International Journal for Research in Engineering Application & Management (IJREAM)
ISSN : 2454-9150 Vol-05, Issue-03, June 2019

Effect of Thermal Cycles On Concrete: An Overview

B. Vidya, Assistant Professor, Department of Civil Engineering, GVP College for Degree and PG Courses, Rushikonda, Visakhapatnam , Andhra Pradesh , India. vidya.barri@gmail.com

K. Srinivasa Rao, Professor, Department of Civil Engineering, College of Engineering, Andhra University, Visakhapatnam , Andhra Pradesh , India. killamsetti@yahoo.com

Abstract - Concrete is made up of two major components; hardened cement paste and graded aggregates. When such a material is subjected to heating/cooling cycles, unequal expansion/contraction of the components occurs due to the difference in coefficient of thermal expansion. This creates internal stresses which could lead to cracking of the composite material. For concrete material, this phenomenon is termed as thermal incompatibility of concrete constituents. Concrete is exposed to elevated temperatures during fire or when it is close to furnaces and nuclear reactors. The mechanical properties of concrete, such as strength, elastic modulus and deformation, decrease remarkably upon heating which results in a decrease in the structural quality of concrete. High temperature is one of the most important physical deterioration processes that influence the durability of concrete structures and may result in undesirable structural failures.

This paper presents a review of the work of various researchers on the mechanical properties of concrete subjected to the cycles of heating and cooling at elevated temperatures.

Keywords – Concrete, thermal cycles, internal stresses, mechanical properties.

I. INTRODUCTION

Codes contain minimum fire protection requirements based on a combination of knowledge of the physical properties and past experience of the behavior of various building materials when exposed to fire and upon fire endurance ratings specified by the survival times of specific structural assemblies or components in standard laboratory fire tests. Usually only the ambient temperature regime to a maximum is controlled in these tests. Therefore, such tests do not provide much information about the effect of specific high temperatures on the properties of concrete and its constituent materials.

To improve fire resistance in design, or to assess the condition and possibilities of repair of a structure damaged by fire, more needs to be known about the thermal and mechanical properties of steel and concrete at elevated temperatures and residual properties after slow or quench cooling. It is relatively easy to determine the residual properties by standard test methods and the results do provide much of the information needed to determine what can be saved after a fire. However, a researcher has to focus in determining the residual properties of concrete at sustained or cyclical high temperature. This kind of information has become increasingly in demand for several reasons. First, advanced industrial applications, in particular for nuclear reactors, require a greater knowledge of the properties of various types of concrete when subject to complex, sustained or repetitive, mechanical and thermal stress regimes at moderately high temperatures.Second, new concrete constituents and proportions continue to become available as some industrial and military applications require special concrete that is resistant to specific service temperature regimes.

Under normal conditions most concrete structures are subjected to a range of temperature no more severe than that imposed by ambient environmental conditions. However, there are important cases where these structures may be exposed to much higher temperatures e.g., jet aircraft engine blasts, building fires, chemical and metallurgical industrial applications in which the concrete is in close proximity to furnaces, and some nuclear power-related postulated accident conditions. Under such applications the effect of elevated temperature on certain mechanical and physical properties may determine whether the concrete will maintain its structural integrity.

Thermal cycling causes progressive degradation of concrete. The loss of strength in the concrete with temperature is influenced by number of factors. The method of testing, that is, the rate of heating, the duration of heating, size and shape of the test specimen, cooling regimes, number of thermal cycles and the loaded condition (loaded or unloaded during testing) have a significant effect on the change of strength with temperature. However, in this paper the literature study is restricted to duration of heating and number of thermal cycles.

 DOI : 10.35291/2454-9150.2019.0162

ISSN : 2454-9150 Vol-05, Issue-03, June 2019

II. LITERATURE REVIEW

Campbell Allen and Low [1] investigated the effect of elevated temperatures on concrete for reactor vessels. Cycles of temperature up to 300°C were applied to the concrete made with Ordinary Portland cement and dolerite aggregate. Progressive loss of compressive and tensile strength was observed, combined with large reduction of elastic modulus. Upto 250°C the loss of compressive strength of concrete cylinder after one thermal cycle is small, in fact at 200°C a slight increase in strength is apparent and is linked with the accelerated hydration of the cement during heating cycle.

Campbell Allen and Desai [2] studied the influence of aggregate on the behavior of concrete at elevated temperatures. Three aggregates, lightweight expanded shale, fireclay brick and a pure limestone, have been used in high strength concrete subjected to cycles of temperature upto 300°C. The temperature cycles were carried out in a laboratory oven with mechanical ventilation. Upto 20 cycles were applied with a maximum temperature selected as 300°C, 200°C and 65°C. All concretes showed marked deterioration of mechanical properties but the extent of deterioration was governed by the breakdown of bond between the aggregate and the mortar.

Bairagi and Dubal [3] investigated the effect of thermal cycles on compressive strength, modulus of rupture, dynamic modulus of elasticity of concrete. Tests were carried out on M20 concrete mix (1:2.4:3.6) with a water-cement ratio 0.55. The concrete specimens were heated to maximum temperatures of 60°C and 90°C from a room temperature of about 27°C, for a number of thermal cycles varying from 0 to 365 cycles. For higher number of thermal cycles, the rate of reduction was found to be decreasing.

Ramakrishnan [4] determined effects of cyclic heating on the strength of Portland cement concrete subjected to high temperature, and compare the effects of cyclic heating on concrete contaminated with hydraulic fluid and jet fuel with non-contaminated concrete. Specimens were tested after each of the following heating/cooling cycles: 0, 15, 30, 60, 120, 240, and 400. After every 15 heating/cooling cycles, the contaminated specimens were soaked in jet fuel or hydraulic fluid overnight before the next heating/cooling cycles. Test results indicate that jet fuel contamination is more detrimental than hydraulic fluid contamination. Compressive strength, flexural strength, and pulse velocity are adversely affected by the cyclic heating.

Khan [5] investigated on flexural strength of concrete subjected to thermal cyclic loads. The tests were carried out on normal weight concrete specimens of size 100 mm × 100 mm × 500 mm. The concrete was subjected to a constant temperature of 200°C for 7, 14, 21 and 28 heating cycles. One heating cycle corresponds to eight hours heating and subsequent cooling in twenty four hours. After the desired number of thermal cycles, the specimens were tested for flexural strength of concrete. Thermal cycling causes loss of strength in concrete.

Hakeem [6] studied the fracture properties of UHPC mixtures reinforced with steel fiber (fiber content varying from 0 to 6.2 % by weight) and subjected to thermal cycles were investigated to examine the effect of heat–cool cycles. The standard prism of 100 × 100 × 400 mm^3 with a central notch was used in a three-point bend test to determine fracture properties that include critical stress-intensity factor (K_{ic}), critical crack tip opening displacement (CTOD*c*), energy release rate, and total fracture energy. Test results show that UHPC reinforced with 6.2 % steel fiber exhibited excellent fracture properties with significant ductility. Both thermal cycling and prolonged self-curing of water-cured UHPC specimens enhance fracture properties because of more complete hydration of cement in UHPC.

Mohamad and Samir [7] studied the behavior of confined siliceous-aggregate concrete exposed to elevated temperature conditions such as those experienced during fire. Equally spaced steel rings were employed in the cylinders to simulate the effect of confinement on the material. At temperatures above 400°C severe cracking was observed in the specimens exposed to 3 and 5 cycles of heating. Results have indicated an improvement in the residual compressive strength up to about 30% and in the ductility of concrete at elevated temperatures due to the effect of confinement by ties.

Garg and Singh [8] produced cementitious binders by blending 60-70% fly ash with calcined phosphogypsum, hydrated lime sludge, Portland and chemical activator in different proportions. The results show that strength development of binders takes place through formation of enttringite, C-S-H and wollastonite. The durability of cementitious binder has been studied by its performance in water and by accelerated aging, i.e., alternate wetting and drying as well ae by heating and cooling cycles at temperatures from 27 to 50°C. The results indicate that the strength of the binder decreased with increasing cyclic studies at different temperatures.

Komendant [9] investigated the effect of testing temperature on the compressive strength as well as the influence of thermal cycling between 43°C and 71°C on the strength and elastic properties of concrete with constant rate of 3°C/min. They observed that the compressive strength of the concrete is reduced by 3–11% at 43°C and 11–21% at 71°C.

Haddad [10] investigated the role of synthetic and short brass-coated steel fibers in preserving bond between reinforcing steel and concrete, subjected to cycles of heating and cooling. The bond behavior was evaluated by means of cylindrical pullout specimens (75 mm x150 mm)

 DOI : 10.35291/2454-9150.2019.0162

ISSN : 2454-9150 Vol-05, Issue-03, June 2019

reinforced with 18 mm rebars embedded along the full length of the specimens. The results showed that heating and cooling cycles caused a significant loss in splitting tensile and bond strengths after 80 cycles of heating and cooling that reached as high as 44% and 28% respectively. Fibers contributions to preserving bond strength of reinforced concrete were dependent upon both fiber type and content. Results showed that the use of fibers would allow relatively high free-end slippage between embedded steel and reinforcement prior to failure. The study showed that the percentage loss in bond strength at various heating and cooling cycles was larger than that in splitting tensile strength.

Davis [11, 12] investigated the effects of heating–cooling cycles between 40°C and 200°C, and 40°C –350°C on bond strength using pullout specimens. The results indicated that high percentage of total bond loss to take place after the first cycle and that the percentage loss reached as high as 28% after 20 cycles of heating and cooling.

Bertero and Polivka [13] Studied the effect of thermal cycling on plain concrete indicated significant reductions in compressive and tensile strengths that reached up to 45% when adopting a thermal cycling of up to 300°C. It showed that the amount of damage is dependent on concrete proportions and type of aggregate used, and on whether specimens were sealed during testing or not.

Polivka [14] examined concrete that allowed moisture a controlled escape or sealed it in, over durations up to 14 days of thermal exposure cycling up to 143°C (300°F). They showed the following: For a constant moisture condition (sealed) of the concrete, its thermal coefficient of expansion decreased during thermal cycling to 143°C (300°F). A similar decrease was observed for concretes that successively dried out during thermal exposure. After the first thermal cycle (21 to 143 to 21°C) (70 to 300 to 70°F) of the concrete in a moist condition, a significant residual expansion was observed, and this expansion successively increased with the number of cycles.

Anders [15] conducted experiments in order to investigate the effects of different types of cements and aggregates, increased number of thermal cycles and different storing climates on concrete mixtures. It is demonstrated that the compressive strength starts to decrease at temperatures above 250°C. The temperature levels were chosen as 250°C, 500°C and 900°C. After being exposed to 250°C, the residual compressive strength decreased by about 20%. If the specimens were heated upto 900°C storing the specimens in different climate seems to increase the residual compressive strength compared to an immediate testing after cooling down of the specimen.

Sjostrom [16] studied the effect of heating and cooling cycles on compressive strength, ultrasonic pulse velocity, resonance frequency and residual expansion of limestone concrete. Specimens were cured at 27°C for 28 days prior to initiation of test program. Cubes were tested at the end of 20, 40 and 80 heating – cooling cycles. Compressive strength of concrete cubes subjected to thermal cycles is expected to rise due to continued hydration of cement. Effect of thermal cyclic loading on limestone concrete assessed by longitudinal resonance frequency (RF) and ultrasonic pulse velocity measurements showed retrogression in quality. Specimens subjected to 30°C-60°C and 30°C - 90°C thermal cycles showed a reduction in RF of 12% and 13% respectively at the end of 70 cycles whereas quartzite concrete is only 5% which occurred during the initial 3-5 cycles. This is due to reduction in weight caused by moisture loss from the concrete during this period. The limestone rock was found to have pronounced residual expansion behavior when compared to quartzite rock.

Roberto and Gambarova [17] studied the mechanical properties of two high strength concretes (f_c= 72 and 95 Mpa), with siliceous aggregates (mostly flint) under uniaxial compression after single thermal cycle at 105, 250, 400 and 500°C. The results show that while concrete toughness increases after at high temperature, strength and stiffness decrease dramatically and the recovery of strength in time is either nil or negligible. Two concretes were very sensitive to high temperature, both the strength and stiffness decrease at and beyond 250°C; after a cycle at 250°C the residual strength is down to 80 to 66% of strength at room temperature but at 400°C residual strength decreases by 35- 25%. The degradation of Young’s modulus is more impressive.

Farhat and Assadi [18] investigated the effect of thermal cycles on the behaviour of reinforced concrete beams. The concrete beams were heated to a maximum temperature of 90˚C from the room temperature of about 25˚C. The number of thermal cycles varied from 0 to 90 cycles. After the requisite number of thermal cycles, the beams were tested at room temperature in four-point bending. All beams exhibit excessive cracking accompanied with a further reduction in stiffness just after the initial flexural cracking has started. This phenomenon can be attributed to the increase in the number of micro cracks in concrete after 90 thermal cycles. It is shown that thermal cycling can increase the maximum load carrying capacity of reinforced concrete beams.

Carette [19] investigated the changes in mechanical properties of a limestone aggregate concrete after exposure to temperatures of 75°C and 300°C for periods up to 8 months and 600°C for 1 month. After 8-month’s exposure to 75°C, compressive and splitting-tensile strengths were 98 and 94% respectively, of their reference values. However, after exposure to 600°C for just 1 month, compressive and splitting-tensile strengths were only 23 and 38%, respectively, of their reference values. In companion mixes

 DOI : 10.35291/2454-9150.2019.0162

ISSN : 2454-9150 Vol-05, Issue-03, June 2019

where either fly ash or blast furnace slag was used, improvement in retention of mechanical properties occurred after exposure to sustained high temperatures as a result of partial replacement of the cement.

Mears [20] investigated the effect of long-term exposure (up to 13 years) at moderate elevated temperature (65°C) on the mechanical properties of a limestone aggregate concrete. Tests conducted during this study were somewhat unusual because the specimens were first subjected to a simulated temperature-vs-time cement hydration cycle. Also, because the concrete mix was being evaluated for an application that experienced exposure to sulfate bearing groundwater at elevated temperatures (~65°C), both ordinary and sulfate-resistant Portland cements were investigated. Results indicated that there was no evidence of long-term degradation in compressive strength for any of the concrete mixes and heat treatments utilized, and that for a given compressive strength the dynamic modulus of elasticity was lower for the concrete that had been heated. Cooling down and reheating the limestone and flint aggregate mixes for a total of 87 cycles did not appear to cause degradation in strength.

Defigh-Price [21] conducted 5-year testing program to determine the effects of long-term exposure to elevated temperature on the mechanical properties of concrete used in construction of the radioactive underground storage tanks at Hanford Engineering Development Laboratory (HEDL). Tests were conducted using specimens fabricated from the same mix proportions and materials specified for the concrete used to fabricate the tanks (20.7MPa and 31.0 MPa design compressive strengths). Concrete strength, modulus of elasticity, and Poisson's ratio values were determined from specimens subjected to 121˚, 177˚, or 232°C for periods of up to 33 months. The effect of thermal cycling was also investigated. Results showed that the compressive strength in general tended to decrease with increasing temperature and also with length of exposure; however, with the exception of the cylinders exposed to 232°C, all compressive strength results obtained after a 900-d exposure period exceeded the design values noted previously. Splitting-tensile strength results also decreased somewhat with increasing temperature and length of exposure. Modulus of elasticity was affected the most by the elevated-temperature exposure; after 920 d of heating at 232°C, it had a value that was only 30% the value obtained from an unheated control specimen.

Gillen [22] investigated the laboratory results by testing samples removed from the underground storage tanks and process buildings at HEDL. Cores 76-mm in diameter were obtained over the length of the haunch wall and footing of a single-shell tank that was built in 1953; contained waste for about 8 years; reached temperatures in the range of 127°C to 138°C; and experienced a radiation field of 0.10 to 0.13°C/kg/h (400 to 500 R/h). Although considerable scatter was obtained from the data because of different concrete pours and different environmental exposures, after about 29 years of exposure only one data point fell below the 20.7-MPa design compressive strength.

Nasser and Chakraborty [23] examined the effect of temperature on sealed and unsealed air-entrained concrete containing fly ash, conventional water reducer, and superplasticizer. The properties of compressive strength and modulus of elasticity were studied at seven different temperatures ranging from 11°C to 232°C and at seven different exposure periods from 1 to 180d. The results indicate that up to a temperature of 121°C there was no degradation in compressive strength for exposures up to 180d. With increasing temperature, the strength decreased with the extent of strength reduction generally proportional to the exposure temperature and time at temperature (e.g., at 232°C and 180-d exposure the strength was about 50% its reference value). The modulus of elasticity started to decline monotonically at temperatures ≥ 71°C with the decline in modulus proportional to the exposure temperature and time at temperature (e.g., at 232°C and 180-d exposure the modulus was about 25% its reference value).

Carrette and Malhotra [24] had conducted experiments to evaluate the relative performance of limestone and dolostone aggregate ordinary Portland cement concretes under sustained exposure to high temperature. After 28-d moist cure followed by 26 weeks of room temperature curing, the test specimens were exposed for up to 4 months to temperatures ranging from 76°C to 450°C, and 1 month for a 600°C exposure. The loss of compressive strength of specimens exposed to elevated temperature was proportional to the exposure temperature. At temperatures of 150°C and higher, an increase in length of exposure from 48 h to 4 months resulted in further decreases in strength. In all cases, any major loss in strength was found to occur within the first month of exposure. In general the leaner concretes (water-cement ratio = 0.6) were slightly less affected than the richer concretes in terms of relative strength loss after exposure.

Suzuki [25] investigated the effect of elevated-temperature exposure at 65°C, 90°C, or 110°C for periods up to 3.5 years in Japan in support of nuclear power plant facilities. Either basalt or sandstone coarse aggregates were utilized in the concrete mixtures. Cementitious materials studied included Class B fly ash, moderate heat cement plus fly ash, and normal Portland cement. Heating conditions adopted were: (1) long-term heating tests [allowable temperature except for local areas (long-term) (65°C), allowable local temperature (long-term) (90°C), temperature at which water is considered to evaporate rapidly (110°C)]; (2) short-term heating tests [allowable temperature (short-term) (175°C)]; and (3) thermal cycling tests for up to 120 cycles [cycled heating temperatures

DOI : 10.35291/2454-9150.2019.0162

(20°C to 110°C to 20°C) to simulate temperature variations during operational periods]. During the thermal-cycle heating test, compressive strength after heating was greater than before heating under both sealed and unsealed conditions. However, the ratio of increase was smaller than under constant heating, suggesting the influence of thermal cycling. For the same number of thermal cycles, the compressive strength was consistently higher for the sealed specimens relative to that obtained from unsealed specimens. Under unsealed conditions specimens exhibited little influence of number of cycles on compressive strength for thermal cycle numbers greater than five (i.e., little change in compressive strength value for cycles greater than five). Under unsealed conditions the modulus of elasticity exhibited a similar trend to that obtained for constant heating in that it was reduced by about 50%.

Kasami [26] conducted studies to evaluate the drying effect of elevated-temperature exposure on the properties of concrete. Specimens made from four concrete mixes of ordinary Portland cement and river-gravel aggregate were tested to investigate the compressive, tensile, and bond strengths; moduli of elasticity; and weight loss after 90-d exposure to temperatures of 35˚, 50˚, 65˚, 80˚, 110˚, 200˚, and 300°C. The influence of aggregate on the properties of heated concrete was significant. Sandstone and basalt aggregate concretes indicated smaller reductions, while limestone, andesite, and serpentine aggregate concretes showed greater reductions in strengths after exposure. Changes in chemical composition in the cement paste were not noticeable below 100°C; however, the porosity was found to be affected by the exposure temperature. The unusual deterioration in strengths at around 50°C can be due to either the expansion of cement paste or to the change in porosity caused by evaporation of free water.

Kanazu [27] conducted studies to rationalize the design method for facilities used to store spent fuel and to obtain fundamental data for estimating the long-term safety of the facilities under elevated temperature exposure conditions. Four concrete mixes were employed in the study: two ordinary Portland cement concretes having design compressive strengths of 24 and 40 MPa, and two concrete mixes having design compressive strength of 40 MPa in which 55% (by weight) of the ordinary Portland cement was replaced by blast furnace slag. Shale and limestone coarse aggregate were used in the concrete mixes. Conclusions derived from the study were that the decrease in compressive strength at temperatures of 65˚ and 110˚C basically ended after three months under unsealed conditions and after 1 to 2 years exposure for sealed conditions as the moisture condition stabilized.

III. DISCUSSION ON RESULTS

Based on information presented in the paper, several observations can be made relating to the behavior of Portland cement concrete materials at elevated temperature.

A. General Behaviour

- Deterioration of concrete's mechanical properties can be attributed to three material factors: (1) physicochemical changes in the cement paste, (2) physicochemical changes in the aggregate and (3) thermal incompatibility between the aggregate and the cement paste. Concrete properties are influenced by environmental factors such as temperature level, heating rate, applied loading, and external sealing influencing moisture loss.
- Key material features of Portland cement paste that influence properties of concrete at high temperature are its moisture state (i.e., sealed or unsealed), chemical structure (i.e., loss of chemically-combined water from C-S-H in unsealed condition, CaO/SiO_2 ratio of hydrate in sealed condition, and amount of $Ca(OH)_2$ crystals in sealed and unsealed condition), and physical structure (i.e., total pore volume, average pore size, and amorphous/crystalline structure of solid).
- Micro cracking is a major cause of deterioration when concrete is exposed to high temperatures and is reported to initiate around calcium hydroxide crystals and then around unhydrated cement particles.
- The aggregate-cement paste bond region has been shown to be the weakest link because it is normally weaker than the cement paste which is normally weaker than the aggregate. If the aggregate-cement paste bond fails on heating, chemically, or as a result of thermal incompatibility between the aggregate and cement paste, the concrete will exhibit a significant reduction in strength, even if both the aggregate and surrounding mortar matrix remain intact.
- Normally aggregates are more stable at elevated temperature than the hardened cement paste when exposed to high temperatures, although decomposition of some less thermally stable aggregates may occur when exposure temperatures are extremely high. Lightweight aggregates exhibit little thermal expansion and therefore little damage to concrete while having small thermal conductivity. It has been noted that the thermal stability of aggregates increases in order of gravel, limestone, basalt, and lightweight.
- In general, for structural applications involving service temperatures in the range of ambient to 300°C or 400°C, provided many temperature cycles of large magnitude are not present, Portland cement concrete are the best materials if heat-resistant aggregates (basalt, limestone, or serpentine) are used. The critical temperature for Portland cement concrete is 400°C above which concrete would disintegrate on subsequent post-cooling to ambient conditions. Cracking of heated concrete during post-

 DOI : 10.35291/2454-9150.2019.0162

cooling can be ascribed to the rehydration of dissociated calcium hydroxide resulting in a 44% volume increase. Reduced calcium hydroxide in cement paste due to the presence of pulverized fly ash that can consume the calcium hydroxide can reduce cracking. At higher temperatures or for prolonged exposure to temperatures around 600°C, special procedures would have to be considered such as removal of the evaporable water by moderate heating.

B. Mechanical Properties

Stress-Strain Behavior

- Under steady-state conditions, the original concrete strength, water-cement ratio, heating rate, and type of cement have minor influence on the stress-strain behavior. Aggregate-cement ratio, aggregate type, and presence of a sustained load during heating affect the shape of the stress-strain curve. Harder aggregates (siliceous, basaltic) exhibit a steeper decrease of initial slope due to elevated temperatures than softer aggregates (lightweight). Other parameters that affect the stress-strain relationship at elevated temperature are the moisture condition and the number of thermal cycles.
- Aggregate type has an effect on ultimate strain under high temperature conditions (i.e., carbonate aggregate concrete strain at peak strength was up to 40% greater than that for siliceous aggregate concrete). Siliceous aggregates expand the most and give the largest damage, and are further damaged on cooling.
- As the temperature increases the ultimate strain increases and the stiffness decreases. Specimens tested at temperature are stiffer than specimens permitted to cool to room temperature prior to testing; type of cement and duration of thermal treatment have a minor effect on slope of stress-strain curve. Compressive peak strain increases almost linearly with temperature. Peak strain after exposure (residual) is higher than peak strain measured at temperature and is greater for concrete cooled rapidly with water than cooled slowly by air.
- Unsealed specimens are stiffer than sealed specimens but strains at ultimate are reduced.
- Mineral additions can improve the stress-strain performance of concrete at elevated temperature.
- The mechanical strains in biaxial compression loading were found to be dependent on the stress level, the stress ratio, and the test temperature. When concrete is under a biaxial tension-compression state of stress the capability of concrete to resist cracking is diminished, both the tensile and compressive strengths are found to decrease rapidly with increasing exposure temperature, and the concrete fails abruptly due to tensile stress.

Modulus of Elasticity

- Elastic modulus decreases with elevated temperature exposure due to breakage of bonds in the cement paste microstructure with the reduction in modulus increasing as the heating rate increases. Variation of modulus values at temperatures up to 80˚C is considerable, primarily as a result of use of different aggregate materials, and above 100˚C the decrease is linear with increasing temperature up to a critical temperature at which concrete experiences deterioration.
- Type of aggregate has strong influence on modulus with lightweight concrete exhibiting the lowest decrease with temperature and siliceous aggregate concrete the highest. Aggregates that are more compatible with the cement paste and chemically stable provide lower loss of modulus. Concrete containing aggregates with low thermal expansion experience a greater reduction in modulus than those with a higher thermal expansion.
- Modulus after high temperature exposure (residual) is lower than that obtained at room temperature.
- Normal strength concrete (fc' < 60 MPa) retains their modulus better at temperature than high strength concrete.
- Sealed (mass concrete) specimen modulus values tend to be more sensitive to elevated temperature than specimens that are unsealed.
- The presence of a preload improves the modulus retention under high temperature exposure.
- The method of cooling after elevated temperature exposure affects the residual modulus of elasticity with rapid cooling (water quenching) producing the lowest values of residual modulus.

Compressive Strength

- Original concrete strength of normal strength concrete, type of cement, aggregate size, heating rate, and water-cement ratio appear to have a minor effect on the relative concrete strength at elevated temperature.
- Type of aggregate appears to be one of the main factors influencing concrete compressive strength at high temperature with siliceous aggregate concrete having lower strengths (by percentage) at high temperature than calcareous and lightweight aggregate concretes.
- Concrete in the temperature range of 20°C to 200°C can show a small strength loss. Between 20 and 120°C any strength loss that occurs is attributed to the thermal swelling of the physically bound water,

 DOI : 10.35291/2454-9150.2019.0162

that causes disjoint pressures. A regain of strength is often observed between 120°C and 300°C and is attributed to greater van der Waals forces as a result of the cement gel layers moving closer to each other during heating. Between 200°C and 250°C the residual compressive strength is nearly constant. Beyond 350°C there can be a rapid decrease in strength.

- Strength losses for unstressed concrete up to about 300˚C are generally < 20% irrespective of type of cement or aggregate. At temperatures > 300˚C strength losses can become relatively great and at temperatures > 450˚C concrete compressive strength drops significantly due to differences in thermal expansion coefficients between aggregate and cement paste (i.e., loss of bond) and decomposition of calcium hydroxide.
- The presence of preload, within reasonable limits, improves retention of compressive strength at elevated temperature for both Portland cement concrete and blended cement. Although data are limited, a similar conclusion can apparently be derived with respect to residual compressive strength retention. Improved performance has been attributed to densification of the cement paste resulting in a large transient creep component and possibly a reduction in porosity relative to the unloaded state, and pre compression can reduce the tensile stresses in the concrete, particularly during cooling.
- Moisture content at time of testing has a significant effect on the strength of concrete at elevated temperature with strength of unsealed concrete being higher than strength of sealed concrete.
- Factors that contribute to the general trend for concrete compressive strength to decrease with increasing temperature are: aggregate damage; weakening of the cement paste-aggregate bond; and weakening of the cement paste due to an increase in porosity on dehydration, partial breakdown of the C-S-H, chemical transformation on hydrothermal reactions, and development of cracking.
- Concrete containing fly ash can exhibit an increase in strength in the temperature range of 121 to 149˚C due to the formation of tobermorite which has been reported to be two to three times stronger than C-S-H gel. Although limited, results for concrete containing supplementary cementitious materials indicate that the residual compressive strength retention is highest for concretes containing slag and fly ash, followed by concrete containing metakaoline, with silica fume exhibiting the lowest residual compressive strength at the higher temperatures.
- The higher the cement content the greater the loss in strength. Strength loss in saturated normal strength concrete is greater than dry concrete and higher moisture contents contribute to increased spalling of concrete during significant thermal gradients such as could occur under fire conditions.
- Concrete that is rapidly cooled form elevated temperature (e.g., water quenching) exhibits a lower residual compressive strength than specimens that are gradually cooled from elevated temperature prior to testing. The effect of rapid cooling seems to decrease somewhat at high temperatures; however, the residual compressive strength already has been severely reduced by exposure to these temperatures.
- Concrete containing lightweight/thermally stable aggregates exhibit greater retention of compressive strength at temperature (relative) than those permitted to cool to room temperature (residual) prior to testing.
- Residual and relative compressive strengths of fibrous concrete at temperatures above 200˚C both exhibit a trend for a linear decrease in strength with increasing temperature.

Thermal Cycling

- Thermal cycling, even at relatively low temperatures (e.g., 65˚C) can have a degrading effect on concrete's mechanical properties. Compressive strength, tensile strength, and bond strength to steel reinforcement decrease under thermal cycling.
- The largest percentage decrease in properties for thermal cycling at higher temperatures (e.g., 200˚ to 300˚C) occurs during the first thermal cycle with the extent of damage dependent on the aggregate type and is associated with loss of bond between the aggregate and cement paste matrix.
- Compressive strength of specimens was adversely affected due to repeated heating. At temperatures more than 400°C, severe cracking of specimens occurs (plain concrete).
- The mode of failure of heat cycled concrete is altered from that of unheated concrete in that the failure of heated concrete is more gradual and accompanied by larger strains.
- The adverse effect of thermal cycles on the properties of concrete is probably due to the thermal incompatibility of concrete constituents. Thus care should be taken while selecting the aggregate and it should be ensured that the coefficients of thermal expansions of the cement paste and aggregate do not differ much so as to avoid the thermal incompatibility between them.
- Cyclic heating regimes of confined concrete, performed by subsequent heating and cooling to the same boundary temperature levels, cause an increase in the maximum strain at elevated temperatures.
- Confined concrete shows higher compressive strength and maximum strain at elevated temperatures than those of plain unconfined concrete. The effect of increasing the number of

 DOI : 10.35291/2454-9150.2019.0162

cycles of heating causes an increase in the strength of confined concrete specimens at temperature up to 400°C. Conversely, at temperatures above 400°C, the concrete specimens experienced a loss of integrity under the effect of cycles of heating greater than 1.

- When different cementitious binders subjected to alternate heating and cooling cycles the strength is reduced with an increase in temperature.
- There is gain in strength after cooling in all grades of controlled and bacterial concretes may be due to the absorption of moisture from the surrounding medium which leads to extra hydration. The moisture content has a significant bearing on the strength of concrete. At elevated temperatures, the dehydration of the cement paste results in its gradual disintegration. Since the paste tends to shrink and aggregate expands at high temperature, the bond between the aggregate and the paste is weakened, thus reducing the strength of the concrete. The type of aggregates and mixture proportions influence the degradation in the strength of heated concrete.
- Weight reduction takes place in the specimens at all temperatures of exposure due to the release of water. Because of the release of bound water from the cement paste, air voids are formed in the concrete. The structural integrity of the specimens deteriorates as confirmed by the increase in weight reduction with increased temperature. The reduction in weight confirms the loss of mass by the concrete material and the increase in the proportion of air voids.

Tensile Strength

- Aggregate type and mixture proportions have a significant effect on the tensile strength vs temperature relationship of concrete.
- The effect of elevated temperature on the tensile strength of concrete shows a similar trend to its effect on compressive strength, but tensile strength is more sensitive to deterioration at elevated temperature.
- The decrease in tensile strength of calcareous aggregate concrete with temperature is greater than that of siliceous aggregate concrete at 500˚C, being about twice as much at this temperature.
- Concrete with lower cement contents have lower reduction in tensile strength than those with higher cement contents.
- At relative low temperatures (T < 175˚C) sealed specimens seem to exhibit improved retention of split tensile strength relative to results obtained from unsealed specimens.
- The rate of heating has minimal effect on the tensile strength at high temperature.
- Residual tensile strength (cold testing) is somewhat lower than the tensile strength determined at temperature (hot testing).
- Quenching specimens in water after exposure to high temperatures produces a significant decrease in flexural and splitting-tensile strengths (as well as compressive strength), with the decrease increasing as the maximum exposure temperature increased.

Long-Term Exposure (Aging)

- Results for exposure of concrete to elevated temperature for relatively long periods of time are limited.
- For moderate exposure periods (e.g., < 180 days) and temperatures (e.g., T < 232˚C), the concrete compressive strength and modulus of elasticity of sealed specimens tended to decrease with increasing exposure time and temperature, while specimens that were not sealed exhibited an improvement of or very slight reduction in compressive strength and improved retention of the modulus of elasticity relative to sealed specimens. The decreased performance of the sealed specimens was attributed to deterioration in the structural properties of the cement gel resulting from the saturated steam pressure at high temperatures. Modulus of elasticity was affected more than compressive strength as a result of extended exposure at elevated temperature.
- In general, most of the loss of concrete's mechanical properties under elevated temperature exposure for extended exposure periods will occur during the first two or three months exposure for unsealed conditions and at longer periods for sealed conditions as the moisture condition stabilizes (e.g., one to two years).
- There is an indication that partial replacement of Portland cement with fly ash or blast furnace slag imparts improved performance at elevated temperature.

IV. CONCLUSIONS

Maximum decrease in properties for thermal cycling at higher temperatures (200 to 300˚C) occurs during the first thermal cycle with the extent of damage dependent on the aggregate type and loss of bond between the aggregate and cement paste matrix. Thermal cycling, even at relatively low temperatures (65˚C) can have a degrading effect on mechanical properties. Compressive strength, tensile strength, and bond strength decrease under thermal cycling. Compressive strength was adversely affected due to repeated heating. At temperatures more than 400°C, severe cracking of specimens occurs in the case of plain concrete. Cyclic heating regimes of confined concrete, performed by subsequent heating and cooling to the same boundary temperature levels, cause an increase in the maximum strain at elevated temperatures.

DOI : 10.35291/2454-9150.2019.0162

This review clearly demonstrates the need and importance of studies to be taken up on the effect of thermal cycles on the behavior of concrete.

REFERENCES

[1] Campbell Allen D and Low E W E, "An investigation on the effect of elevated temperatures on concrete for reactor vessels," *Nuclear Structural Engineering*, No 2, 1965, 382-388.

[2] Campbell Allen D and Desai P M, "The influence of aggregate on the behavior of concrete at elevated temperatures," *Nuclear Engineering and Design*, No 6, 1967, 65-77.

[3] Bairagi N K and Dubal N S, "Effect of thermal cycles on the compressive strength, modulus of rupture and dynamic modulus of concrete," *The Indian Concrete Journal*, August 1996, 423-426.

[4] Ramakrishnan V, Hani F Shafai and George Wu, "Cyclic Heating and Cooling Effects on Concrete Durability", *ACI special publication* 126, 1285-1304.

[5] Khan, "Flexural strength of concrete subjected to thermal cyclic loads", *KSCE Journal of Civil Engineering*, Volume 18, Issue 1, January 2014 pp 249-252'

[6] Hakeem I, Azad A K, and Ahmad S, "Effect of Steel Fibers and Thermal Cycles on Fracture Properties of Ultra-High-Performance Concrete," *Journal of Testing and Evaluation*, Vol. 41, No. 3, 2013, pp. 1-7.

[7] Mohamad J Terro and Samir A Hamoush, "Effect of confinement on siliceous aggregate concrete subjected to elevated temperature and cyclic heating", *ACI Materials Journal*, Vol.94, Issue: 2, March-April, 1997.

[8] Mirdul Garg and Manjit Singh, "Strength and durability of cementitious binder produced from fly ash- lime sludge-portlant cement", *Indian Journal of Engineering & Materials Sciences*, Vol.13, February 2006, pp. 75-79.

[9] Komendant J, Nicolayeff V, Polivka M, Pirtz D, "Effect of temperature, stress level, and age at loading on creep of sealed concrete", *ACI special publication* 55, 1978, 55–82.

[10] Haddad H Rami and Abendeh M Raed, "Effect of thermal cycling on bond between reinforcement and fiber reinforced concrete", *Cement and Concrete Composites* 26(2004), 743-752.

[11] Davis HS, "Effects of high-temperature exposure on concrete", *Materials Research Standards* 1967; 7(10): 452–561.

[12] Davis HS, "Aggregate for radiation shielding concrete", *Materials Research Standards* 1967; 7(11): 494–501.

[13] Bertero VV and Polivka M, "Influence of thermal exposures on mechanical characteristics of concrete", *International Seminar on Concrete for Nuclear Reactors*, ACI Special Publication, 1(34), 1972. p. 505–31.

[14] Fahmi M Hani, Polivka Milos and Boris Bresler, "Effect of sustained and cyclic elevated temperature on creep of concrete", *Cement and Concrete Research*, Vol.2, pp. 591-606, 1972.

[15] Anders S, "Comparison of residual strength of concrete with quarzitic, limestone and slag sand constituents after cyclic high-temperature exposure, *Concrete Repair, Rehabilitation and Retrofitting IV- Dehn et al.(Eds)*, Taylor and Francis Group, London, 2016.

[16] Sjostrom C, "Durability of building materials and components-7", E & FN Spon, Vol.2, 2014.

[17] Roberto F and Pietro G Gambarova, "Effects of high temperature on the residual compressive strength of high strength siliceous concretes", *ACI Materials Journal*, Vol.95, No.4, July- August, 1998.

[18] Farhat F and Assadi S, "The effect of hot-dry environment on reinforced concrete beams", 32nd *Conference on Our World in Concrete & Structures*, 28-29th august, 2007.

[19] Carette G G, Painter K E, and Malhotra V M, "Sustained High Temperature Effects on Concretes Made with Normal Portland Cement, Normal Portland Cement and Slag, or Normal Portland Cement and FlyAsh", *Concrete International* **4**(7), pp. 41–51, July 1982.

[20] Mears A P, "Long Term Tests on the Effects of Moderate Heating on the Compressive Strength and Dynamic Modulus of Elasticity of Concrete", Paper SP 34-20 in *Concrete for Nuclear Reactors*, pp. 355- 375, American Concrete Institute, Farmington Hills, Michigan, 1972.

[21] Defigh-Price C, "Effects of Long-Term Exposure to Elevated Temperature on Mechanical Properties of Concrete", *ACI Symposium on Concrete and Cementitious Materials for Radioactive Waste Management*, New York, November 1, 1984.

[22] Gillen M P, "*Strength and Elastic Properties of Concrete Exposed to Long-Term Moderate Temperatures and High Radiation Fields"*, RHO-RE-SA-55 P, Rockwell Hanford Operations, Richland, Washington, 1984.

[23] Nasser K W and Chakraborty M, "Temperature Effects on Strength and Elasticity of Concrete Containing Admixtures", *Proceedings of Symposium Temperature Effects on Concrete*, ASTM Special Technical Publication 858, American Society for Testing and Materials, West Conshockon, Pennsylvania, 1985.

[24] Carrette G G and Malhotra V M, "Performance of Dolostone and Limestone Concretes at Sustained High Temperatures", *Proceedings of Symposium Temperature Effects on Concrete*, ASTM Special Technical Publication 858, pp. 38–67, American Society for Testing and Materials, West Conshockon, Pennsylvania, 1985.

[25] Suzuki T, Tabuchi M and Nagao K, "Study on the Degradation of Concrete Characteristics in the High Temperature Environment", *Concrete Under Severe Conditions: Environment and Loading* 2, pp. 1119–1128, E & FN Spon Publishers, 1995.

[26] Kasami H, Okuno T, and Yamane S, "Properties of Concrete Exposed to Sustained Elevated Temperature", Paper H1/5 in *Proc. 3rd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1975.

[27] Kanazu T, Matsumura T, and Nishiuchi T, "*Changes in the Mechanical Properties of Concrete Subjected to Long-Term Exposure to High Temperatures"*, Report No. U95037, Abiko Research Laboratory, Central Research Institute of Electric Power Industry, Japan, March 1996.

 DOI : 10.35291/2454-9150.2019.0162