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Effect of High Temperatures on Ultimate and Post-Ultimate Reserve Shear Strength of Monolithic Concrete Interfaces

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Ultimate shear strength,
Post-ultimate shear strength.

Abstract

An experimental study is performed to assess the effect of high temperatures on ultimate and post-ultimate reserve shear strength of monolithic normal strength concrete interfaces. For this purpose, push-off specimens with constant normal stress across the interface were casted. Specimens were heated to 350, 550 and 750°C in a muffle furnace and were cooled down naturally up to the room temperature. Results showed that after exposure to 350, 550 and 750°C, ultimate shear strength was reduced by 15.9, 25.4 and 44%, respectively. Whereas, post-ultimate reserve strength remains unaffected for an exposure temperature of 350°C. When the specimens were exposed to 550 and 750°C, the reduction in post-ultimate reserve shear strength was found to be 12.4 and 21.7%, respectively.

1.Introduction

Usually, shear forces produce inclined cracking in reinforced concrete members but there are some instances where these forces may produce a sliding failure along a definite plane. Examples of these definite planes are, an existing or a potential crack, an interface between two concretes casted at different times, an interface between two different materials. These planes are called as shear plane or slip plane and their strength is known as interface shear strength. These planes should be designed carefully to ensure that the shear capacity of such interfaces should be greater than or at least equal to the diagonal tension capacity of the adjoining members. This is attained by providing reinforcement, generally perpendicular to the shear plane. Reinforcement crossing the shear plane provides clamping force at the slip plane which restrains the potential sliding of the two faces. To ensure yielding, reinforcement across the shear plane is anchored properly on both the sides. Numerous studies investigated the effect of concrete strength, percentage of reinforcement crossing the interface, presence of recycled aggregate etc. on the interface shear strength of slip planes. A brief overview of these studies is presented below [1, 2].

Anderson (1960) [3] investigated the interface shear strength across construction joints. For this purpose, push-off test with an interface area 64520 mm^2 and a reinforcement ratio between 0.2% and 2.48% across the interface were tested. Concrete compressive strength of the precast portion was 51.71 MPa. Cast-in-place side had a concrete compressive strength of 20.68 MPa or 51.71 MPa. Results showed that as the concrete strength of the cast in-place concrete increases, the interface shear capacity increases. Also, as the reinforcement ratio increases, the interface shear capacity increases. Following equations were proposed for the computation of interface shear strength. For cast-in-place slab with a concrete compressive strength of 20.68 MPa

$$\tau_u = 4.41 + 229\rho \quad (1)$$

For cast-in-place slab with a concrete compressive strength of 51.71 MPa

$$\tau_u = 5.52 + 276\rho \quad (2)$$

Hofbeck et al. (1969)[4] investigated the influence of following parameters on interface shear transfer capacity of reinforced concrete: (i) pre-existing crack on shear plane; (ii) yield strength, diameter and arrangement of shear reinforcement; (iii) concrete compressive strength; and (iv) dowel action. Pre-existing crack on shear planes reduced the shear transfer capacity and increased the slip of the interfaces at all load levels. Interface shear transfer capacity was affected by yield strength, diameter and arrangement of shear reinforcement, only if the clamping stress was changed. Influence of concrete strength was found to be insignificant for the specimens with clamping stress lower than 4.14 MPa. For higher values of clamping stress, interface shear capacity was found to be lower for lower concrete compressive strength. Contribution of dowel action was found to be significant only for the specimens with cracked shear planes. Walraven and Stroband (1994) [5] tested push-off specimens for interface shear transfer up to a concrete strength of 100 MPa and found that increase in concrete strength did not presented an equivalent increase in interface shear transfer strength. It was also found that shear friction equations in the existing codes can still predict a lower bound of interface shear transfer strength. No modifications were suggested in the existing interface shear transfer strength equations. Waseem and Singh (2016) [6] investigated the interface shear strength of concrete with recycled coarse aggregates. Variables of the study were concrete compressive strength, clamping stress and recycled aggregate replacement ratio. A marginal increase in interface shear strength was found when the natural coarse aggregate was replaced by recycled coarse aggregate. Predictions of interface shear strength made by modified Zia envelop were found to be in good agreement for natural as well as recycled aggregate concrete. Sneed et al. (2016) [7] investigated interface shear strength of normal-weight, sanded lightweight and all lightweight concretes with uncracked, pre-cracked and cold jointed specimens with rough and smooth interfaces. Interface shear strength of the monolithic specimens with or without pre-existing crack and cold jointed specimens with roughened interface was found to be increased as the unit weight of concrete was increased. Interface shear strength of cold jointed specimens with smooth interface was found to be independent of the concrete unit weight. Sanded lightweight specimens with monolithic uncracked and pre-cracked interface or cold jointed specimens with rough interface had higher interface shear strengths than that of the specimens made with all lightweight concrete having same interface condition and reinforcement ratio. Interface shear strength of roughened cold jointed specimens made with expanded slate aggregate was found to be higher than that of the specimens made with expanded clay aggregate. Shear strength of cold jointed specimens with smooth interface was found to be unaffected by the type of aggregate.

2. Testing process

2.1. Test specimens and properties

Push-off / shear friction specimen shown in Figure.1, similar to the one tested by Hofbeck et al. (1969) [4], Walraven and Stroband (1994) [5], and Waseem and Singh [6] was used to evaluate the shear transfer strength of concrete at ambient and after elevated temperatures. Dimensions of the specimens used by different researchers are given in Table 1. The terms L, B, and W are shown in Figure 1. The design of shear friction specimen is such that the concentric compressive load applied is converted into shear which is resisted by the stresses produced in concrete and clamping steel bridging the shear plane. Main steel, also known as flexural steel is provided parallel to the shear plane to prevent premature flexural failure of the specimens. 12 no. 12 mm diameter bars were used as the main steel and two closed loops of 8 mm diameter was provided to simulate the clamping stress acting across the shear plane (ρ = 201.06/31250 = 0.0064).

Table 1. Dimensions of push-off/shear friction specimens tested by different researchers

Author (s)	L (mm)	B (mm)	W (mm)	A_c (mm^2)
Hofbeck et al. (1969)[4]	254	127	254	32258
Walraven and Stroband (1994)[5]	300	120	400	36000
Waseem and Singh (2016)[6]	210	150	300	31500
Present study	250	125	125	31250

L = length of the shear plane; B = thickness of the shear plane; W = width of the specimen; A_c = area of the shear plane (L x B)

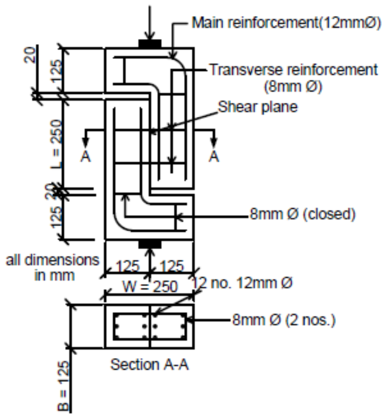

Figure 1. Details of test model

2.2. Concrete mix

Ordinary Portland cement with a minimum 28 days compressive strength of 43 MPa was used. River gravel with 12.5 mm maximum size and having a fineness modulus of 6.88 was used as coarse aggregate. River sand sieved through 4.75 mm mesh with a fineness modulus of 2.80 was used as fine aggregate. A superplasticizer (SP [polycarboxylic acid based]) was also used to attain the adequate workability of the concrete mix. Ingredients of the concrete mix designed through the procedure of IS 10262-2009 [8] are given in Table 2.

Table 2. Ingredients of the concrete mix

Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer (%)
400	825	1004	168	0.2

2.3. Reinforcing steel

Hot-rolled TMT bars were used for preparing the reinforcement cages of the shear friction specimens. Properties of the reinforcing steel are given in Table 3. Clamping stress provided across the shear plane was ρf_y = 0.0064 x 567.2 = 3.63 MPa.

Table 3. Properties of reinforcing steel

Elastic modulus,E (MPa)	Yield strength, f_y (MPa)	Ultimate strength f_u (MPa)	Elongation (%)
2.05×10^{11}	567.2	648	19.3

2.4. Casting and curing of specimens

The experimental program was planned to test the specimens for shear transfer strength at four temperature levels (Ambient, 350, 550 and 750°C). Two companion specimens were casted for each temperature level. Shear-friction specimen with reinforcement cage and during casting are shown in Figure 2. Concrete cylinders were also casted with shear friction specimens to evaluate the compressive strength of concrete used in the casting of the specimens. After 24 hrs of casting, specimens were removed from the moulds and shifted to freshwater tanks for curing.

(a)

(b)

Figure 2. Shear-friction specimen(s) (a) before casting (b) during casting

2.5. Heating of the shear-friction specimens

Specimens to be tested after elevated temperatures were shifted to a muffle furnace for heating. Based on literature review [9-11] and experience of the authors, heating was executed at a rate of 5°C /min to avoid spalling of the concrete. Temperatures of the furnace and different locations inside the specimens were recorded using k-type thermocouples. Supply to the furnace was discontinued soon after the temperature of the furnace and three locations of the specimen became equal and the hole in the furnace wall was opened to cool down the specimens naturally.

2.6. Testing of the specimens

Figure 3 shows the experimental setup used in the present study. Specimens were tested until failure by applying a concentric compressive load on specimens using a universal testing machine. Specimens were kept on roller support and were free to move in a horizontal direction to ensure the application of concentric load on the shear plane. Movement of the two halves of the specimen in the longitudinal and transverse direction was recorded using LVDTs attached on either side of the specimen. Tests were performed in a displacement control mode at a loading rate of 0.0167 mm/s.

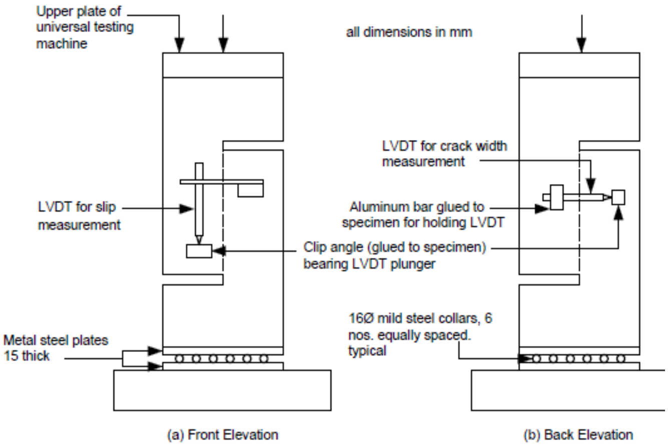

Figure 3. Experimental setup for the determination of shear friction in concrete

3. Results and discussion

3.1. Thermal behaviour of shear friction specimens

Increase of temperature with time in a specimen exposed to 750°C is shown in Figure 4. Ramp input shown by black line is the expected curve resulting from a heating rate of 5°C /min. The red curve is the actual temperature development in the furnace which is not exactly the same as the ramp input curve because of minor leakage through the gap between the furnace wall and the furnace door. Thermal radiation and thermal convection are responsible for the increase of temperature in a furnace which is directly proportional to the temperature difference between the furnace and the specimen. At the beginning of the elevated temperature test, the temperature increased at a slower rate due to a smaller temperature difference between the furnace wall and specimen. Approximately after 60 min, when the temperature difference between the furnace wall and specimen increased, the rate of temperature development also increased. In the last 70 min, the temperature at the three locations inside the specimen increased at a slower rate due to a smaller temperature difference between furnace and specimen.

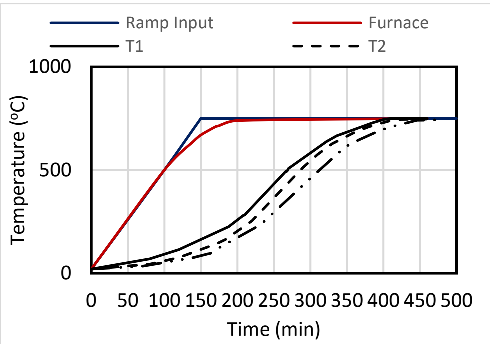

Figure 4. Temperature-Time curve of a specimen exposed to 750°C

3.2. Effect of temperature on shear stress-crack response curves

Relative movement of the shear plane in vertical and horizontal directions is called crack slip (s) and crack width (w), respectively. The ratio of concentrated load to the area of the shear plane is shear stress ($\tau = P/A_c$). Fig.5 shows that in specimens tested at ambient temperature conditions, relative movement of the shear plane in vertical direction started at approximately 60-80% of the ultimate load. In specimens tested after elevated temperatures, the relative movement of the shear plane started earlier than that in the specimens tested at ambient temperature conditions. Increase of temperature results in the reduction of stiffness of shear stress-crack response curves. An increase in exposure temperature also increased the slip corresponding to ultimate shear stress. Moreover, the inclination of the descending branch of shear stress-deformation curves decreases with an increase in exposure temperature. This implies that elevated temperatures produced a smaller and ductile transfer of shear stresses.

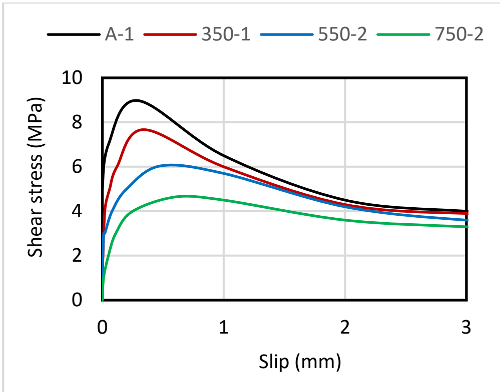

Figure 5. Shear stress-crack slip curves

3.3. Effect of temperature on shear transfer and post ultimate reserve strength

Shear transfer strength or ultimate strength of the interface is defined as the ratio of the ultimate load to the area of shear plane/interface ($\tau_u = P_u/A_c$). While reserve strength of the interface is the ratio of residual load sustained by the shear plane in post peak regime to the area of shear plane($\tau_r = P_r/A_c$). The post ultimate reserve shear strength is the value of stress at larger slips where the shear stress-crack slip curve becomes horizontal (Figure 5). Main results of the test program are given in Table 4.

Table 4. Test results

Specimen	f_c' MPa	P_u kN	τ_u MPa	Avg τ_u MPa	P_r kN	τ_r MPa	Avg τ_r MPa
A-1	42	280.6	8.9	8.67	112.8	3.6	3.64
A-2	42	260.9	8.3		114.3	3.6	
350-1	39	239.6	7.6	7.29	114.1	3.6	3.61
350-2	39	215.6	6.9		111.5	3.5	
550-1	39	215.6	6.9	6.47	98.44	3.1	3.19
550-2	39	188.7	6.0		100.6	3.2	
750-1	40	145.3	4.6	4.85	88.1	2.8	2.85
750-2	40	157.8	5		90	2.8	

Ultimate strength of concrete reduced after experiencing elevated temperatures. For an exposure temperature of 350°C, ultimate strength was reduced by 16%, while post ultimate reserve strength was found to be unaffected. Ultimate strength is a function of concrete compressive strength and the restraint provided across the shear plane. While post ultimate reserve strength is due to the dowel action of reinforcement crossing the shear plane [1, 2]. Up to an exposure temperature of 500°C, the residual compressive strength of concrete reduces while the residual yield strength of reinforcement remains unaffected. Therefore, post ultimate reserve strength was not influenced by an exposure temperature of 350°C. It may also be suggested that for 350°C, reduction in ultimate strength is only due to the reduction in compressive strength of concrete. After an exposure temperature of 550°C, ultimate and post ultimate reserve strengths were reduced by 25.4 and 12.4%, respectively. Ultimate and post ultimate reserve strengths were also found to be reduced by 44 and 21.7%, respectively, when samples were exposed to 750°C. Figure. 6 and 7 shows the variation of relative ultimate strength and relative post ultimate reserve strength of concrete with different exposure temperatures. Relative strength is the ratio of shear strength after elevated temperature to the shear strength at ambient temperature (τ_u^T/τ_u or τ_r^T/τ_r) .

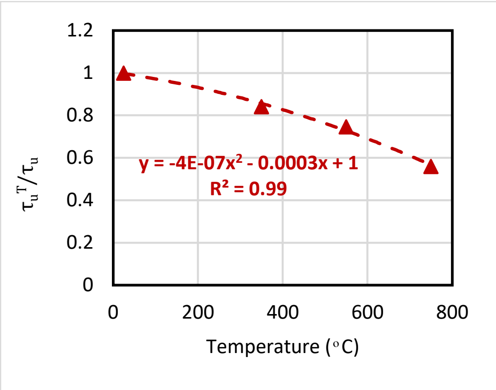

Figure 6. Variation of relative ultimate strength with temperature

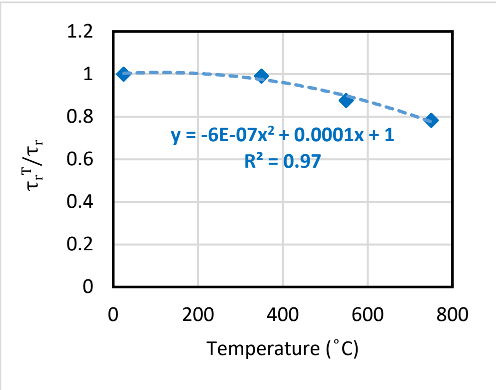

Figure 7. Variation of relative post-ultimate reserve strength with temperature

4. Conclusions

The effect of elevated temperature on ultimate shear strength and post ultimate reserve strength of the monolithic concrete interface have been investigated by conducting push-off tests. Shear stress-crack slip curves indicated that increase of temperature caused lower and ductile shear transfers. It was also found that the exposure temperature increase resulted in the reduction of the ultimate shear strength of the concrete interfaces at all the temperature levels. Reduction in the post-ultimate reserve shear strength was observed only when the yield strength of the clamping steel was reduced i.e., for exposure temperatures higher than 500°C.

Nomenclature

A_c : The area of shear plane
B : The thickness of the shear plane
E : Elastic modulus of steel
f'_c: The compressive strength of concrete
f_u : The ultimate strength of reinforcing steel
f_y : The yield strength of reinforcing steel
L : The length of the shear plane
P_u : Ultimate load
W : The width of the specimen
ρ : The percentage of shear reinforcement
τ_u : The ultimate shear strength
τ_u^T : The ultimate shear strength after temperature, T.
τ_r : The post-ultimate reserve shear strength
τ_r^T : The post-ultimate reserve shear strength after temperature, T.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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