STUDY OF MECHANICAL PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURES - A REVIEW

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Abstract

Concrete, the second highest consumed material after water in the world, plays a vital role in the construction field because of the versatility in its use. Developments during the last two decades have shown a marked increase in the number of structures involving the long time heating of concrete.

In recognition of its importance, many researchers have attempted to investigate the effect of elevated temperature on mechanical properties of concrete. These researchers, during their investigation, used materials with varying combination and different experimental conditions. These materials include cement, different percentages of admixtures like fly ash, silica fume, metakaolin, finely grounded pumice(FGP), group granulated blast furnace slag(GGBS), polypropylene fibre(PP fibre), palm oil fuel ash(POFA), Portland pozzolana cement(PPC), rice husk ash(RHA), different fine and coarse aggregates, super plasticisers, retarders and the conditions included a temperature range of 28^{o}C to 1200^{o}C . The other conditions that were varied are the shapes and sizes of test specimens, curing methods, curing conditions and test methods. The analysis of these investigations and their results are reviewed and presented in this paper.

Key words: *concrete, mechanical properties, elevated temperature, admixtures, curing methods*

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1. INTRODUCTION

The extensive use of concrete as a structural material for the high-rise buildings, nuclear reactors, pressure vessels, storage tanks for hot crude oil & hot water and coal gasification & liquefaction vessels increases the risk of concrete being exposed to elevated temperatures. Concrete is most suitable to resist high temperatures because of its low thermal conductivity and high specific gravity (Arioz.o, 2007)[1]. The mechanical properties like strength, modulus of elasticity, colour etc., are affected by the high temperatures exposure. High Performance Concrete (HPC) made with the partial replacement of cement by additives such as fly ash, silica fume, metakaolin, finely grounded pumice(FGP), group granulated blast furnace slag(GGBS), polypropylene fibre(PP fibre), palm oil fuel ash(POFA), Portland pozzolana cement(PPC), rice husk ash(RHA) provides higher fire resistance. These concretes play very important role in the present day durable concrete construction utilizing the mineral and chemical admixtures with low water cement ratio and high strength aggregates (Bentz.D.P. et al., 1991)[2]. The researchers focused on the use of HPC subjected to elevated temperatures to know their fire resistance. It was investigated that the loss in structural quality of concrete due to a rise of temperature is influenced by its degradation through changes induced in basic processes of cement hydration and hardening of the binding system in the cement paste of concrete (Con. X et al, 1995 and Escalante – Garcia.J.I et al.,1998)[3,4].Similarly many researchers worked on various materials and combinations of materials that can resist the changes in the mechanical properties of concrete when subjected to high rise in temperatures.

The present review presents information of such investigations that provide insight into the effect of elevated temperatures on the mechanical properties of various High Performance Concretes made by adding different admixtures. Table 1 gives the experimental conditions and parameters used by various investigators.

2. EXPERIMENTAL INVESTIGATIONS

The effect of elevated temperature on mechanical properties and microstructure of silica flour concrete was investigated and studied (Morsy. M.S. et al 2010)[5] using ordinary Portland cement (OPC) and silica flour (SF) in percentages varying from 0,5 to 20% with water/binder ratio of 0.5. After 28 days of curing, the specimens were exposed to 100oC to 800oC. The specimens were allowed to cool naturally to room temperature, and tested for compressive strength and indirect tensile strength. The investigation also included the phase decomposition study using differential scanning calorimeter (DSC) analysis and identification of the changes in the microstructure of the specimens using the scanning electron microscope (SEM).

The above investigation reported that the exclusion of water at 100oC has resulted in a reduction of residual compressive strength. Between 100 and 400oC, it was reported that silica flour concrete unlike control concrete resulted in increase in compressive strength due to hydrothermal interaction of the silica flour particles liberating free lime. Further increase in temperature beyond 400oC, the compressive strength of blended concrete has decreased.

The indirect tensile strength of concrete with only OPC decreased with increase in the exposed temperature, whereas the replacement of OPC by 20% silica flour in concrete resulted in a stable tensile strength up to 400oC followed by sharp decrease. The decrease in the indirect tensile strength from 200oC to 800oC was due to the formation of micro cracks. It was also suggested that the exclusion of free water and fraction of water of hydration of concrete due to high temperatures resulted in the reduction in tensile strength. Dehydration of concrete causes decreases in its strength, elastic modulus, coefficient of thermal expansion and thermal conductivity.

Salient Features of Test

Silica flour concrete exposed to elevated temperatures from 100oC to 800oC caused dehydration of concrete which resulted in decrease in compressive strength and the decrease in indirect tensile strength is due to formation of micro cracks, with the result of decomposition of the hydration products at 800oC.

Studies were conducted on the effect of high temperature on the residual performance of Portland cement concretes (Evandro Telentino et al 2002)[6] using Normal Strength Concrete (NSC) and High Strength Concrete (HSC) and the test specimens were cast using the coarse aggregate, river sand as the fine aggregate and sulfonated melamine super plasticiser as water reducing admixture. Specimens were exposed up to 600oC for 2 hours and tested. The uni-axial test for compressive strength, ultrasonic pulse velocity measurements for modulus of elasticity and mercury intrusion posometry tests and nitrogen sorption tests were conducted on samples.

The increase in temperature, though resulted in significant reduction in compressive strength was mere pronouncing on HSC than NSC. At 600oC, the reduction in compressive strength of NSC was 58% while that in HSC was 69%. The reduction in modulus of elasticity in NSC was 49% while that in HSC was 59% due to the structure of concrete transformed coarser in both cases.

Salient Features of Test

The reduction in compressive strength and modulus of elasticity at 600oC is due to micro structural damage of concrete with increasing temperature. The temperature influence on the strength of HSC is higher than NSC because of the cement matrix in HSC must carry higher loads than in NSC.

The effect of elevated temperature exposure on heating characteristics, spalling and residual properties of high performance concrete (HPC) was experimentally investigated (Phan L.T. at el 2001)[7] on test specimens using the Type I Portland cement, crushed limestone aggregate, natural sand, silica fume in the form of a slurry with a concentration of 54% (by mass)and a high range water reducing admixture (HRWRA) based on a sulponated naphthalene.

The effects of three different w/c ratios (0.22 to 0.57) on compressive strength and the inclusion of silica fume 0 - 10% as cement replacements on residual properties and spalling characteristics of HPC at elevated temperature were examined. All the specimens were heated from 100 to 450oC. The experimental investigation observed that the presence of silica fume in HPC mixture with w/c of 0.33 or less increases the potential for explosive spalling of concrete heated to target temperatures of 300 and 400oC. Evidence of a more restrictive heat - induced mass loss process experienced by the exploded specimens, coupled with the sudden, drastic disintegration of the test specimens in to small fragments due to internal pore pressure build up is the primary cause for the explosive spalling mechanism. HPC with higher original compressive strength, or lower w/cm ratio, sustained lower strength loss due to higher temperature exposure than those with lower original compressive strength. It was also concluded that the presence of silica fume appears to result in lower strength loss and dynamic modulus of elasticity up to the temperature of 200oC. More than 50% decrease in modulus of elasticity was observed between room temperature (23oC) and 300oC and the rate of decrease is reduced between 300oC to 450oC. Further it was concluded that the exposure to 450oC caused to lose more than 70 percentage of their initial modulus of elasticity.

Salient Features of Test

Explosive spalling of specimens containing silica fume is due to the internal pressure developed and the buildup of thermally induced strain energy was also at maximum and there might be a role of thermal stress in the failure.HPC mixtures which experienced explosive spalling had a more restrictive process of capillary pore and capillary bound water loss than those which did not experience spalling.

The presence of silica fume appears to result in lower strength loss and dynamic modulus of elasticity up to the temperature of 200oC. The experimental investigation on the effect of transient high temperature as heavy weight high strength concrete was carried out (Mahdy. M et al 2002)[8] using Portland cement, magnetite as both coarse aggregate and in some mixes, as fine aggregate, Silica fume slurry as mineral admixture and chemical admixture SP6 liquid super plasticizers (SPB) with W/C ratio of 0.5. Compression tests were carried out on specimens for three exposure durations of 0, 1hr and 2hrs with temperatures of 100 to 700oC and the specimens were left to cool in air at room temperature.

It was reported that the compressive strength of both normal and high strength concrete at 100oC decreased compared to the room temperature and with the further increase in temperature, the strength of 10 to 30 % above the room temperature strength and at temperatures of 500 and 700oC, the strength in each case dropped sharply. Silica fume concrete with magnetite as fine aggregate gave a residual compressive strength 12 – 29% higher than HSC without SF when cooled immediately following attainment of the required temperature, 15 – 23% higher after 1 hr. exposure and 2 -10% after 2 hr. exposure. The silica fume, with magnetite as a fine aggregate, enhanced the residual compressive strength of the concrete as high strength concrete than with sand as fine aggregate. There is no effect of coarse aggregate content on residual compressive strength after exposure to high temperature.

Salient Features of Test

The silica fume concrete with magnetite as fine aggregate gives higher percent of compressive strength than that of HSC without silica fume when compared to concrete with sand used as fine aggregate. This is due to the fact that cement paste with sand shrinks, as absorbed and hydration of water is driven out more than that with magnetite paste, while the aggregate expands resulting in loss of bond.

The effect of temperature on structure quality of high strength concrete with silica fume was experimentally studied (Ivan Janotka et al 2003)[9] using OPC, silica fume, super plasticiser and sand. The concrete specimens with w/c ratio of 0.32 were cast and cured for 28 days. All the specimens were stored at temperature of 40oC, 60oC, 100oC and 200oC after curing. Reference concrete proportion was studied curing in a wet air.
Concrete specimens were tested for weight and length changes, dynamic modulus of elasticity, compressive strength and impact strength. In addition, stress - strain curve of the concrete specimens in compression exposed to temperatures at 100oC and 200oC was also determined. The relations between the compressive stress, Poisson's ratio and volume deformations were also evaluated.

It was inferred that the strength, elasticity modulus and deformation of concrete are irreversibly influenced by temperature elevation mainly to 100oC and 200oC. The decisive changes leading in the final effect to the structural deterioration are taking place immediately after the temperature elevation (the observed time - limited loss in weight and elasticity modulus, and expansion increase). Concrete exhibited a pronounced "Softening" through the formed pore matrix and compressive strength are influenced at individual temperature levels only negligibly. Also the effect of pore structure coarsening at the end of recovering periods after 100oC and 200oC exposures very evidently resulted in significant concrete and cement paste strength decrease. Rapid cooling after temperature elevations evokes equal and irreversible structure quality deterioration of concrete and cement paste. The "self curing" of concrete and cement paste after short and long recovering at 20oC does not attribute to the structural integrity improvement. Concrete and cement paste is persistently deteriorated, and the impossibility to acquire their origin physical state before temperature attack is observed.

Salient Features of Test

The sudden temperature elevations contributed the quick release of bound water from hydrated cement paste and caused the expansion of concrete specimens. Also the structural integrity of the specimens is deteriorated which is confirmed by loss in weight of the specimens due to elevated temperature. The immediate cooling of the specimens after exposure at 100oC and 200oC caused the extreme shrinkage and structural quality connected with the crack propagation and loss in mechanical properties like strength.

The flexural strength of fly ash concrete under elevated temperatures was investigated (Potha Raju. M et al 2004)[10] using OPC, fine sand and coarse aggregate with 0, 10% , 20% and 30% fly ash and M28, M33 and M35 mixes with w/c 0.55, 0.50 and 0.45 respectively and cured for 28 days. Flexural strength tests were conducted on specimens exposing to three different temperatures of 100oC, 200oC, 250oC in addition to room temperature (28oC) exposing the specimens to1hr, 2hrs and 3hrs.

The above investigations reported that the fly ash concrete showed consistently the same behavioral pattern as that of concrete without fly ash under elevated temperatures up to 250oC under flexure. The flexural strength of both concretes decreased with increase in temperature. Concretes with 20% fly ash replacement showed better performance than the concrete without fly ash, by retaining more of its strength. The maximum losses recorded in all mixes without fly ash were in the range of 10-39.4%; in all mixes with 10% fly ash, they were 4 -31.7%. It was also inferred that the exposure time has a significant effect on the residual flexural strength of cement, as bulk loss of strength occurs within the first 1hr of exposure in all mixes and the loss of residual flexural strength in the first 1hr of exposure range from 10% to 36% with no fly ash, from 4% to 28% with 10% fly ash, and from 6% to 32% with 20% fly ash, compared to unheated concrete with no fly ash.

Salient Features of Test

The better performance of fly ash concrete could be due to pozzolanic action of fly ash and reduced loss of moisture in fly ash concrete. The increase in compressive strength with fly ash concrete at elevated temperature is due to the silica reaction in the fly ash with free lime in the concrete, which is responsible for formation of C-H-S gel and The exposure time has a significant effect on the residual flexural strength of concrete, as bulk loss of strength occurs within the first 1 hr of exposure.

The effect of elevated temperature on the concrete compressive strength was investigated (Bishr H.A.M. 2008)[11] using OPC, basalt aggregate, local sand, silica fume of 0 to 15% replacing cement. The specimens were cast and cured for 28 days in water and exposed to 20 to 900oC. All the specimens were tested for their residual compressive strength.

The above investigation reported that the compressive strength of concrete with or without silica fume decreases with increasing temperature, the peak value in the ratio of the compressive strength at high temperature to that at ambient temperature was observed around 300oC which could be due to the evaporation of free water inside the concrete. Also it was inferred that for all mixes, the compressive strength was found to increase after four hours of exposure to an elevated temperature up to 300oC. Further reduction in compressive strength was observed after exposure to 700oC and increasing the temperature up to 900oC caused serious deterioration where the decreasing ratio in the compressive strength reached to 81% of the unheated strength.

Salient Features of Test

Silica fume concrete is more sensitive to high temperatures than blended cement concrete where the poor performance of silica fume concrete, exposed to elevated temperature compared to plain concrete can be attributed to the effect of vapour pressure built-up inside the concrete causing expansion and cracking because of the highly dense concrete. It lose the integrity above 500oC. the increase in Compressive strength at 200oC is due to internal autoclaving formed in cement paste. The peak value of the strength was around 400oC and spalling noticed with low w/c ratio.

The mechanical properties of high – strength concrete subjected to high temperature by stressed test was experimentally investigated (Gyer - Yong KIM et al 2009)[12] using OPC, sea sand as fine aggregate, crushed granite aggregate as coarse aggregate, fly ash, silica fume and super plasticiser. The specimens of high strength concrete with normal strength of 40, 60 and 80 MPa were cast with w/b % of 46, 32 and 25 and the specimens were cured for 28 days and tested for compressive strength after subjecting to temperature ranging from 100oC to 700oC at 100oC.

In the above investigations it was observed that when exposed to 100oC, the high strength concrete showed a loss of 20% of compressive strength and as the strength of concrete increased, the loss of strength, exposure to high temperature, also increased. After an initial loss of strength, the high strength concrete recovered its strength between 200oC and 300oC reaching a maximum value of 8% -13 % above the room temperature strength. As the strength of concrete increased, the recovery point of strength from exposure to high temperature also increased.

The high strength concrete loses a significant amount of its compressive strength above 400oC and attains a strength loss of about 55% at 700oC. The change of strength in temperature range of 100oC - 400oC is marginal. The elastic modulus of the high strength concrete decreased by 10%-20% When exposing in the temperature range of 100-300oC. At 700oC, the elastic modulus was only 45% - 50% of the value at room temperature.

Salient Features of Test

The strength reduction in concrete, at elevated temperature, is due to the dehydration of the cement paste which results in gradual disintegration of concrete. The paste shrinks and expands at high temperatures and the bond between the aggregate and the paste is weakened, thus reducing the strength of the concrete. The elastic modulus decreased with increased temperature as the dehydration progressed and the bond between materials was gradually lost.

The residual Compressive Strength of Laterized Concrete Subjected to Elevated Temperatures was investigated (Felix F. Udoeyo et al 2010) [13] using OPC, two types of fine aggregates, namely sand and laterite crushed granite rock as coarse aggregate preparing six concrete mixtures containing 0 to 50% replacement levels of sand by laterite with w/c ratio of 0.5 and cast and cured in water for 28 days. Specimens were subjected to heat pretreatment for 1hr for a maximum temperature of 700oC. Nine specimens were cooled naturally, another set of nine rapidly by immersion in water and three control specimens at room temperatures were tested for their compressive strength.

The investigations inferred that the compressive strength of LATCON decreased in a similar manner to that of plain concrete when subjected to elevated temperatures between 200 and 600ºC. Deterioration in strength for both types of concrete was severe at 600ºC. However, plain concrete maintained a greater proportion of its relative residual strength than LATCON. The results indicate that the cooling regime also significantly influenced the residual compressive strength of LATCON. LATCON specimens cooled naturally after heat pretreatment maintained relatively higher residual strength values than those cooled rapidly by the immersion in water. It was also suggested to investigate for other less harmful alternative methods of rapid cooling, as the rapid cooling adapted in their study led to severe loss in strength.

Salient Features of Test

The workability of concrete increases with laterite content and the water absorption decreased with increase in laterite content duo to the presence of clay fines. The residual compressive strength of plain and laterite concrete exposed to increased temperatures, decreased for both the water - cooled and air - cooled regimes. The type of cooling regime has influence on the decrease in the compressive strength. The effect of laterite content has greater bearing on the compressive strength of concrete and is due to possible thermal dilations in the concrete resulted in large internal stresses and, ultimately, led to internal micro cracking and fracture. Dense pore structure of LACTON with greater laterite clay fines could increase vapor pressure upon heating, resulting in increased cracking and severe losses in compressive strength.

The effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume was studied (Bahar Demirel et al 2010)[14] adding ASTM type1 Portland cement, 10% silica fume by weight of cement by substituting cement with finely grounded pumice (FGP) at proportion of 5% to 20% by weight, aggregates composing of 65% sand and 35% gravel. Specimens (100x100x100 mm3) were cast and cured in lime saturation water for 28 days and exposed to 400, 600 and 800oC. The specimens were tested for compressive strength and the porosity, ultrasonic pulse velocity; sorptivity and the microstructure analysis of the specimens were performed using scanning electron microscope (SEM).

It was inferred that the unit weight of the concrete decreased due to the fact that certain proportions of mineral admixtures like FGP and SF with low specific gravity. Greater amounts of FGP not only resulted in a decrease in compressive strength and ultrasonic pulse velocity values of the concrete but also led to an increase in the porosity and sorptivity values. This result occurred because in the concrete with FGP, a greater reduction occurs in the proportion of cement as the FGP content increases. The pozzolanic reaction in pozzolan/cement is known to become dominant at ages after 28days; therefore, the 28 day observation in this study may not be sufficient to observe a pozzolanic effect of the FGP.

Salient Features of Test

The highest weight loss occurred in specimens with FGP plus SF that were subjected to 800oC.The reduction in the compressive strength of concrete was significantly larger for samples exposed to temperatures higher than 600oC. This result is due to the lost water caused by crystallization resulting in a reduction of the Ca(OH)2 content, in addition to the changes in the morphology and the formation of micro cracks. The decomposition of Ca(OH)2 and C-S-H gels, especially at 800oC, resulted in the total deterioration of concrete. This study demonstrates that the critical temperature for concrete specimens containing FGP or FGP and SF is 600oC because all the hydrated phases including C-S-H and Ca(OH)2 appeared to have amorphous structures at this temperature instead of their characteristic crystal structures. the decomposition of Ca(OH)2 and C-S-H gels, especially at 800oC, resulted in the total deterioration of concrete. The drastic reduction in ultrasonic pulse velocity values between 400 and 800oC indicates that the physical state of the concrete samples deteriorated rapidly beyond 400oC. SEM investigations conducted on the specimens confirmed the deformation of well-developed Ca(OH)2 crystals and the C-S-H gel at temperatures beyond 600oC.

The effect of high temperatures on concrete compression strength, tensile strength and deformation modulus was investigated (De Souza A. A. A. et al 2010)[15] using a proportion of 1:3:3 (cement, sand, stone1) and the water/cement ratio 0.6, cast the specimens and cured for 3 months. The specimens were exposed to a temperature of 300oC, 600oC and 900oC for 2 hours. At the end of 2hours, 6 test bodies were rapidly cooled by immersing them in running water and are tested for compression and tension, and results were compared with those of unheated concrete. The remaining 54 test bodies were slowly cooled and the remaining to room temperature; they were tested for the compressive strength. Of the remaining 48 test bodies, 24 were immersed in water and 24 were wrapped up in plastic film and all the 48 test bodies were tested for their mechanical properties on 7th, 28th 56th and 112th days. Test bodies wrapped up in plastic film provided as assessment of rehydrating concrete after they were subjected to high temperature.

It was observed that the concrete, when submitted to temperatures close to 900ºC, its mechanical properties, either to tension or compression, can reach values close to zero. The longitudinal deformation modulus values were reduced close to zero for the temperatures lower than 900oC.It was also inferred that the Rehydration after heating can contribute for recovering a significant portion of a concrete initial mechanical strength, either to compression, tension or deformation modulus. Recovery is also inversely proportional to the temperature, the concrete was subjected. The cement recovered up to 60% of their initial mechanical strength even when the test bodies were subjected to 900oC. Also the recovery of mechanical properties after rehydration was also relatively fast.

Salient Features of Test

The significant decrease in compressive strength of concrete was due to the loss of free water and the water contained in the gel, thus causing a high level of surface cracking. Aggregates expansion caused the internal stresses resulting in reduction of compressive strength. The immersion of specimens in water rehydrated and recovered the part of initial strength and the recovery is between 40% to 90%during 112 days. Greater loss of tensile strength was due to the micro cracking of concrete. The recovery of 50% to 90% tensile strength was due to rehydration was also observed. The deformation modulus has got reduced from 20% to 0% at temperatures from 600oC to 900oC and 80%of deformation modulus was recovered for temperature below 600oC on rehydration.

The effect of elevated temperature on the properties of High-Strength Concrete containing cement supplementary materials was experimentally investigated (Sri Ravindrarajah. R. et al 2002)[16] using 0.30 water- binder ratio and four mixes of concretes, one is general purpose, second mix by 62% blast furnace slag concrete replacing the cement, third mix by replacement with low calcium fly ash and the fourth mix by replacement with 40kg/m3 of condensed silica fume. All mixes were prepared by using crushed basalt as coarse aggregate, river sand and super plasticiser for all concrete mixtures. Concrete specimens were cast cured for 28 days in water. All specimens were subjected to high temperature exposure ranging from 200oC to 1000oC for 7 hours and then quenched in water. The specimens were tested for compressive strength, tensile strength, flexural strength, dynamic modulus of elasticity and heating effect on colour of concrete.

It was inferred that the High-strength concrete, independent of the binder material type used, experience weight loss and the relationship between the weight loss and maximum temperature was non-linear and the compressive and tensile strengths showed noticeable losses (above 15%) even at the temperature of 200oC; and it was observed that the elastic modulus was dropped marginally by about 5%.

It was also reported that the concrete with silica fume suffered the most; under increased exposure temperature below 800oC.High-strength concrete has shown 90% drop in its strengths once exposed to 1000oC irrespective of the type of binder materials used. Modulus of elasticity of high-strength concrete was less sensitive to the maximum temperature than either compressive or tensile strengths and the ultrasonic pulse velocity measurement can be used to estimate the temperature-related damage in concrete. Concrete subjected to elevated temperatures suffered noticeable colour changes.

Salient Features of Test

The elevated temperatures on concrete specimens caused noticeable decrease in compressive, tensile, flexural, modulus of elasticity, pulse velocity and colour changes due to the evaporation of water from large capillaries and evaporable water from gel pores and small capillary pores with substantial shrinkage of concrete. Calcareous aggregates dissociated by releasing carbon dioxide at temperature over 800oC. Cement paste lose its cementing property and thus significantly reducing the hardened concrete properties. Irrespective of binder type, the concrete strengths, modulus of elasticity, and pulse velocity decreased at elevated temperatures. The loss of pulse velocity is due to the combination of effects of drying, internal cracking as well as to the changes in the micro structure of the paste on heating.

The effect of cooling method on residual compressive strength of high strength concrete cured for 28 days and 180 days and heated to elevated temperature was investigated to demonstrate (Balendran. R.V. et al 2001) [17]using OPC, coarse granite aggregate, river sand, silica fume along with super-plasticisers and retarders in the casting of test specimens. Three trail mixes were conducted for each grade to obtain respective target strength 60MPa, 90MPa, 110MPa and 130 MPa. The test specimens were cured in water for two curing ages 28 days and 180 days and the specimens were exposed for 4hrs to temperatures of 200oC and 400oC. The concrete specimens were cooled down in two ways, after heating, slow and quick cooling by placing in water. The specimen were tested for its compressive strength.

It was observed that the cooling method has an effect on the residual compressive strength of HSC and quick cooling caused more drop in residual strength than slow cooling and their drop is more pronounced at 400oC. The HSC cured for longer period (180 days) exhibited more loss in compressive strength under both cooling methods, with quick cooling impeding the strength more than slow cooling. The concrete would suffer a server damage if it has been cured for 180 days or more and got exposed to a temperature of above 400oC and was quickly cooled later, with loss as much as 40-45% of its original compressive strength and hence this renders “cooling method” as an important parameter to be considered while designing research methodologies for investigating fire properties of HSC.

Salient Features of Test

The slow and quick cooling methods have an effect on residual compressive strength of HSC heated to elevated temperature. The loss in strength is more pronounced in case of quick cooling than in slow cooling for both curing ages of 28 days and 180 days and is more significant for the curing age of 180 days. The effect of quick cooling of concrete causes full hydration of concrete after 180 days of curing and is more prone to damage of concrete after exposed to high temperatures as in fire. The thermal gradient set by the immediate cooling severely hampers the residual compressive strength of fully hydrated cement gel (CSH). The cooling method is a very important parameter to be considered while designing research methodologies for investigating fire properties of HSC.

The coupled Effect of High Temperature and Heating Time on the Residual strength of Normal and High Strength Concrete was investigated (Toumi.B. et al 2009)[18] by making use of commercial Portland cement, crushed lime stone as aggregates, Silica fume and polypropylene fibre (PP fibre) along with super plasticizer and casted beams using three concrete mixes, NSC, HSC and High Strength Concrete incorporating polypropylene fibre (HSC-PP) with the w/c ratio of 0.45 and 0.30 respectively using 10% Silica fume by weight of cement and super plasticiser and stored in lime water 28 days.

The unheated samples were tested for compressive and tensile flexural strengths. Other specimens were exposed to target temperatures of 300, 500 and 700oC for duration of 3,6 and 9 hours and were tested for residual compressive strength and the residual flexural tensile strength.

It was concluded that the residual strength of concrete decreases as the prolonged duration of temperature exposure are increased. The strength degradation of heated concretes was seen at peak temperature and the increase of exposure time. It was also inferred that adding polypropylene fibers to HSC mixtures improves their residual compressive and tensile strengths and contrasting the residual compressive strength, the residual flexural strength of HSCs without and with polypropylene fibers always drops continuously under rising temperatures. The polypropylene fibers melt at high temperatures (e.g. fire) providing voids that help reduce explosive characteristics of concrete.

Salient Features of Test

The concrete strength decreased with increasing temperature and heating time. The grade of concrete affects the residual compressive and flexural strength: the decrease in the strength of ordinary concrete is more than that in HPC, the effect being more pronounced as the heating time increases. Polypropylene fibres were found to have a beneficial effect on residual strength of HPC at least at high temperatures over their melting and vaporization.

The Influence of elevated temperatures on physical and compressive strength properties of concrete containing palm oil fuel ash was investigated (Mohammad Ismail et al 2011)[19] using OPC, palm oil fuel ash (POFA), dry mining sand and crushed granite along with super plasticiser. Specimens were cast and stored under wet burlap for 24hrs and immersed in water for 28 days.

Maintaining target temperature for 1 hr, all the specimens were exposed to heat of 100,300,500 and 800oC, except control specimen. Some specimens were allowed for air cooling at room temperature and some others were subjected to water cooling by water spaying and allowed to remain under the same condition of temperature.

It was inferred that except in the air-cooling of POFA concrete, there was a continuous decrease in the residual compressive strength with increasing temperature. Highest reductions were observed in OPC concrete which include; 22.5%, 33% and 78% at 300oC, 500oC and 800oC respectively. The corresponding values against POFA are 2.9%, +5.1% (increase) and 51.7%. At temperatures of about 350–550oC, positive achievements on residual performance over original performance could be realized in favour of POFA concrete especially when no water is involved in its cooling. Also observed that air-cooling exhibited superior qualities over water-cooling by maintaining higher residual properties and at 300oC and 500oC the retained residual performance by air-cooling over water-cooling was up to 13% and 34% in relation to OPC and POFA concretes respectively.

Close observations on crushed specimens revealed that the surface colour penetrates into the concrete and this depends upon the intensity of the inward heat. While clear surface discolouration is seen to last up to about 10 mm deep, particularly on specimens exposed to 500oC or less, the colour penetrates deeper in the case of specimens subjected to 800oC. The formation of large cracks on specimens revived through water-cooling could serve as a stimulus for encouraging fire fighting with means other than the use of normal water-spray. It was suggested that, more research is needed especially on high strength POFA concrete, which may in addition to its high density entertain spalling at lower temperatures because of the moisture expected in the porous POFA particles.

Salient Features of Test

The residual performance was found to be higher in POFA concrete than in the normal concrete. Water cooling was realized to aggravate strength reduction in both normal and POFA concretes when compared to air - cooling. High temperature and cooling system were also found to have great importance on physical properties, such as; mass loss, discolouration and crack patterns.

The Compressive and splitting tensile strength of autoclaved aerated concrete (AAC) containing perlite aggregate and polypropylene fibre subjected to high temperatures was experimentally investigated (Borvorn Israngkura Na Ayudhya 2011)[20] using AAC cementitious materials containing perlite at 15%, 20% and 30% sand replacements and the polypropylene fibre content of 0 to 2% by volume. Concrete specimens were cast and kept in pressurized chamber at temperature of 180-190oC for 8 hours. The specimens were exposed to a temperature of 100 to 1000oC for a period of 3 hours. Compressive and splitting tensile strength tests were carried out. The unheated AAC specimens were tested for their strength and compared with that of the heated specimen of AAC mixed perlite for different percentage replacement and for different % of mix of PP fibre.

It was observed that the strength of AAC has reduced when the exposure temperature increased and above 400oC a rapid decline in strength was observed. High exposure temperatures, 800oC and 1000oC, did have significantly affect the strength of the specimens. Also observed that introducing 0.5% by volume of PP fiber dosage in mixing dose give the highest strength of AAC but further addition of dosage beyond 0.5% of PP fiber caused the decrease in strength.

It was reported that replacement sand with perlite increased the unheated compressive and splitting tensile strength. 30% of replacement gave the highest strength results. The compressive strength decreased when the content of perlite increased with no fibre. This can be attributed to the transition amount of crystallization of tobermorite. In addition, as perlite dosage increased, the quantity of mixing water also increased considerably, which had a negative effect on strength performance. Also concluded that the strength of material gradually increased as the exposure temperature went up to 100°C. Above 100°C the strength of material declined, regardless to the content of fiber and perlite. At 100°C, the heated strength of compressive and splitting was higher, approximately 5-9% of its unheated specimens, regardless the presence of fibre. The compressive and splitting tensile strength of specimens rapidly deteriorated at around 500-600% of its unheated specimens when the exposure temperature reached 1,000°C. It was also inferred that there was not enough evidence to support an increase of strength when perite and PP fibre was used together with AAC mixture. There was significant change in colour at different elevated temperatures from 200°C to 800°C.

Salient Features of Test

The unheated compressive and splitting tensile strength of AAC specimens containing PP fibre was not more effective foe residual compressive strength than splitting tensile strength. This indicated that the primary mechanism causing strength degradation was micro cracking, which occurred as water expanded and evaporated from the pores of the structure. the 30% perlite replacement of sand gave the highest strength.

The effect of elevated temperature on strength of differently cured concretes was studied (Krishna Rao.M.V. et al 2011) [21] using OPC and Portland Pozzolana cement (PPC), river sand , coarse aggregate, Micro silica and Concure WB water based concrete curing compound. The experiments were conducted on a design M40 grade concrete mix proportion with 10% micro silica with w/c ratio of 0.43. Specimens were cast and cured by conventional water curing and also by application of membrane forming curing compound for 28 days and specimens were exposed to 150 to 450oC for 1 hour and the some specimens were left unheated. After 1 hour they were air cooled to room temperature and the compression test and Non-destructive tests such as Rebound Hammer, U.P.V per standards of British Standards were conducted.

It was concluded that the concrete mixes suffered an increasing loss in their compressive strength on exposure to increasing sustained elevated temperature in general. The loss of strength is comparable in the mixes prepared by using OPC and 10% SF, when cured by conventional water curing. Results indicated the losses in relative strength due to high-temperature exposure and the presence of 10% silica fume seemed to have no significant effect. The 28-day compressive strengths of concrete specimens cured by conventional water curing have been more than those cured by membrane curing in both unheated and high temperature exposures. Less weight loss was observed less in membrane cured concrete specimen when compared to conventional water cured specimens.

It was also reported that the Rebound number on different cubes have been more or less the same and ranged from 23-28 for conventional wet curing specimens and 22-26 for the specimens cured with membrane forming cured compounds respectively. Also inferred that the pulse velocity values of unheated specimens and also those exposed to 150oC for 1 hour possessed ‘good’ concrete quality grading, irrespective of method of curing But, the specimens exposed to 300oC and 450oC for the same 1 hour duration indicated concretes of ‘medium’ quality and ‘doubtful’ quality respectively.

Salient Features of Test

The compressive strength and weight of concrete decreased with increasing temperature. It has a bearing cementing material and method of curing. Specimens subjected to conventional curing performed relatively better than those of membrane curing.

The effect of high temperature and fibre content on the residual mechanical properties of concrete was investigated (Young-sun Kim et al 2012)[22] using OPC, sea sand as fine aggregate, crushed gravel as coarse aggregate, poly carboxylic based super plasticiser and polypropylene fibres. The w/c ratios of 0.55 to 0.35 with varying PP fibre of 0.05 to 2% by volume of cement The specimens were cast and cured in water and tested at room and high temperature. The first specimen for the unstressed test (pre-load of 0%) and the second and the third were pre-loaded to 20 and 40% of their ultimate compressive strength for 1 hr at room temperature respectively.

The above investigations inferred that polypropylene fibre reinforced concrete exposed to high temperature has a significant decrease in the parameters evaluated (compressive strength, modulus of elasticity, strain at peak stress) with respect to those kept at room temperature. It has no particular impact in the mechanical properties with the amount of 0.05–0.2 vol.% PP fibre used for preventing explosive spalling. The residual mechanical properties of concrete with PP fibres subjected to high temperature were increased with the increase of pre-load level. The pre-load is not efficient for the risk of spalling and the brittle failure tendency. Also it was observed that the excessive pre-load could shorten life of concrete in fire and also reported that the concrete need more than 0.05 vol.% PP fibers to prevent explosive spalling for all w/c ratios.

Salient Features of Test

PP fibre with a small cross-sectional area is effective in preventing the spalling and has no effect in increasing the residual mechanical properties. Concrete with pre-load after subjected to high temperatures was better in the energy absorption capacity than unstressed concrete, and the difference between the values of them decreased with the increase of compressive strength. The external loading influenced to increase not only the residual mechanical properties of concrete but also the risk of spalling and brittle failure tendency.

The role of fly ash composite concrete under sustained elevated temperature was investigated (Vishwanath. K.N. et al 2012)[23] using cement, crushed aggregate and river sand and fly-ash for mix replacing conventional Portland cement with 35%, 40% and 45% and concrete specimens were cast and cured for 28,56 and 90 days. All the concrete mixtures were exposed to 200oC and 300oC for 2 to 5 hours and then tested for compressive and tensile strengths. The states of Cao and quartz, hydration reaction were also analyzed by using XRD graphs.

The above investigation reported that the early age strength of fly ash concrete is in line with that of controlled concrete elements. For a moderate temperature rise of 200°C, fly ash concrete as well as controlled concrete elements have similar target mean strength at the end of 5 hours exposure. Elements with the higher fly ash content showed marginal improvement in their final strength for the curing periods of 56 and 90 days which is mainly due to the spherical shape of fly ash particles compared to the morphology of cement alone.

It was also reported that 35% fly ash replacement has a tendency to alter its capacity to take the compressive loading over the duration of exposure. At 28 days, elements with 40% replacement cement will sustain the achieved compressive strength for extended exposure duration. The controlled concrete have higher residual strengths and also the concrete blended with fly ash improved mechanical properties even after subjected them for prolonged exposure for different temperature ranges.

Salient Features of Test

Fly ash composite concrete sustained the achieved compressive strength for extended exposure duration and showed a study increase in their tensile strength taking capacity. This is due to the higher fly ash content having additional alumina leads to formation of more cementitious material filling the pores and increased density.

The behavior of HPC with fly ash after elevated temperature was studied (Huai- Shuai et al 2013)[24] using two high performance concrete mixes with characteristic compressive strength of 50MPa and 60MPa using natural river sand, crushed stone as coarse aggregate, fly ash of 20% and 21% by weight of cement and water reducing agent. The specimens were cast and cured for 28 days. At 120 days, the specimens were exposed to elevated temperature of 200oC, 300oC, 400oC, and 500oC and cooled naturally to room temperature and were tested.

The above investigation reported that the thermal properties, at elevated temperatures, exhibited by high- performance concrete are similar to those of plain concrete and the failure modes of HPC under uniaxial compression with and without friction-reducing pads were column – type fragments and taper - type fragments, respectively. It was also observed that the splitting tensile strain along the unloaded plane(s) was the cause of failure for both.

It was also concluded that above 300oC, the two types HSC lose their cleavage strength at faster rate and the cleavage strength at 500oC of two mixes is above 62.2% and 65.2% of the original strength (at 20oC), respectively.

The flexural strength dropped sharply compared to the original strength with the temperature increased from 200oC to 500oC.It was suggested that the data established on the effects of thermal properties of HPC elevated temperature can be used to develop mathematical models to predict the fire resistance of HPC structure member.

Salient Features of Test

The faster rate of drop in the strength of HPC at elevated temperature is due to the dehydration of the cement paste which results in gradual disintegration. The paste also tends to shrink and aggregate expands and the bond between the aggregate and the paste is weakened. The flexural strength and ultrasonic pulse velocity also dropped sharply at elevated temperatures. The variation in colour was also observed at elevated temperature.

The performance of rice husk ash concrete at elevated temperatures (Chandan Kumar.P et al 2013)[25] was investigated using Portland pozzolana cement, fine aggregate, coarse aggregate, Rice Husk Ash (RHA), water and super plasticiser, complast and M20 grade concrete was designed and cement in proportion of 0% to 20% is replaced with RHA. The concrete specimens were cast by maintaining the workability of 75mm and cured for 28 days in water. The test specimens were exposed to temperature of 100oC to 700oC for 2 hrs and air cooled and tested for compressive strength at the age of 7 and 28 days.

The above investigation inferred that the replacement of RHA in the range of 5% to 20% does not change the compressive strength of concrete. However, the workability decreases with the increase in RHA replacement level. To compensate the loss of workability super plasticizer in the dosage of 10ml, 12ml, 14ml and 16ml was required for 5%, 10%, 15% and 20% RHA replacement concrete respectively. The residual compressive strength of concrete for all the RHA replacements increases at the initial temperature of 100oC -150oC and thereafter decreases gradually up to temperature of 700oC because pore water evaporates at 100oC and the concrete matrix becomes brittle.

It was also reported that 15% replacement of RHA is found to be optimal as the residual compressive strength at various temperature in the range of 100oC - 700oC showed similar strength to that of cement without RHA at 28 days.

The overall performance of 10% RHA replacement level at both 7 and 28 days showed better residual compressive strength than that of normal concrete and other replacements.

Salient Features of Test

The addition of RHA can influence the physico - mechanical properties of concrete and causes significant increase in the hydraulic stability of cemented paste and enhances the strength, leaching and durability of cement. It was inferred that the rice husk ash usage in concrete as replacement, the emission of green house gases can be decreased to a greater extent with which more number of carbon credits can be gained.

The residual compressive strength of normal and high strength concrete at elevated temperatures was studied (ApehAban Joseph 2013) [26] using Portland cement , fine aggregate and coarse aggregate and water with water-cement ratios of 0.6, 0.39, concrete specimens were cast and cured for 28 days. On curing, they were dried and subjected to varying temperature (200oC – 800oC) for 2 hours. The specimens were then cooled in air and quenched in water. All the specimens were tested for compressive strength.

The above investigations reported that the concrete constituent materials used for the study met suitability requirements of relevant codes. and irrespective of concrete grade, concrete cooled in air has higher residual strength compared to that cooled rapidly in water. It was also concluded that the residual compressive strength loss increases with increase in temperature for both concretes. The CEN Euro code and the CEB design curves were applicable to Normal Strength Concrete but not applicable to HSC which needed further attention. It was also suggested for an effective approach other than quenching with water for a structure after a fire is imperative.

Salient Features of Test

The decrease in strength in both NSC and HSC at elevated temperatures is as a result of heat induced material degradation and the mechanical properties of concrete are dependent on their original non- heat treated values. The decrease in strength of both NSC and HSC also depends on the type of curing.

Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with lime stone and siliceous aggregates was investigated (Savva.A et al 2005) [27] using OPC, crushed lime stone and siliceous aggregates, three pozzolans either 10% or 30%. One natural of volcanic origin, Milos earth (ME) and two Greek lignite fly ashes, Ptolemaida fly ash(high calcium fly ash and with both pozzolanic and hydraulic activity) and Megalopolis fly ash.(Low calcium fly ash with a significant pozzolanic activity). Concrete specimens of size 150x150x150 mm cubes or 150x300 mm cylinders with w/b ratio of 0.5 were cast and cured for 28 days. At ages of 3, 7, 14, 28, 60 and 1095 days, specimens were tested by means of the rebound hammer and pulse velocity and compressive strength was determined after 3 years, the specimens were heated in an electric furnace at four temperature level from 100 to 750oC for 2h duration .and cooled down to room temperature.

The specimens were tested for residual compressive strength, modulus of elasticity, rebound values and ultrasonic pulse velocity. The investigation reported that the strength, modulus of elasticity, rebound values and ultrasonic pulse velocity are affected differently during heating. Concretes made with 10 MFA showed same behaviour between 100 to 750oC with pure OPC irrespective of type of aggregate.

Concrete with pozzolanic materials showed better strength results than the pure OPC concretes, up to 300oC irrespective of type of binder, and a decrease in strength was observed for the exposed heating above 300oC. Between 100oC and 300oC, the initial strength of all mixtures increases and is higher for siliceous concretes. At 600oC, the strength was reduced to about the half; the reduction is from 75% to 93% at 750oC.

A continuous drop in modulus of elasticity ranged from 94% to 99% at 750oC was noticed at all temperatures irrespective of type of binder and aggregate and it was higher for the lime stone concretes.

Salient Features of Test

The compressive strength, modulus of elasticity, rebound values and ultrasonic pulse velocity are affected differently during heating between 100 to 750oC for all types of aggregates and irrespective of type of binders. the initial strength was higher between 100oC to 300oC and was higher for siliceous concretes. Temperatures between 300 to 750oC was critical to the strength loss and it was observed that the greater the percentage of the replacement OPC, the greater the reduction in initial strength. Continuous drop of modulus of elasticity was also noticed at all temperatures.

CONCLUTIONS

The review provides the following conclusions based on the experimental investigations of various researchers:

- The use of natural and chemical admixtures like silica fume, fly ash, finely ground pumice, Palm Oil Fuel Ash, Rice Husk Ash as replacement of cement caused the decrease in the compressive strength, modulus of elasticity, tensile strength, ultrasonic pulse velocity and colour change of the concretes at elevated temperatures.
- The use of different w/c ratios and different types of aggregates exhibited reduction of mechanical properties of concrete at elevated temperatures particularly above 600^{o}C.
- Different curing methods irrespective of types of concretes made with different admixtures also

caused the reduction in the mechanical properties at elevated temperatures.

- Polypropylene fibres in concretes reduced the explosive spalling of concretes at elevated temperatures.

SCOPE OF FUTURE INVESTIGATION

Further research work can be carried out on NSC,HSC and HPC at elevated temperatures using ternary or tertiary concretes along with hybrid fibres, steel and glass, other pozzolanas like metakaolin, GGBS, Silica Fume, Fly ash, sewage wastes, agricultural wastes and other industrial wastes which are abundantly available reducing the consumption of cement creased with increase in the exposed to maintain the ecological balance.

Research on performance based designs are to be taken up in designing the fire resistant structures and analytical modeling is also very important part to be taken up.

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