Compressive Strength and Modified Pull-Out Bond Strength between Concrete and Reinforcement at Elevated Temperatures

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Abstract— Concrete is considered one of the most fire resistant and durable material however, exposure to long-time elevated temperature affect the mechanical properties of concrete. This paper focuses on finding the degradation of concrete mechanical properties (compressive strength and modified pull-out bond Strength) at elevated temperatures ranging from 300-900 °C. Two different types of specimens were fabricated for finding the compressive and modified pull-out bond strength. The specimen for compressive strength had diameter of 150mm and height 300mm whereas, for pull-out bond strength tests, the specimens had similar dimensions with steel deformed bar embedded 300 mm inside the specimen and 600 mm outside the specimen. The cylinders were exposed to each elevated temperature i.e. 300 °C, 500 °C, 700 °C and 900 °C for a period of 2-hours in furnace and allowed to cool gradually afterwards. The compressive and pull-out test results indicated that strength loss increases with increase in temperature whereas loss in bond strength is more than the compressive strength loss at each elevated temperature.

Index Terms— concrete, compressive strength, modified pull-out bond strength, elevated temperatures.

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1 INTRODUCTION

Fire is considered a potential risk to reinforced concrete structures and can ignite any moment without the consciousness of the residents. The major causes of fire ignition in buildings are short circuiting of electric appliances, gas leakage from heating appliances, unattended cooking and earthquakes which results in catastrophic fires. The risk of fire ignition cannot be controlled however certain precautions can be taken to mitigate the risk. The concrete members must also satisfy the fire satisfy codes [1],[2] so that the structures does not collapse during fire and allow enough time for the occupants to escape the building.

Concrete is considered an inert material; however, extreme or prolong exposure to elevated temperature may affect the properties and characteristics of concrete. Up to 290 ºC rise in temperature, concrete is unaffected but as the temperature increases beyond 290 ºC, degradation in properties of concrete starts [3]. As the temperature further increases, water evaporation takes place and results in drying of cement paste. Calcium hydroxide ($Ca(OH)_2$) and calcium aluminates ($CaAl_2O_3$) in concrete decomposes which changes color of concrete to pink or reddish at about 590 ºC [4]. The induced thermal stresses may result in spalling of concrete and bond loss between concrete and rebar at around 950 ºC[5],[6]. Concrete is composed of various constituents' i.e. coarse aggregates, fine aggregates and cement. The majority of concrete volume is occupied by coarse aggregates and knowledge about aggregates properties is necessary to know. Two types of aggregates are mainly used in concrete i.e. carbonated and siliceous aggregates.

Materials consisting silica, quartz, granite and sand stone can be classified into siliceous aggregates. The granite, schist, quartzite and sandstone undergoes a phase change at about 600 ºC to 650 ºC, which causes sudden change in volume and spalling of concrete surface takes place. Concrete containing siliceous aggregates strength reduces up to 50% at 550 ºC [7].

Carbonated aggregates such as dolomite and limestone forming concrete are relatively unaffected by temperature up to 600 ºC but as the temperature increases beyond 600 ºC, the strength loss is significant and reduces up to 20% at 800 ºC [7].

In addition to compressive strength of concrete, bond quality between rebar and concrete is the most essential necessity of reinforced concrete (RC). The strength of RC depends on the combine action of concrete and reinforcement steel to externally applied load. Bond strength is actually the resistance provided to tensile forces by concrete to prevent shear failure at the interface between concrete and rebar [8]. In order to activate bond mechanism, slip or relative displacement between rebar and surrounding concrete is required. Tensile stresses perpendicular to the rebar is induced by compressive stresses in the compression struts resulting in the internally inclined bond cracks around the ribs of rebar and are known as Goto-cracks [8]. Circumferential tensile strength of concrete balances the compressive stresses in compression struts. As these compressive stresses surpass the concrete tensile strength, cracking occurs longitudinal to the steel bar [9]. Further increase in pull-out load results in shearing of concrete teeth between the ribs until the total strength of the bond is achieved. Progressive slip may shear off all the teeth and only friction forces will remain in between the contact surface of steel and concrete. The fore mentioned failure type is known as Pull-out bond failure. The failure mode depends upon the bar diameter, rib size, position of the bar, spacing between bars, transverse reinforcement and concrete cover as well. The ratio of clear cover to diameter of rebar indicates the failure type. When ratio is less than 2.3 splitting failure will occur and when greater than 3, pull-out failure will occur whereas c/d_s = 2.3-3 indicates transition zone [10].

Previous research shows that compressive strength of concrete decreases with rise in temperature however; little research is available on bond strength at elevated temperatures. Therefore this study aims to find the compressive and bond strength loss at different elevated temperatures i.e. 300 ºC, 500 ºC, 700 ºC and 900 ºC.

2 EXPERIMENTAL WORK

2.1 Materials

The materials needed for specimens' preparation are coarse aggregates, fine aggregates, type-1 Portland cement and grade-60 rebars of length 900 mm.

2.2 Size Distribution of Aggregate Particles

A collection of sieves arranged according to ASTM standards are introduced with a dry sample of 3000 grams of coarse and 500 grams of fine aggregates. The sieves are shook, until in one minute time no more than 1% of the specimens by weight were passed through the sieves. The sieve analysis was conducted for continuous shaking by means of a mechanical shaker. Table-1 and table-2 demonstrates the data acquired from sieve analysis of fine and coarse aggregates:

TABLE 1
COARSE AGGREGATES SEIVE ANALYSIS

Seive Size (mm)	Retained weight (g)	% Retained (%)	Cumulative % Retained (%)	Cumulative % Passing (%)
25	0	0	0	100
19	517	17.2	17.2	82.7
12.5	1521	50.7	67.9	32.06
9.5	594	19.8	87.7	12.2
4.75	343	11.4	99.1	0.83
Pan	25	0.8	100	0

TABLE 2
FINE AGGREGATES SEIVE ANALYSIS

Seive Size (mm)	Retained weight (g)	% Retained (%)	Cumulative % Retained (%)	Cumulative % Passing (%)
4.75	0.0	0.0	0.0	100
2.36	6	1.2	1.2	98.8
1.18	16	3.2	4.4	95.6
0.6	124	24.8	29.2	70.8
0.3	120	24	53.2	46.8
0.15	194	38.8	92	8
Total	486	F.M	2.3	

2.3 Mix Design of concrete

ACI method of mix design was followed for finding the proportions of concrete to achieve strength of 21 MPa after twenty-eight days of water curing. Sieve analyses of coarse and fine aggregates were performed according to ASTM C136[11], and ASTM C33[12] guidlines. Rodded unit weight of coarse aggregates was found according to ASTM C29[13]. The adsorption and specific gravity tests of coarse and fine aggregates were performed according to ASTM C127[14], ASTM C128[15]. By employing the guidelines of American Concrete Institute (ACI) the proportions obtained for cement, fine and coarse aggregate is 1: 1.96: 3.16 with water/cement ratio as 0.55. Compressive strength tests according to ASTM C39[16] guidelines were performed on concrete cylinders after seven and twenty-eight days of curing for confirmation of the desin ratio.

2.4 Specimens Dimension

Two types of cylinders specimens were chosen for the testing purpose based on the literature review. One type of concrete cylinders for finding the compressive strength, which had height of 300 mm and diameter 150 mm whereas, other type for bond strength, which had same dimension but a rebar of height 900mm was embedded in to cylinder. The grade-60 #4 rebar (12.5 mm diameter) was embedded in the center of cylinder up to 300mm depth and 600mm outside the concrete cylinder. The outside length of 600 mm was the minimum required length to grip the bar in tongs of universal testing machine (UTM) for pull out. The specimens are shown in **figure-1**.

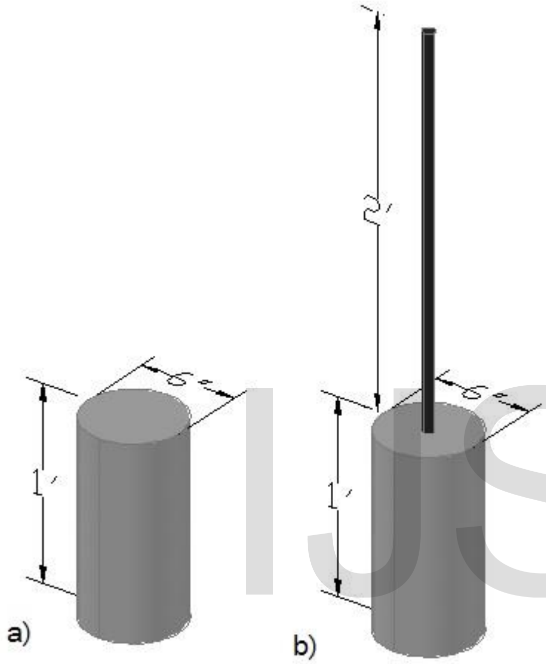

Fig. 1. a) Compressive test specimen b) Pull-out bond test specimen

2.5 Fabrication of cylinders

A total of 30 cylinders were fabricated according to the guidlines of ASTM for the purpose of testing. 15 cylinders were prepared for compressive strength test in which 3 cylinders were reserved as control specimen and the remaining 12 cylinders were burnt at various elevated temperatures. Similarly for pull-out bond strength tests, 15 cylinders were prepared in which 3 were reserved as control specimens and the remaining 12 were exposed to various elevated temperatures. The average value of 3 cylinders was recorded as a test result value. The distribution of cylinders for different temperatures is shown in **table-3**.

TABLE 3
DETAILS OF SPECIMENS TESTED AT DIFFERENT TEMPERATURES

Exposed Fire (ºC)	Compressive strength test samples	Pull-Out Bond Strength test samples
25	3 (Control)	3 (Control)
300	3	3
500	3	3
700	3	3
900	3	3

2.6 Cylinders Exposure to Fire

After the cylinders were cured in water for 28-days, the cylinders were taken out of water tank and allowed to dry out in laboratory condition for 7 days. The cylinders were then exposed to fire in rotatory Kiln available at Pakistan Council of Scientific & Industrial Research (PCSIR) Complex Peshawar in batches of 3 cylinders. Exposure time of cylinders was 2 hours and the time would start after the furnace reached the desired temperature. The furnace temperature was measured through thermal gun and temperature was controlled manually through ball valve supplying the natural gas (methane). The cylinders exposed to fire are shown in **figure-2.**

Fig. 2. a) Rotatory Kiln b) Kiln temperature measured through thermal gun

In case of pull-out specimens' exposure to fire, the unembedded portion of rebar was first coated with 60mm of fire-clay to avoid the steel exposure to fire as shown in **figure- 3**. Fire-clay was chosen because of its low thermal conductivity.

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Fig. 3. Pull-Out specimens coated with fire clay

2.7 Compressive and Pull-Out Bond strength tests

Cylinders after exposure to fire were allowed to cool down in kiln and were taken out of kiln the next day. The cylinders burnt at different temperature were labeled and categorized. The compressive and pull-out bond strength tests were performed on Universal Testing Machine (UTM) available at University of Engineering & Technology (UET) Peshawar. The test setups are visible in **figure-4**.

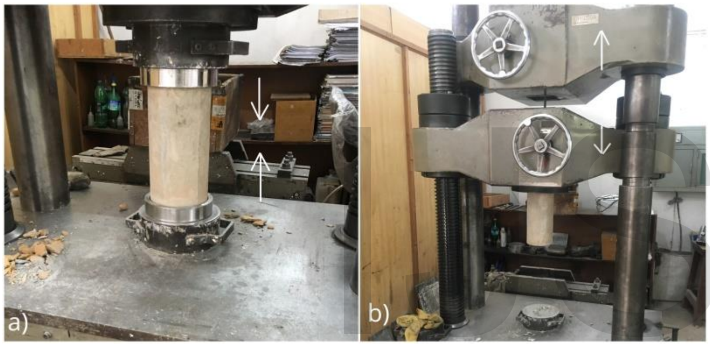

Fig. 4. a) Compression test setup b) Pull-Out bond strength test setup.

3 RESULTS AND DISCUSSIONS

3.1 Fire-Curve

The time-temperature curve for the kiln is recorded by measuring temperature at various time intervals. The fire curve for the kiln followed a similar pattern that of standard fire curve (ISO-834)[17] and ASTM E-119[18] with slight lagging in temperature values. Both the fire curves and their lagging can be viewed in **Figure-5**. The experimental fire curve of the kiln showed a similar response as that of the standard fire curve. However, the experimental curve lags behind the standard curves upon reaching the temperature of about 600 °C. The lagging in the experimental fire rating curve could be caused by the characteristics of fuel.

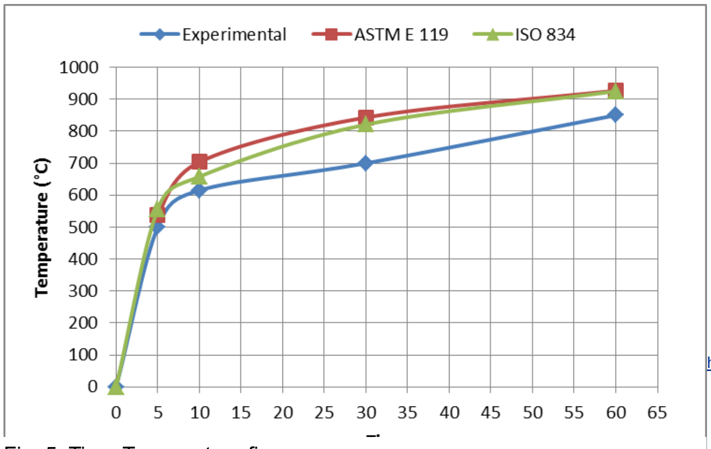

Fig. 5. Time-Temperature fire curves

3.2 Physical Appearance of Cylinders

The concrete cylinders after burning in fire were observed visually and changes in physical appearance were observed.

Cylinders burnt at 300 °C as shown in **figure-6** were having no damages; concrete surface remained intact with no cracks and no spalling. No changes in color were observed. Similar results has been reported by Macgregor[7].

Concrete cylinders burnt at 500 °C (**figure-7)** were having minor damages, hair line cracks appeared over the surface whereas, no spalling was observed. The color of cylinders changed to light reddish or pinkish which is also observed by Gosain et. al[3].

Fig. 6. Cylinders burnt at 300 °C .

Fig. 7. Cylinders burnt at 500 °C.

Fig. 8. Cylinders burnt at 700 °C

fig. 9. Cylinders burnt at 900 °C

Cylinders burnt at 700 °C (**figure-8)** were having significant damages; visible pattern of cracks appeared over the surface with minor spalling of concrete. The color of concrete changed to whitish grey.

The cylinders burnt at extreme temperature 900 °C were severly damaged; most of the concrete spalled of the surface and color of concrete changed to buff-type. The post-fire appearance of cylinders is visible in **figure-9.**

3.3 Post-Fire Compressive and Bond strength

The cylinders after exposure to fire were then tested in UTM for compressive strength and pull-out bond strength. Three cylinders at each temperature were tested and average value of three tests was recorded as a final result value. The compressive and pull-out bond strength was calculated using **equation 1 & 2** respectively.

$$C = \frac{F \ x \ 9806.65}{\frac{\pi D^2}{4}} \quad (1)$$

$$P = \frac{F \ x \ 9806.65}{\pi \ x \ d \ x \ l} \quad (2)$$

Where;
C = Compressive strength in MPa
P = Bond strength in MPa
F = Load or force in tons
D = Diameter of concrete cylinder in mm
d = Diameter of rebar in mm
l = Length of bar embedded in concrete cylinder in mm.

The compressive strength and bond strength values are presented in **table-4&5** respectively.
It can be found from table-3 &4 that the cylinders burned at 300 °C had a compression strength loss of around 14 percent while the pull-out strength decreased by 19.3 percent compred to the control specimen. Various research studies found a compressive strength loss of around 15 percent when concrete cylinders were burned at a temperature of 300 °C. However, Ergun et. al. [19] observed a pull-out force loss of about 30-35 percent. This variance in bond strength values may be due to difference in compressive strength of concrete, bond characteristics, rebar properties and length of the fire-exposure.

TABLE 4
COMPRESSIVE STRENGTH TEST RESULTS

Temperature	**25 °C**	**300 °C**	**500 °C**	**700 °C**	**900 °C**
Specimen 1 (values in tons)	38	36.5	28.1	17.2	11.6
Specimen 2 (Values in tons)	40.2	35	28.8	22.8	7.4
Specimen 3 (Values in tons)	39.7	30.3	27.6	19.1	8.5
Average Values in tons	**39.3**	**33.9**	**28.2**	**19.7**	**9.2**
Compressive Strength (Mpa)	**21.13**	**18.24**	**15.14**	**10.59**	**4.92**

TABLE 5
PULL-OUT BOND STRENGTH TEST RESULTS

Temperature	**25 °C**	**300 °C**	**500 °C**	**700 °C**	**900 °C**
Specimen 1 (values in tons)	7.56	7.1	5.8	2.5	0.44
Specimen 2 (Values in tons)	8.46	5.56	5.7	3.6	0.3
Specimen 3 (Values in tons)	9.32	7.8	5.5	1.4	0.34
Average Values in tons	**8.4**	**6.8**	**5.667**	**2.5**	**0.4**

Pull-Out Bond Strength (Mpa)	**6.81**	**5.5**	**4.57**	**2**	**0.29**

The cylinders tested at 500 °C had a compressive strength loss of about 28 percent while bond strength decreased by 22 percent. Husem[20] also noted equal strength decrease in compression.

From the experimental findings, the compressive strength decreased by 50 percent and the pull-out bond strength decreased by 70 percent at an elevated temperature of 700 °C as shown in table 3 & 4. Several experimental studies[20],[21],[22], [23] found the same pattern in compressive strength decrease at elevated temperature of 700 °C.

At extreme temperature 900 °C, significant strength loss has been observed both in compression and pull-out. The compressive strength reduced to about 25 percent whereas, pull-out bond strength reduced to approximately 5 percent. Theses results are in compliance with husem [20] and botte [24] findings however 5 % higher strength loss has been observed by them.

The compressive and bond strength loss at various elevated temperatures is also presented graphically in **figure-10** where a clear image can be drawn about strength reduction at different temperatures.

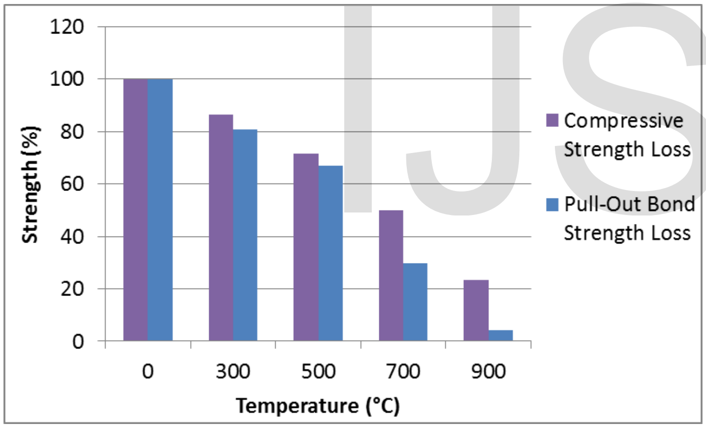

Fig. 10. Compressive and bond strength loss at elevated temperatures

4 CONCLUSIONS

In this experimental study two different types of concret cylinders were fabricated and exposed to various elevated temperatures (300 °C, 500 °C, 700 °C and 900 °C). The objective of this research was to find the compressive strength and bond strength reduction at higher temperatures and also to relate the compressive and bond strength loss at increased temperatures.

Following conclusions has been drawn from this experimental study:

1. The compressive strength and bond strength loss increases as the temperature increases.
2. The bond strength loss is more severe than the compressive strength loss at specific elevated temperature.
3. Concrete burned upto 300 °C are considered undamaged and does not need to worry about however, mechanical properties decreases significantly beyond 300 °C.
4. Concrete burnt upto 900 °C is considered fully damaged and needs to be replaced with new concrete.

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