength of Materials pp. 55-90