A Comparative Study of Fire Resistance of Concrete Incorporating Ultrafine Slag

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1 Introduction

The inherent fire resistant personality of concrete is advantageous over many other constructional materials; but safety against fire must also be incorporated in the very design of concrete structures. In addition, ensuing stresses owing to the expansion of the structural components because of exposure to fully grown fires and resulting strains should also be resisted. For a safe and sound structure, fire contemplations must be elemental in the conceptualization along with the design-related junctures. This ascent of temperature forces the free water of concrete to convert itself from liquid stage into gaseous stage. Such alterations change the transmission rate of heat from the core concrete section (interior) heading for the periphery (exterior) and vice versa. This amplification in temperature creates a potency drop in context to the elasticity modulus of both concrete and steel. However, the cadence of descent in strength depends upon the stroke of temperature amplification of fire along with the natural insulation traits of concrete. The modification in concrete characteristics because of the elevation in temperature depends upon the sort of aggregates incorporated. Hence, we can say that study of the residual properties of concrete are imperative while assessing the load carrying competence of concrete along with inspecting the supplementary use of the damaged structures in an event of a fire. Prior investigations stand witness to the fact that the type of concrete, its ingredients, the duration and temperature of maximum exposure, mineral admixtures usage, their nature and magnitude of their involvement in concrete chemistry develop the fire endurance

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properties of concrete, exposed to high temperatures. As elevated temperatures are administered within concrete, the incongruities of thermal deformations within the rudiments of concrete instigate cracking. The microstructure change, owing to dehydration and steam pressure, builds-up and accumulates inside the pores. This shift in volume will conclude itself in building up of great internal stresses which shall ultimately lead toward release of accumulated energy via micro-cracks. Elevated temperature additionally spawns numerous chemical and micro-structural changes like the moisture exodus, thermal inaptness of interface between cement paste and aggregate. All such processes will pose a demeanor outcome on the strength and stiffness of concrete.

2 Literature Review

Concrete has been known to be the best fire resistant and economical building material as evaluated with other available building material (Kodur and Raut (2010)). The admirable fire resistance of concrete is owing to its constituents, which upon chemical combination, give birth to a material which is essentially of inert nature and possesses low thermal conductivity with an admirable heat proficiency and slower strength deterioration with rising of temperature. Slow rate of transfer of heat accompanied by delayed loss in strength enables concrete to perform as an efficient fire-shield not only between neighboring spaces but also in providing resistance to fire damage. The behavioral response of a fire-exposed structural member made up of concrete is reliant, upon thermo-mechanical and deformation characteristics of the composition of materials, participating as concrete. With respect to temperature variation, such properties are divergent in nature along with the accountability falling on the composition and characteristics of the individual constituents. A structural member subjected to a pre-determined and definite time interval of fire exposure, shall result in a predictable distribution of temperature within the member. Change in behavioral characteristics along with deformations has always been noticed in the constitutive materials of the structural members when subjected to fires. The modulus of elasticity of concrete is also an important parameter influencing the fire resistance of concrete which falls with elevation in temperature. At elevated temperatures, disintegration of products of cement hydration and bond rupture at the microstructure realm of cement paste diminishes the elastic modulus. The loss of moisture, temperature and the sort of aggregate used, can be held responsible for such a diminution.

2.1 *Transient Strain*

The strain occurring at high temperatures within concrete, when concrete structural members exposed to fire has been found to add to deformations; moreover, strains being generated in the initial phases of heating of concrete is known as transient strain and are not time wise-reliant. Such strains are caused by thermal incompatibilities among aggregate and the cement paste. Transient strain of concrete, is a complex phenomenon analogous to high temperature creep, and is inclined toward the parameters such as loading under elevated temperatures, potency under the mix proportions, hydrations, etc. (Kodur 2014). Transient strains and creep fall under the category of time-oriented deformations of concrete and have been identified to be highly enhanced at elevated temperatures under compressive stresses (Bazant and Kaplan 1996). Increased creep in concrete registered under elevated temperatures has been articulated to be due to the exodus of moisture from the concrete matrix. Such phenomenon was additionally amplified by thinning out of moisture and bond rupture within the cement gel (C–S–H). We can infer that the liability of creep origin and its progressiveness is significantly due to two processes—"Dispersion of moisture and concrete dehydration due to high temperatures"; and; "Accelerated process of bond breakage." To summarize, we can establish that aspects like the modification of the concrete's chemical composition along with the misalignment of thermal expansion, originate internal stresses along with micro-cracking in the concrete components (aggregate and cement paste); this was found to be due to complex transformation of moisture along with chemical disparity in the composition of the cement paste and the thermal spreading out among the cement paste in addition to the non compliance of aggregates with each other resulting in transient strain in the concrete (Schneider 1988). Transient strain occurs during the first time heating of concrete, but it does not occur upon repeated heating (Khoury et al. 1985).

2.2 *Fire-Induced Cracks*

Fire efficiency of structural members is evaluated in terms of the duration of exhibiting stability with respect to structural integrity; the changes in state of concrete due to fire result in chemical variations in the concrete structure which end up adversely influencing its mechanical strength. Under administered fire, temperature generally exceeds 1000 °C (Buchanan 2002; Purkiss 2007). But several authors agree that concrete reaching up to a temperature of 500–600 °C should be treated as damaged (Kowalski 2010). Concrete, at elevated temperatures, undergoes significant physico-chemical changes. These cause thermal, mechanical, and deformation characteristics of concrete properties to behave abnormally at high temperatures and has been believed to be responsible for more complexities, such as crack genesis and maturing into spalling. Studied have shown that in normal concrete, under-fire spalling was observed to be initiated by cracks origination at an temperature of 250 °C. At about 300 °C, concrete began to loose strength and at 400 °C, significant spalling was visibly evident. Within 550–600 °C, the load bearing capacity was lost and finally, at 600 °C and above, concrete was seen to loose its ability to function as a structural member. The surface with close proximity to fire suffered maximum damage[1] (Baley 2002). A case study emphasizing upon the penetration of fire-induced cracks in concrete inferred that depth of ingress of cracks was in accordance to the fire temperature and generally, penetration depth was evidently very profound, reaching to a depth of 300 mm and more inside the concrete. The heat-cool cycle due to dousing out of fire and resulting effect on the expansion-contraction of the concrete's constituents was held responsible by the authors for such a deep crack penetration (Georali and Tsakirdis 2005).

2.3 Fire-Induced Spalling

A trace of the prior cases presented a variance in opinion upon the spalling caused by fire and it questions the exact mechanism of spalling in concrete. Some investigators inferred spalling in a concrete structural member's subjected fire was explosive in nature while other studies presented little or insignificant spalling. A possible explanation for such contradicting phenomenon is all the factors involving spalling and their interdependencies; major causes were chalked out were concrete not being watertight and migration of moisture in concrete reported at elevated temperatures. Following are two theories of significance via which the explanation of phenomenon of spalling can be explained (Kodur 2000).

1. *Accumulation of pressure*: The hypothesis of spalling is supposed to originate by of pore pressure accumulation under-fire exposure (Diederichs et al. 1995; Hertz 2003). The enormously soaring water vapor pressure generated in event of a fire is incapable to exit the matrix owing to the highly densified and compact (low permeability) nature of concrete. When the tensile resistance of concrete gives-into the effective pore pressure (which is measured as porosity times pore pressure), chunks of concrete wear away from the structural member. This pore pressure is supposed to cause progressive failure which has lead to the belief that lower is the permeability of concrete, greater shall be fire-induced spalling. This degeneration of concrete may or may not be likely to explode on the surface depending on fire and concrete characteristics. (Harmathy 1993; Anderberg 1997).
2. *Thermally induced dilatation of restrained nature*: This philosophy considers that spalling is a result of restrained thermal dilatation in proximity of the heated surface, resulting in the occurrence of compressive stresses parallel to the heated surface. The compressive stresses generated fracture in the concrete which was brittle in nature (spalling). Pore pressure enacts a significant role on the inception of instability of the concrete matrix which is visible as the thermal spalling of explosive proportions (Bažant 1997). This massive vapor pressure, originated from a rapid augmentation of temperature, cannot escape owing to high density (low permeability) of concrete matrix, and this pressure accumulation often reaches the levels of saturation vapor pressure. Authors have reported that the pore pressure can reach up to 8 MPa at around 300 °C; such internal pressures are

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[1] Alliance for concrete codes and standards, balanced code provisions for residential structures.

often too high to be resisted by the tensile strength of concrete. The drained conditions in the vicinity of the burnt concrete surface along with the low permeability of concrete leads to enormous pressure gradients close to the surface and are known as moisture clogging (ASTM 2011; ISO/DIS 2008). When the pressure generated by the vapor overcame the tensile resistance of concrete, pieces were seen to fall-off from the structure under evaluation; in such a study, the significant parameters which gained attention were strength, porosity, density, load, fire intensity, aggregate type, relative humidity, amount, and type of admixtures used (Kodur and Phan 2007; Kodur et al. 2003; Phan 2007). All above enumerated parameters were found to be very much dependable upon each other and this made forecasting of spalling became quite a complex task. Spalling was found to be associated with the cumulative epoch of concrete and its ambiguity is amplified during the entire serviceable life of concrete. In order to provide the necessary remedies, engineers recommended that the capability of aged (existing) concrete structures in resisting duress induced by fire and the structural loads needs to be assessed with regards to the risk of spalling resulting from fire (Wang et al. 2013). Most authors have concurred to the fact that aggregate expands and cement paste shrinks when subjected to heating (Khoury et al. 1985, 2002). The thermal incompatibility among the aggregate and cement paste, during initial phases of heating, had been considered damageable to concrete, and the expansion due to heat was considered as the superficial and a significant cause of spalling but owing to the dawn of new age modern methods of testing, certain authors contradicted such a reasoning. During the virgin heating, concrete's components move reciprocally, i.e., attenuation in cement paste accommodates the expanding aggregate and consequently, concrete under compression and subjected to high temperature, adjusts to the combined duress of fire and external load; this ends up eventually into unstable spalling when a certain limit is reached where-in the mutual adjustment cannot sustain itself anymore. Hence, shortening was also seen to appear against elongation in loaded structural elements (Chudzik et al. 2017).

An extensive review about the genesis and control of spalling can be summarized as follows. Concrete witnesses thermal distresses in terms of stresses and strains, upon fire exposure. The earlier approach to a fire proof design was targeted at the maximum temperature of the duress which was quite unsafe and an immature approach to the engineering aspect. It was later summarized that the rate of elevation of the temperature is also a very contributing factor, along with the maximum fire temperature. The maximum temperature determines the resulting temperature within the concrete and the rate of its ascent decides the episode of spalling. Serious structural damage has been visibly evident due to rapid heating inducing explosive spalling in structures. Concrete is advantageous as fire proof due to its non-combustibility and little thermal diffusivity but it experiences explosive spalling and deterioration of properties under heating which need to be addressed at the materials realm to produce a cost-effective concrete. The declines of properties such as compressive strength depend upon the constituents, their compatibilities, and molecular changes under fire.

Investigations of the loss of properties of concrete under fire keeping in mind the occurrence of explosive spalling should be the prime intentions of experiments carried out at the materials level. In such cases, the prologue of a thermal barricade at the correct locations needs to be considered along with a secure structural design to guarantee that the structure does not collapse in event of a fire and that the safety is made certain. Properties worth inspecting are the compressive strength and the strain behavior at the materials level. Rapid heating during fire induces explosive spalling with serious consequences to structure and people (Khoury 2008).

3 Experimental Investigations

Fresh Portland cement incorporating 12% alccofine-1203 by weight was assorted with fine and coarse aggregate. The relative amount of cement and aggregates was 1:1.35:2.19 and 12% cement (by weight) was replaced by the inclusion of alccofine. Optimum water cement ratio obtained which was 0.43 and used for the preparation of the specimen. Optimum dosage of alccofine has been established as 12% from previous investigations for maximum strength gain.

3.1 Alccofine

Alccofine 1203 exhibits superior approach than all other mineral admixtures used in concrete within our country. Because of its fundamental CaO content, ALCCOFINE 1203 triggers dual reactions during hydration phenomenon.

1. Primary reaction of cement hydration.
2. Pozzolanic reaction.

ALCCOFINE like pozzolans forms additional C–S–H gel by consuming the calcium hydroxide which happens to be a by-product obtained as a result of the hydration of cement. This has a domino effect in formation of a denser pore structure and evidently higher strength gain. ALCCOFINE 1203 is a particularly processed product based on slag of soaring glass content with high reactivity obtained via controlled granulation process. Its unprocessed materials are made up primarily of low calcium silicates. Processing along with other chosen ingredients results in desired particle size distribution (PSD). The computed blain value as per PSD is around 12000 cm^2/g and is beyond doubt ultrafine. Owed to its exceptional chemistry and ultrafine particle size, ALCCOFINE 1203 provides reduced water demand for a given workability, even up to 70% replacement level as per requirement. Authors have reported enhanced hardened characteristics of concrete with incorporation of Alccofine 1203 and the compressive strength of concrete using alccofine, in general upon investigation was found to be improved (Saurav AG 2014).

The outcome of analytical evaluation shows that the chemical components in ALCCOFINE 1203 are important features in controlling the theology of the concrete. The mechanism by which ALCCOFINE 1203 disperse cement particles is of proactive in nature with a dual nature of generating a negative charge on cement particles and causing dispersion via "electrostatic repulsion" and in the advance stages of the chemical reaction among the Alccofine 1203 and cement particles, dispersion is found to be steric-hindrance administered mechanism. The cement particles have a penchant for flocc formation when in contact with water. During such a process, they entrap water between them, resulting in lesser water available for hydration of cement which ultimately influences adversely upon the cement paste consistency. The consistency can be improved by higher water content but it brings a fall in the strength. ALCCOFINE 1203 remedies this issue owing to its surface-active agents which have charged periphery. When mixed with the cement particles, there occurs modification among the surface charges causing dispersion and releasing of any entrapped water. Hence, the consistency and flowability are improved and that too at low water cement ratio. These chemical enhanced assets are active only for limited period of time, and as soon as the desired intent is achieved, the cement paste starts stiffening. ALCCOFINE 1203 commences its enchantment in the green state instantly after mixing.

3.2 Casting and Curing of Specimens

Concrete under investigation was compacted via the compaction table and de-molded after a passing of 24 h from the initiation of casting and water-submerged for 7, 14, and 28 days awaiting the time of testing (Fig. 1).

3.3 Fire Resistance Test

The 100 mm × 100 mm × 100 mm size cubes were casted and mold was reserved in a wet place for 24 h, submerged under water for 28 days at room temperature after demoulding. Cubes were heated in the electric muffle furnace afterwards which is provided with a thermostat to preserve constant temperatures of different ranges. At a time, 24 cubes, i.e., eight sets of three cubes each, were prepared among which half were submerged for 14 days and other half for 28 days. These sets were heated for 1, 2, and 3 h at four different temperatures (27, 500, 650, 800 °C). After that, these sets were left at room temperature for 24 h for cooling. Compressive strength has been calculated as per BIS 516-1959. Each of the samples selected for testing should be exposed to the desired duration of constant temperature once it has reached the desired temperature. After fire resistance test, compressive strength of the samples was determined to detect effect of fire on strength properties of concrete cubes (Figs. 2 and 3).

Fig. 1 Cubes being casted and on vibrating table

Fig. 2 Cubes incorporating alccofine at varying temperatures placed in muffle furnace

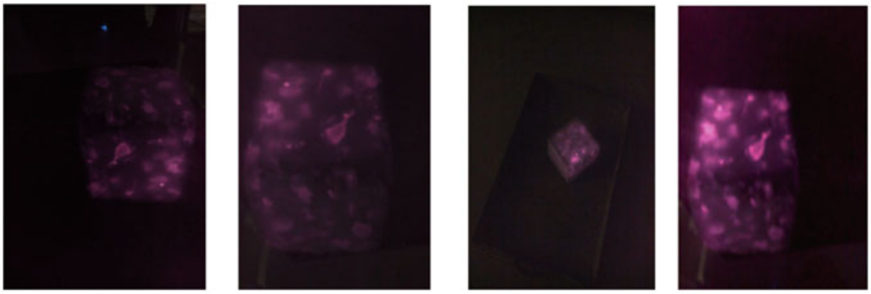

Fig. 3 Cubes taken out from furnace after desired exposure duration

Fig. 4 Superficial cracks on cubes due to varying thermal gradient

3.4 Development of Cracks at Elevated Exposure Temperature

Concrete on heating expands and contracts on cooling. Restraint to contraction causes the development of tensile stresses. The temperature-related contraction stress can cause cracking. Cracks may also be caused by differential temperatures in thick members. When the surface layer cools and contracts, movement is restrained by the core of the member which is still at a higher temperature, and hence cracks may form in the surface (Fig. 4).

3.5 Testing of the Specimens

Subsequent to heating in the oven, the concrete specimens were tested using a compression testing machine having a capacity of 400 tons and the evaluation of compressive strengths at 07, 14 days, and 28 days are as shown in Tables 1, 2 and 3 (Figs. 5, 6, 7 and 8).

Table 1 Compressive and % residual compressive strengths of cubes after exposing to elevated temperature cured for 7 days

Temperature (°C)	Compressive strength (N/mm^2)			% residual compressive strength (N/mm^2)		
	1 h	2 h	3 h	1 h	2 h	3 h
27	42	42	42	100	100	100
500	48	40	29.09	114.28	95.238	69.26
650	45	38	20.65	107.142	90.476	49.166
800	19.7	21.11	17.75	46.904	50.261	42.0261

Table 2 Compressive and % residual compressive strengths of cubes after exposing to elevated temperature cured for 14 days

Temperature	Compressive strength (N/mm^2)			% residual compressive strength (N/mm^2)		
	1 h	2 h	3 h	1 h	2 h	3 h
27	48	48	48	100	100	100
500	54	46	35.09	112.50	95.833	83.54
650	45	40	26.65	93.75	83.33	55.520
800	25.5	27.11	23.75	53.125	56.479	49.479

Table 3 Compressive and % residual compressive strengths of cubes after exposing to elevated temperature cured for 28 days

Temperature	Compressive strength (N/mm^2)			% residual compressive strength		
	1 h	2 h	3 h	1 h	2 h	3 h
27	58.2	58.2	58.2	100	100	100
500	67.51	57.42	41.31	116.006	98.65	70.97
650	63.17	55.65	30.61	108.53	95.61	52.59
800	26.29	27.252	28.60	45.17	46.82	49.14

Before After Before After

Before After

Fig. 5 Random specimens before and after testing

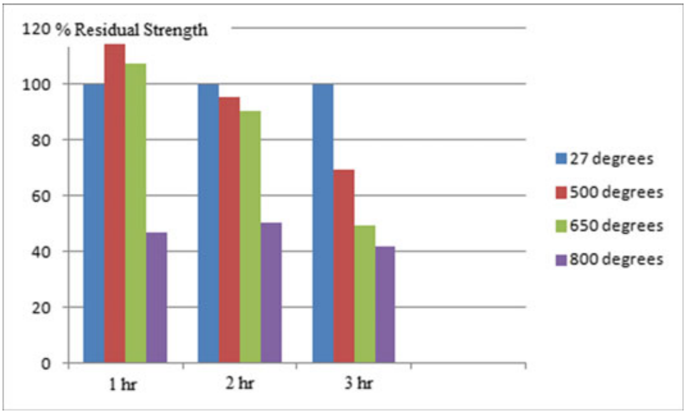

Fig. 6 Variation of % residual compressive strength with varying temperature at 7 days of curing

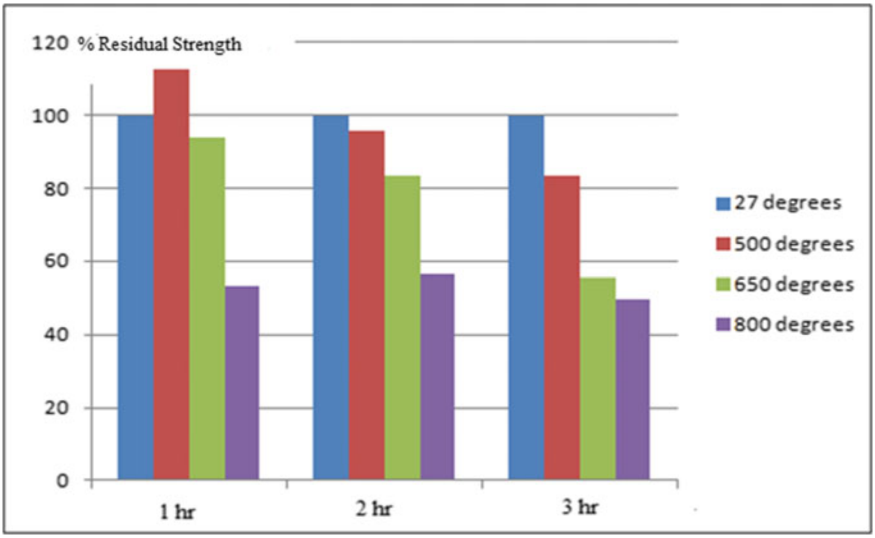

Fig. 7 Variation of % residual compressive strength with temperature at 14 days of curing

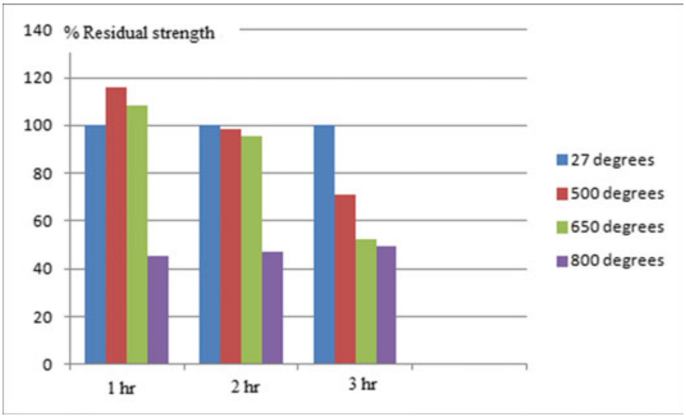

Fig. 8 Variation of % residual compressive strength with temperature at 28 days of curing

4 Results and Discussions

4.1 Inferences Based upon Appearance

At 500 °C, concrete experienced minor cracks along with dehydration of the cementitious paste with absolute loss of liberated moisture and a diminution in paste volume.

At 650 °C, prominent cracking of both the cementitious paste and aggregates due to expansion. Color of concrete turned some-what pinkish.

At 800 °C, cComplete dehydration of the cementitious paste accompanied with substantial shrinkage cracking was observed. Concrete became crispy and easily broken down upon contact. Color of concrete tainted to gray.

5 Conclusion

The disparity of compressive strength with the augmentation in temperature is studied in terms of the percentage residual compressive strength for different durations of 1, 2, and 3 h. Initially, the strength improved with temperature 27–500 °C for different durations and ahead of that, it was reduced. Utmost compressive strength was perceived when the cube was heated at 500 °C for 1 h duration. The compressive strengths are increased up to 27–500 °C and beyond that, it was rapidly reduced with increasing temperature. The compressive strength was lost to a large extent when they are heated to temperatures greater than 500 °C. Addition of Alccofine 1203 provided a revolutionary advent to the fire resistance of concrete and evidently restricted spalling up to a stage, owing to its presence in the concrete matrix.

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