EFFECT OF HEAT ON COMPRESSIVE STRENGTH OF CONCRETE

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ABSTRACT

This paper evaluates the effect of heat on the compressive strength of concrete by way of comparing the strength of concrete that was subjected to heat treatment with unheated one. Concrete ingredients available locally were obtained for the production of cubes into a dimension of 15x15x15 cm. A total of 12 cubes were cast and then cured at room temperature (28 °C). The cubes were divided into four sets. Each set comprised of 3 cubes for each Water-Cement ratio. Two of these sets were cured for 14 and 28-day out of which one set each was heated at a temperature of 200^{oc} for about 4 hours. They were then crushed subsequently to compare their strength. The results revealed that at the 14-day curing, the average compressive strength of unheated cubes was 19.4N/mm^2 for heated cubes and 17.4N/mm^2 for unheated ones. While at 28-day crushing, the average strength for unheated and heated cubes was 25.8N/mm^2 and 23.3N/mm^2 respectively. In both cases, the difference in strength is between 2N/mm^2 and 2.5N/mm^2 which is significant and can have a practical impact.The conclusion was drawn from the results obtained that the strength of concrete decreases as it is exposed to high temperature.

Key Words: Concrete, Curing, Compressive Strength, High Temperature.

INTRODUCTION

Concrete's thermal properties are more complicated than for most materials because not only is the concrete a composite material whose constituents have different properties, but its properties also depend on moisture and porosity. Exposure of concrete to high temperature affects its mechanical and physical properties (Naus, 2010). Elements could distort and displace, and, under certain conditions, the concrete surfaces could spall due to the build-up of steam pressure. Because thermally induced dimensional changes, loss of structural integrity, and release of moisture and gases resulting from the migration of free water could adversely affect plant operations and safety, a complete understanding of the behavior of concrete under long-term elevated-temperature exposure as well as both during and after a thermal excursion resulting from a postulated design-basis accident condition is essential for reliable design evaluations and assessments. Because the properties of concrete change concerning time and the environment to which it is exposed, an assessment of the effects of concrete aging is also crucial in performing safety evaluations. Presented in this research is an investigation into the effect of high temperature on the strength of concrete (Toumi et al., 2009).

Naus (2005) explained the process of manufacturing Portland cement as by mixing finely divided calcareous materials (i.e., lime containing) and argillaceous materials (i.e., clay). The four compounds that make up more than 90% of the dry weight of the cement are tricalcium silicate (3CaO•SiO2), dicalcium silicate ($2CaO{\bullet}SiO^2$), tricalcium aluminate ($3CaO{\bullet}A1_20^3$), and tetracalciumaluminoferrite ($4CaO{\bullet}A1_20^3{\bullet}Fe_20^3$). When water is added to Portland cement, an exothermic reaction occurs, and new compounds are formed (i.e., hydrated cement paste): tobermorite gel [(Ca5Si6016 $(OH)^2{\bullet}4H_20$)], calcium hydroxide, calcium aluminoferrite hydrate, tetracalcium aluminate hydrate, and calcium monosulfoaliminate. Mature cement paste usually is composed of 70–80% layered calcium-silicate-hydrate (C-S-H) gel, 20% $Ca(OH)^2$, and other chemical compounds. The C-S-H gel structure is made up of three types of groups that contribute to bonds across surfaces or in the interlayer of partly crystallized tobermorite material: calcium ions, siloxanes, and water molecules. Bonding of the water within the layers (gel water) with other groups via hydrogen bonds determines the strength, stiffness, and creep properties of the cement paste.

Tobermorite gel is the primary contributor to the cement paste structural properties. Under elevated-temperature exposure, the Portland cement paste experiences physical and chemical changes that contribute to the development of shrinkage, transient creep, and changes in strength. Key material features of hydrated Portland cement paste affecting the properties of concrete at elevated temperature are its moisture state (i.e., sealed or unsealed), chemical structure (i.e., loss of chemically bound water from the C-S-H in the unsealed condition, CaO/SiO^2 ratio of the hydrate in the sealed condition, and amount of $Ca(OH)^2$ crystals in sealed or unsealed conditions), and physical structure, that is, total pore volume including cracks, average pore size, and amorphous/crystalline structure of solid (Naus, 2005).

Concrete is a material used more often in the construction of high rise buildings, and it is a non-flammable material, and as thus been considered as a fire-proof material, hence, it is used in constructions with increased requirements for fire safety, since the concrete properties experience changes after the fire. Hence, it is essential to understand the change in the concrete properties due to extreme temperature exposures (Srinivasa and Vasusmitha, 2012). Thermal treatment is used in the process of concrete curing as well in order to obtain a higher early age strength. This method is widely used for the production of cycle optimization in the production of precast concrete elements (Nikolajs et al., 2013). This research work is aimed at determining the effect of heat on the compressive strength of concrete, comparing two different sets of hardened concretes by subjecting a set to an elevated temperature and leaving the other one unheated.

Several types of research regarding the impact of high temperature on concrete properties and its application have been carried out by several authors. Fillmore (2004) conducted tests on the effects of long-term exposure to elevated temperatures. The results showed that the compressive strength, in general, tended to decrease with increasing temperature and with the length of exposure. The compressive strength is reduced after exposure to about 540^oC. He thereby opined that in conventional concrete, long-term exposure to high temperatures could cause changes in compressive strength, modulus of elasticity, creep resistance, conductivity, diffusivity, and shrinkage/expansion characteristics and that in general terms, the threshold of degradation in the concrete is approximate 95^oC

Ghani et al. (2006), who determined the effect of temperature on different properties of concrete using different mix ratios of 1:1:2, 1:1.5:3, and 1:2:4, and water-cement ratios of 0.35, 0.40, 0.45, 0.50, 0.55, and 0.60, for cubes, cylinder sand beams. The concrete produce was cured in different room temperatures of 5^oC, 55^oC, and 28^oC. Based on theirs, the following assertions were made.

"(i)The high temperature during curing causes an increase in the initial compression strength of concrete that is; the initial compressive strength was lowest for 5 °C, high at room temperature while highest at 55 °C.

(ii)The same trend was observed for three and seven days. However an adverse effect on compressive strength was observed due to rising temperature at the age of 28 days that is the compressive strength was maximum at 5 °C, low for 28 °C and lowest for 55 °C. This trend was observed for all mix ratios". They concluded that there was temperature variation resulting in both positive and negative impacts on different properties of concrete. Also, those kind results were yielded, but keeping in view the demand of concrete's strength the temperature of the environment under which it is mixed, cast, cured and finally tested which must be controlled. Moreover, that increase in temperature increases initial strength while at the same time it reduces the long-term strength.

As the use of high strength concrete and the research on its properties has expanded during the last years, there are well-founded suspicions that the performance of high strength concrete under high temperature is not characterized precisely in design norms. The thermal effect of concrete is used separately or as a steam-heat treatment with possible high-pressure steam. Treatment at an elevated temperature accelerates cement hydration or reactions of other cementitious materials, therefore resulting in higher early age strength compared to the standard conditions. It is observed that after a 28day curing period, at a temperature regime +5°C –+46°C the difference between concrete which has been thermally treated or cured under normal conditions becomes less evident as the similar hydration stage is reached after 28 days. It should be noted that according to practical observations the higher thermal treatment temperature results in a lower final strength of concrete, for example, after 180 days (Mehta et al., 2006).

Srinivasa et al. (2006) researched Effect of Elevated temperature on compressive strength on HSC made with OPC & PPC. They attempted to study the effects of elevated temperatures ranging from 500 C and 2500 C on the compressive strength of HSC made with both ordinary Portland cement (OPC) and Portland pozzolana cement (PPC). The residual compressive strengths were evaluated at different ages. The results showed that at later ages HSC made with Portland pozzolana cement performed better by retaining more residual compressive strength compared to concrete made with ordinary Portland cement.

CHANGES IN PHYSICAL PROPERTIES OF CONCRETE UNDER HIGH TEMPERATURE

Change in Color

In concrete structures exposed to elevated temperature, there used to be color change if heated to a certain level of temperature. It is an accepted phenomenon that when heated to a temperature between 300◦C and 600◦C, concrete containing siliceous aggregates will turn reddish color when the temperature is between 600◦C and 900◦C, it turns whitish grey, and at a temperature between 900◦C and 1000◦C, buff color is present. The color change of heated concrete results principally from the gradual water removal and dehydration of the cement paste, but also transformations occurring within the aggregate. The most intense color change is in the fact that the appearance of red coloration is observed for siliceous river bed aggregates containing iron. This coloration is caused by the oxidation of mineral components. While siliceous aggregates turn red when heated, the aggregates containing calcium carbonate get whitish. Due to calcination process, $CaCO^3$ turns to lime and give pale shades of white and grey (Hager, 2013).

Thermal Expansion

If concrete produced with Portland cement is subjected to heat, some transformations and reactions occur, even if there is only a moderate increase in temperature. As the volume of aggregate materials ranges typically between 65 and 75% of the concrete volume, the behavior of concrete at high temperature is greatly influenced by the type of aggregate used for the production of concrete. Commonly used aggregate materials are thermally stable up to 300°C–350°C. Aggregate characteristics of importance to the behavior of concrete at high temperature include physical properties such as thermal conductivity and thermal expansion, chemical properties such as chemical stability at temperature, and thermal stability/integrity. Aggregate materials may undergo crystal transformations leading to significant increases in volume [e.g., a crystalline transformation of α-quartz (trigonal) to β-quartz (hexagonal) between 500 and 650°C with an accompanying increase in the volume of up to 5.7%. Some siliceous or calcareous aggregates with some water constitution exhibit moderate dehydration with increasing temperature that is accompanied by shrinkage that is, opal at 373°C exhibits shrinkage of about 13% by volume. Refractory aggregates can be utilized to produce significant improvements in the heat resistance of Portland cement concretes. It has been noted that the thermal stability of aggregates increases in the order of gravel, limestone, basalt, and lightweight (Naus, 2005).

Hager (2013) also asserted that expansion occurs in concrete materials when heated. This is due to the thermal strain in concrete under loading. The thermal strains under a load of concrete are measured when concrete is heated under a constant applied compressive load. The load is applied before heating, and strain measurement starts when heating begins, a process known as initial elastic strain subtraction. The load level applied (α) is usually expressed as a percentage of the compressive strength of tested concrete; the load level is maintained at a constant level during heating. The load level remains the predominant factor affecting the development of those strains. Strain in a concrete element (ε) simultaneously exposed to mechanical and thermal load combines mechanical strain, thermal strain, creep strain and the less known transient thermal strain (TTS) which appears during the non-stationary heating of concrete under mechanical load.

Shrinkage and Creep

Shrinkage of concrete has a significant effect on the movement of the structure and its tendency to induce cracking. Shrinkage occurs due to effects of drying or autogenous volume change. Drying shrinkage results from the loss of absorbed water and are the more predominant of the two effects. Autogenous shrinkage is more prevalent in mass concrete structures where the total moisture content remains relatively constant.This results from continued cement hydration reducing the free-water content. Several factors affect concrete drying shrinkage: (i) cement and water contents; (ii) composition and fineness of cement; (iii) type and gradation of aggregate; (iv) admixtures; (v) moisture and temperature conditions; and (vi) amount and distribution of reinforcement.

Although creep is considered only for concretes loaded in compression, a creep of concrete in tension also occurs and is in the same order of magnitude as a creep in compression. Also, upon release of the sustained load, an initial elastic recovery of strain occurs followed by creep recovery that can continue for several days. The magnitude of creep recovery is greater for concrete specimens that were loaded later in their cure cycle, and it is inversely proportional to the period of sustained stress. The effects of temperature on the creep of hardened cement paste can be broadly classified as thermal and structural. The thermal effect of temperature is that which is due to the temperature at loading, being seated in the molecular agitation caused by temperature. The structural effect will depend on the maximum exposure temperature, on the assumption that cooling down to the loading temperature does not reverse any structural changes caused by heating or cause structural changes of its own. The above assumption regarding the cooling will be correct only if differential thermal strains within the specimen are minimized by a slow rate of cooling and if hydration is not allowed to take place (Naus, 2005).

Below are some of the changes that take place in concrete when subjected to heat treatment, as presented by Hager (2013).

Table 2.1 Changes that take place in Concrete when Heated

Temperature range	Changes
20–200°C	slow capillary water loss and reduction in cohesive forces as water expands; 80–150°C ettringite dehydration; C-S-H gel dehydration; 150–170°C gypsum decomposition ($CaSO_4 \cdot 2H_2O$); physically bound water loss;
300–400°C	approx. 350°C break up of some siliceous aggregates (flint); 374°C critical temperature of water;
400–500°C	460–540°C portlandite decomposition $Ca(OH)_2 \rightarrow CaO + H_2O$;
500–600°C	573°C quartz phase change $\beta - \alpha$ in aggregates and sands;
600–800°C	second phase of the C-S-H decomposition, formation of β-C_2S;
800–1000°C	840°C dolomite decomposition; 930–960°C calcite decomposition $CaCO_3 \rightarrow CaO + CO_2$, carbon dioxide release; ceramic binding initiation which replaces hydraulic bonds;
1000–1200°C	1050°C basalt melting;
1300°C	total decomposition of concrete, melting.

(Hager, 2013).

MATERIALS AND METHODS

In this research work, the locally available material was obtained from vendors within Sokoto metropolis and used. The aggregate used was ¾" down. Ordinary Portland cement (Sokoto Cement) was utilized for the concrete production. Mix ratios of 1:2:4 along with water/cement ratio (w/c) for each mix were used for this research work. For this mix ratio, cubes were cast using square sized molds of 15x15x15 cm. A total of 12 cubes were cast and then cured at room temperature (28 °C). The cubes were divided into 4 set. Each set comprised of 3 cubes for each W/C ratio. Two of these sets were tested after 14 days, out of which one set was heated at a temperature of 200^{o}c for about 4 hours. The same procedure was repeated for testing the remaining two sets at the age of 28 days, and a set was heated at a temperature of 200^{oc} for about 4 hours. Tables 4.1 and 4.2 show the results of concrete cubes test after 14 days and 28 days respectively, for both heated and unheated cubes. A comparison of the results was made, and following results were obtained.

RESULTS AND ANALYSIS

The compressive strength results for both heat-treated and unheated cubes after 14 and 28 days curing are presented in tables 1 and 2, with graphical representations in figures 1 and 2 for a precise analysis of the results.

Table 4.1: Compressive Strength of Concrete after 14-day

	Unheated Cubes			Heated Cubes		
Particular of cube	**1**	**2**	**3**	**4**	**5**	**6**
Identification no.	1	3	5	1	3	5
Age of cube (days)	14 days	14 days	14 days	14 days	14 days	14 days
Weight of cube (g)	8075	8040	8060	7920	7960	7944
Density of cube (g/cm^3)	2.39	2.38	2.39	2.35	2.36	2.35
Total compressive force (kN)	440	420	450	380	400	395
Compressive strength (kg/cm^2)	19.6	18.7	20.0	16.9	17.8	17.6
Average compressive strength at 14 days for unheated cubes = 19.4N Average compressive strength at 14 days for heated cubes = 17.4N						

Table 4.2: Compressive Strength of Concrete after 28-day

	Unheated Cubes			Heated Cubes		
Particular of cube	**1**	**2**	**3**	**4**	**5**	**6**
Identification no.	2	4	6	2	4	6
Age of cube (days)	28 days	28 days	28 days	28 days	28 days	28 days
Weight of cube (g)	8100	8120	8090	7779	7818	7721
Density of cube (g/cm^3)	2.40	2.41	2.40	2.30	2.32	2.25
Total compressive force (kN)	570	610	560	510	550	515
Compressive strength (kg/cm^2)	25.3	27.1	24.9	22.7	24.4	22.8
Average compressive strength at 28 days for unheated cubes = 25.8N Average compressive strength at 28 days for heated cubes = 23.3N						

From the tables 4.1 and 4.2, the average compressive strength at 14-day crushing for unheated concreted was found to be 19.4N which is higher than that of heated concrete by 2N. Also, at 28-day crushing, the average compressive strength of unheated concrete differs from that of heated by 2.5N. From that, it can be ascertained from practical observations, that higher thermal treatment temperature results in a lower final strength of concrete (Shehab et al., 2013).

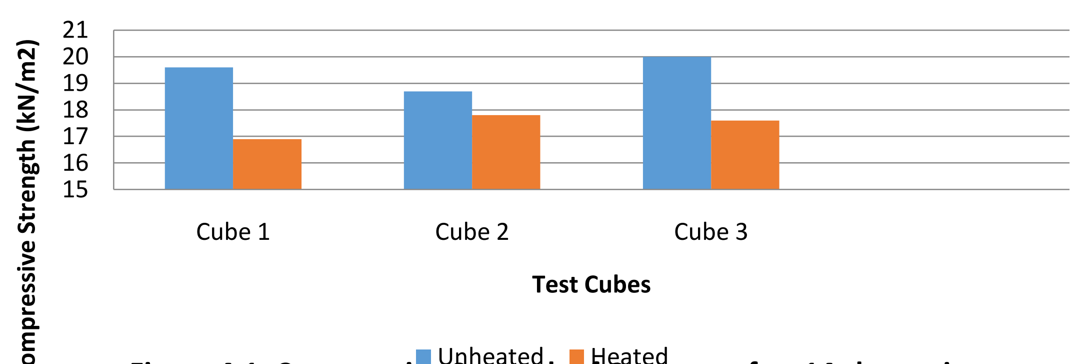

Figure 4.1: Compressive Strength of Concrete after 14-day curing

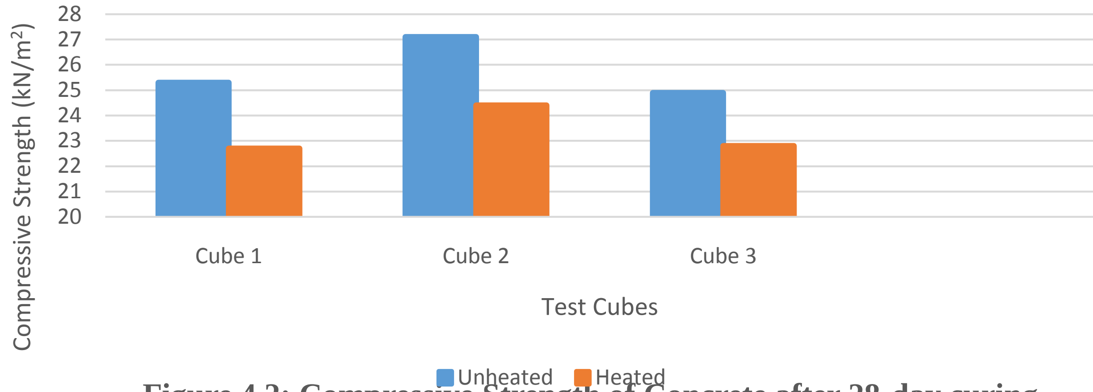

Figure 4.2: Compressive Strength of Concrete after 28-day curing

Figure 4.1 shows the compressive strength of both heated and unheated cubes for 14-day curing. It could be observed that there are significant differences in two out of the three sets of cubes tested, with the heated cubes having less strength. Also, figure 4.2 shows asimilar pattern with a more extensive range between the heated and unheated cubes. In both cases, the difference in strength is between 2N/mm^2 and 2.5N/mm^2 which is significant and can have apractical impact.

CONCLUSION

Based on the experimental results presented in this paper, conclusion may be drawn from the results obtained that the residual strength of concrete decreases as it is exposed to high rise temperature, keeping in view that concrete's strength demands that the temperature of the environment under which it is mixed, cast, cured and finally tested must be controlled.This attested to the fact that increase in temperature increases initial concrete strength while at the same time it reduces its long-term strength. Hence, when designing any concrete mix for structures that may be exposed to high rise temperature or elevated heat, consideration should be given to specific factors that will increase the resistance of concrete to such conditions.

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