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A Study on Behaviour of Normal Strength Concrete and High Strength Concrete Subjected to Elevated Temperatures

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***Abstract*—**Cement concrete is a complex mixture of different materials. Behaviour of concrete depends on its mix proportions and constituents when it is subjected to elevated temperatures. Principal effects due to elevated temperatures are loss in compressive strength, loss in weight or mass, change in colour and spall of concrete. The experimental results of normal concrete and high strength concrete subjected elevated temperatures at 200°C, 400°C, 600°C, and 800°C and different cooling regimes viz. air cooling, water quenching on different grade of concrete are reported in this paper.

***Keywords*—**High strength concrete, Normal strength concrete, Elevated Temperature, Loss of mass.

I. Introduction

CEMENT concrete is widely used as structural material in building construction where fire resistance is one of the key considerations in design. Concrete is nonhomogeneous material and its fire performance is controlled by its constituent materials such as aggregate, cement paste and other ingredients. High strength concrete has a compressive strength generally greater than 60Mpa. The variation of compressive strength in the high strength concrete with temperature is influenced by a number of factors like method of testing i.e., the rate of heating, the exposure duration, the size and shape of the test specimen and the loaded condition etc. [1] The technical literature specifies three methods to assess the strength of concrete at elevated temperatures, viz., stressed tests, unstressed tests and unstressed residual strength test. In the stressed tests, a preload is applied to the specimens prior to heating and is sustained during the heating period. Once the specimen reaches its targeted heated temperature, load/strain is increased until failure of the specimen. In the unstressed tests, the specimen is heated, without preload, until the desired temperature is reached and maintained while the specimen is being tested to failure. In the unstressed residual strength tests, the specimen is heated, without preload, to the target temperature and then is allowed to cool, following a prescribed rate, to room temperature. Load/strain is then applied at room temperature till failure of the specimen [2]. In this paper, the unstressed residual strength test was used, since this method was found to give the lowest strength results among the three testing methods and its results are most suitable for assessing the post-fire (or residual) properties of concrete [3]-[5]. Thermal conductivity of concrete is reduced with the loss of moisture during heating. Aggregate type used in a concrete mixture has significant influence on conductivity [6]-[8]. Concrete with lower water- cement ratio as in the case of high strength concrete can be expected to have a lower thermal conductivity than for lean concrete mixtures. It is found that the loss of strength of concrete with high temperature can be attributed to the thermal incompatibility between the cement paste and the aggregates, building of internal-pressure due to the evaporation of water during the heating process, as well as the chemical changes in the cement paste and aggregates [9]-[11].

The changes in the mechanical properties of concrete with high temperature were also related to the rate of heating. When concrete is heated between 100^o and 200^oC, free water evaporates slowly and no structural damage is observed. However, rapid heating rate results in higher vapor pressure and causes cracks in concrete. Concrete starts to undergo loss in compressive strength when heated between 200^o and 250^0C. At temperatures between 300^o and 500^oC, the compressive strength of concrete is reduced to about 15 to 70% of that of non-heated concrete. When heated, the water trapped in concrete starts to evaporate at 300^0C, thus causing dehydration of the chemical compound CSH (calcium silicate hydrate) which is responsible for bonding the different concrete constituents together. The dehydration of CSH crystals results in a decrease in strength of concrete, a process that is not reversible. At 530^oC, $Ca(OH)_2$ turns into CaO resulting in a 33% shrinkage in volume [12]-[18] .

II. Significance of the Work

The present work focuses on study of compressive strength of normal and high strength concrete subjected to elevated temperatures, effect of cooling regime on high strength concrete and normal concrete, and change of hardness of surface at elevated temperatures.

III. Experimental Details

A. Program

The experimental program consists of casting and testing concrete cubes having compressive strength 20Mpa (M20), 40Mpa (M40), and 60Mpa (M60) grades at different temperatures and different cooling regimes. A total number of 120 cubes of 100×100×100 mm size cast with three grades,

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forty specimens each for M20, M40 and M60. Nine specimens were exposed to 200°C for 60 minutes and three specimens for tested immediately at hot state, three specimens were tested after air cooling for one hour and three specimens were tested after quenching in water for one hour. Similar testing was conducted on specimens exposed to 400°C, 600°C, and 800°C. There were four control specimens for each grade.

Fig. 1 Electrical furnace used for the experimental work

B. Materials Used

Cement used in the investigation was 53 Grade ordinary Portland cement confirming to Indian Standard (IS): 12269. Specific gravity of the cement is found to be 3.11. Fine aggregate conforming to zone II of IS: 383 was used. The bulk density, specific gravity of sand used was 1.56g/cc and 2.65 respectively. River sand was obtained in single consignment and sieved as per IS sieves (i.e. 2.36mm, 1.18mm, 600µ, 300µ, and 150µ). Sand retained on each sieve was filled in different bags and stacked separately for use. Coarse aggregate was procured from a local crushing unit having 20mm nominal size. To obtain a well graded aggregate, 85% of coarse aggregate passing through 20mm size and retained on 12.5mm sieve was added to 15% of coarse aggregate passing through 25mm sieve and retained on 20mm sieve. The specific gravity of coarse aggregate obtained is 2.65. Potable water was used in the experimental work for both mixing and curing. Cement: Fine aggregate: Coarse aggregate: Water for M20 grade concrete is 1:1.86:3.14:0.45, and for M40 is 1 : 1.12 : 2.78 : 0.35 and for M60 is 1 : 1.21 : 2.85 : 0.32.

C. Electric Furnace

The specimens were kept for one hour inside the furnace and later three specimens were quenched in water for rapid cooling and other three specimens were kept aside for air cooling and three specimens were tested immediately after taking out from furnace. The electrical furnace used is shown in Fig. 1.

IV. Results and Observations

A. Behaviour

Both Normal and High strength concrete specimens when subjected to elevated temperatures, small surface cracks were observed. The magnitude and extent of cracks were somewhat negligible up to 400°C. Magnitude and extent of cracks increased for both normal and high strength concrete as the temperature increased above 400°C. However, more cracks were noticed in case of high strength concrete compared to normal concrete. At high temperatures of exposure, the sharp edges of the specimen become blunt. Up to 600°C, the failure pattern of concrete cubes was found to be similar to that of control concrete. Colour change of (light pink) surface of the specimen has been observed at 600°C. The concrete after exposure to 800°Cwas found to be red hot and concrete looked slightly pink even after cooling. The change of colour may be due to the desiccation of water from the surface of the concrete specimen as shown in Figs. 2 and 3. The cubes crushed into small pieces under load and explosive spalling was observed at 800°C.

B. Effect of Elevated Temperatures on Grade of Concrete

The compressive strength results of Normal concrete and high strength concrete subjected to different exposure of temperature presented in Table I. The results clearly indicate that there is a reduction in compressive strength with temperatures of exposure. The reduction in compressive strength with temperature occurred for both normal concrete and high strength concrete. The average loss in strength in M20 grade concrete is about 7.4%, 12%, 19.8%, and 43.5% at 200°C, 400°C, 600°C, and 800°C respectively, whereas concrete of M40 grade has shown a percent loss in strength of 13.4%, 26.9%, 45.8%, and 63.8% at 200°C, 400°C, 600°C, and 800°C respectively. In case of HSC the average compressive strength loss is observed to be 18.6%, 30.6%, 50.7%, and 69.3% at 200°C, 400°C, 600°C, and 800°C respectively. In general the high strength concrete (HSC) mixes normally have high paste to aggregate content compared to normal strength. Hence more loss of strength in HSC may be due to occurrence of micro cracking because of thermal incompatibility of hardened cement past and aggregates. In case of M20 grade concrete increase in strength was observed at 400°C, there may be intensifying hydration with temperature to 400°C. This process is similar to the strength increase behaviour normally observed in steam curing.

C. Effect of Cooling Regime on Compressive Strength of Concrete

Specimen were tested at room temperature (<40°C) in three regimes viz., air Cooling, water quenching and hot condition, The compressive strength results presented in Table I reveals that air cooling of specimens resulted in more loss of strength compared to that of water quenching and hot condition. In case of specimens of normal concrete (M20) subjected to 600°C the percent loss in strength observed to be 14.4%, 17.6%, and 27.2% for the cooling regime water quenching, air cooling and hot state respectively. In case of normal concrete (M40) subjected to 600°C the percent loss in strength observed to be 29.6%, 45.6%, and 62.2% for the cooling regime hot state, water quenching and air cooling respectively. In case of High strength concrete (M60) subjected to 600°C the percent loss in strength observed to be 46.8%, 49%, 56.2% for the cooling regime hot state, water quenching and air cooling respectively. However again at high temperatures of exposure the difference in percent loss in strength between different cooling regime reduces, for example for M40 grade subjected to 800°C has shown percent strength loss to be 62.2%, 68.5%, and 71.2% for the cooling regime hot state, water quenching and air cooling respectively, in case of HSC of M60 grade subjected to 800°C loss of strength obtained as 63.8%, 68.7%, and 75.4% for the cooling regime hot state, water quenching and air cooling respectively.

D. Effect of Elevated Temperature on Hardness of the Surface of the Concrete

In general the surface hardness as represented by the rebound number value in nondestructive test indirectly represents the likely spalling or loosening of surface of concrete. The rebound number values are presented in Table II. An observation of the results indicates that the rebound number values have decreased with elevated temperatures for both normal and high strength concrete. This gives an indication that there may be increased risk of spalling in concretes with elevated temperature. The hardness of surface as indicated by the rebound number was low for concrete specimens at hot condition; however there is an increase of rebound number of the concretes tested after water quenching and air cooling. This means water quenching and air cooling resulted in increase of surface hardness.

E. Loss in Mass after Exposure to Elevated Temperatures

The percent loss of mass values is presented in Table III. The mass of the concrete cube before and after exposure to different cooling regimes at elevated temperatures were taken for mass loss evaluation. As the temperature increases, continuous increase in weight loss is observed. The air cooling and hot condition resulted in more percent loss of mass value compared to water quenching. In case of normal concrete (M20) subjected to 800°C, the percent loss in mass observed to be 3.3%, 3.8%, and 4.2% for the cooling regime water quenching, air cooling and hot state respectively. In case of normal concrete (M40) subjected to 800°C the percent loss in mass observed to be 3.6%, 4.5%, and 5.2% for the cooling regime water quenching, air cooling and hot state respectively. In case of high strength concrete (M60) subjected to 800°C the percent loss in mass observed to be 4.4%, 4.2%, and 5.3% for the cooling regime water quenching, air cooling and hot state respectively. In general percentage Loss in mass with elevated temperatures up to 400°C was observed to be 59% of total weight and remaining 41% weight is loss during rise up to 800°C.

Fig. 2 Concrete specimens subjected to 400°C and 600°C

Fig. 3 Concrete specimens subjected to 800°C

TABLE I
COMPRESSIVE STRENGTH OF CONCRETE SPECIMEN IN N/SQMM AND PERCENTAGE LOSS OF STRENGTH IS GIVEN IN BRACKETS

S No	Temp. °C.	Air cooling			Water quenching			Hot condition		
		M20	M40	M60	M20	M40	M60	M20	M40	M60
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	At room temp	25	48	65	25	48	65	25	48	65
1	200	26 (0)	43 (10.4)	53.45 (17.8)	23.16 (7.4)	40.25 (16.2)	50.6 (22.2)	26.12 (0)	41.6 (13.4)	54.81 (15.7)
2	400	25.33 (0)	29.16 (39.3)	42.12 (35.2)	22 (12)	34.16 (28.9)	45.8 (29.6)	25 (0)	42 (12.5)	47.45 (27)
3	600	20.62 (17.6)	18.15 (62.2)	28.5 (56.2)	21.41 (14.4)	26.12 (45.6)	33.2 (49)	18.21 (27.2)	33.81 (29.6)	34.6 (46.8)
4	800	10.15 (59.4)	13.8 (71.2)	16 (75.4	18.12 (27.6)	15.12 (68.5)	20.4 (68.7)	14.16 (43.4)	18.18 (62.2)	23.61 (63.8)

TABLE II
COMPRESSIVE STRENGTH OF CONCRETE SPECIMEN BY REBOUND HAMMER IN N/SQMM AND PERCENTAGE LOSS OF STRENGTH IS GIVEN IN BRACKETS

S No	Temp. ℃.	Air Cooling			Water Quenching			Hot Condition		
		M20	M40	M60	M20	M40	M60	M20	M40	M60
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	At room temp	22	46	64	22	46	64	22	46	64
2	200	20 (9)	26 (43.5)	42 (34.4)	18 (18)	25 ((45.65)	48 (25)	17 (22.7)	38 (17.4)	46 (28)
3	400	18 (18)	22 (52.2)	28 (56.25)	16 (27.2)	17 (63)	22 (65.6)	17 (22.7)	20 (56.5)	34 (46.9)
4	600	18 (18)	13 (71.7)	11 (82.8)	16 (27.2)	15 (47.69)	13 (79.69)	16 (27.2)	16 (65.2)	12 (81.25)
5	800	13 (40.9)	10 (78.3)	10 (84)	13 (40.9)	10 (78.26)	10 (84)	12 (45.45)	12 ((73.9)	11 ((82.8)

TABLE III
LOSS OF MASS AT HOT CONDITION

Temperature (℃.)	Mass loss under air cooling			Mass loss under water quenching			Mass loss under hot condition		
	M20			M40			M60		
	Before (kgs)	After (kgs)	% loss	Before (kgs)	After (kgs)	% loss	Before (kgs)	After (kgs)	% loss
At room temperature	2.54	2.54	-	2.50	2.50	-	2.50	2.50	-
200	2.48	2.46	0.8	2.50	2.45	2	2.50	2.46	1.6
400	2.48	2.45	1.2	2.51	2.42	3.6	2.49	2.41	3.2
600	2.51	2.41	3.9	2.46	2.34	4.9	2.45	2.33	4.9
800	2.49	2.37	4.2	2.47	2.34	5.2	2.44	2.31	5.3

V. CONCLUSIONS

1. The loss in compressive strength at elevated temperature is more in case of High strength concrete compared to Normal strength concrete.
2. Strength of concrete decreased with increase in temperature. Decrease in compressive strength is more at high temperatures of 800°C.
3. Testing after air cooling of specimens resulted in more loss of strength followed by testing after water quenching and testing at hot condition.
4. The NDT test results indicated more loss of hardness and increased risk of spalling in case of HSC at high temperatures.
5. The hardness of surface is low for the specimen at hot state, followed by the other states i.e. water quenching and air cooling.
6. The mass loss is more up to 400°C. Critical degradation in strength is observed above 400°C.

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