Physical properties and compressive strength of concrete exposed to progressive heat

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***Abstract*—Exposure of concrete to harsh environmental conditions has varying degrees of influence on the performance and service life of structures. The present work reports the results of an experimental investigation conducted to evaluate the influence of ambient laboratory temperature and stepwise elevated temperature of 100°C, 200°C, 300°C, 400°C, and 500°C at a rate of 1°C/min on the physical properties and compressive strength of concrete specimens. The concrete cubes were made in accordance to BSI standards. Unstressed residual thermal effects such as physical appearance, mass loss, and change in compressive strength were investigated via laboratory experimentation. Compared to the ambient exposure, the results showed that loss of pore water and strength reduction were mild up to 100°C, while remarkable deterioration trend was recorded at higher temperatures.**

Keywords—Concrete, compressive strength, unstressed thermal load, mass loss, deterioration, durability

I. INTRODUCTION

The fundamental aim of structural design is to realize an acceptable probability that proposed structures will not only perform satisfactorily during the intended life, but also be able to sustain all the loads and deformations with adequate durability and resistance to the effects of misuse and fire [1], [2]. One of the prime requirements in terms of safety of a structure is that the structure should provide enough protection to the occupants in case of fire. Concrete is a major construction material once believed to be an eternal construction material [3], but are often threatened by aging, usage-dependent fatigue, and deterioration due to harsh environment and other external and internal stressors.

Concrete is a composite material with aggregate as inclusions and cement paste as matrix. The two phases have different thermal and mechanical properties and thus respond differently under elevated temperature. Due to its low thermal conductivity a layer of concrete is frequently used for fireproofing of steel structures which is vulnerable to damage by fire. However, the binding material can decompose if heated to too high a temperature, with consequent loss of strength. Being a porous substance bound together by water-containing crystals, loss of moisture at elevated temperature causes shrinkage and expansion of aggregates thus leading to cracking and spalling of the concrete.

In the past two decades, extensive experimental studies have been conducted on various properties of concrete especially physical, chemical and micro-structural evolution of the binding phase under high temperature [4 – 7]. Pioneer studies conducted on this subject concluded that the residual strength of all the concrete at all elevated temperatures fell below the ambient strength [8], [9]. It was also reported that residual strengths in compression and tension, as well as elastic modulus of concrete dropped drastically at elevated temperature up to 500°C [10]. Khoury *et al.* [11] found that compressive strength of concrete at high temperature was largely affected by individual constituent of concrete, sealing and moisture conditions, loading level during heating period, operational exposure conditions, rate of heating or cooling cycle and duration thermal loading.

Morita *et al*. [12] conducted unstressed residual strength tests and revealed that high strength concrete (HSC) has higher rate of reduction in residual compressive strength than the normal strength concrete (NSC). Castillo and Durani [13] investigated thermal effects on the strength and load-deformation behavior of HSC and NSC under stressed and unstressed test conditions. In the unstressed experiment in the range of 100-300°C, HSC showed a 15 - 20% loss of compressive strength, while NSC recorded negligible strength loss. HSC recovered its strength between 300-400°C, reaching a maximum value of 8 - 13% above the strength at room temperature. At temperature above 400°C, both NSC and HSC progressively lost compressive strength to about 30% of the room temperature strength at 800°C. Furumura *et al.* [14]

observed that the compressive strength for stressed residual tests decreased at 100°C, recovered to room temperature strength at 200°C and thereafter further decreased monotonically with increasing temperature beyond 200°C. However, the compressive strength of concrete for unstressed residual tests decreased progressively with increasing temperature for the entire temperature range without any recovery. Noumowe *et al*. [9] comparatively studied NSC and HSC subjected to elevated temperature up to 600°C under unstressed residual tests and found that the residual tensile strengths for NSC and HSC decreased almost linearly with temperature rise, but tensile properties of HSC were 15% higher than those of NSC. Janotka and Bagel [15] revealed there were no significant changes in strength characteristics of concrete made with blast furnace slag cement up to 400°C.

The purpose of this study was to experimentally investigate the influence of stepwise environmental temperatures at the ambient condition and at intervals of 100°C, 200°C, 300°C, 400°C, and 500°C on the density and compressive strength of concrete. The study simulated fire concrete subjected to fire hazard at a temperature increment rate of 1°C/min at every 100°C and kept constant for 60 minutes prior to subsequent cycles up to 500°. The mass loss and unstressed residual compressive strength loss were considered as indices for condition evaluation.

II. EXPERIMENTAL PROGRAMME

A. *Materials*

Grade 42.5 ordinary Portland cement conforming to BS 12 [16] was used in this study. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 1. Coarse aggregate was crushed granite of maximum nominal size of 19 mm sourced from Abeokuta, Southwestern Nigeria. Fine aggregate was natural coarse sand collected from Ogun River of maximum nominal size of 4.75 mm. The both aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 882 [17]. The properties of fine and coarse aggregates are presented in Table 2 and the particle distribution curves are plotted in Fig. 1. The fine and coarse aggregates utilized as constituents of the concrete were well-graded. Potable water of pH of 7.1 which conformed to the requirements of BS EN 1008 [18] was used in mixing the aggregates and cement.

B. *Concrete Mix Proportions*

Concrete mixture with a water-cement ratio of 0.55 was proportioned for the study. Mixture of concrete was prepared in a rotating drum mixer. The aggregates and cement were placed in the drum and mixed in parts with water to ensure a better bond between the cement paste and the aggregates. All mixing and sampling of concrete were carried out in accordance with the procedures given in BS 1881 [19].The workability of the mix measured in terms of slump was 34 mm. The mix proportioning computed using arbitrary volume method is presented in Table 3. The air and concrete temperatures were 25°C and 26°C, respectively.

TABLE 1: PHYSICAL PROPERTIES OF CEMENT

Standard Consistency (%)	30
Specific gravity	3.15
Initial setting time (min)	118
Final setting time (min)	215
Soundness (mm)	1.0
Compressive strength (N/mm^2)	
3 days	24.5
7 days	30.8

TABLE 2: PROPERTIES OF AGGREGATES

	Sand	Crushed granite
Specific Gravity	2.64	2.70
Bulk Density (kg/m^3)	1240	1464
Moisture content	4.09	0.6
Fineness modulus	3.00	6.15
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

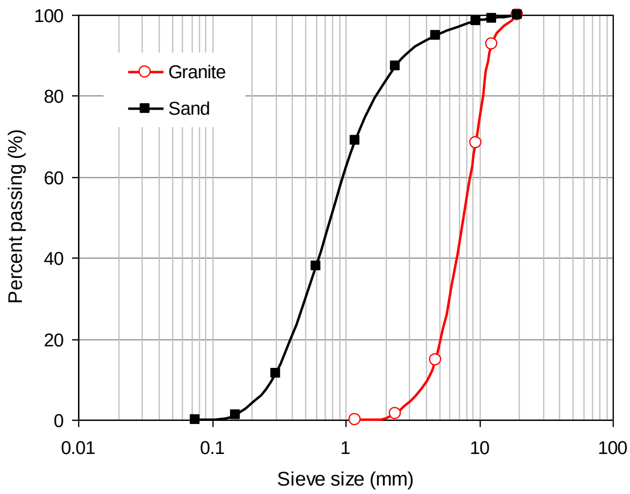

Fig 1. Particle distribution curves of fine and coarse aggregates

TABLE 3: CONCRETE MIX PROPORTION

Mix constituents	Values
Cement (kg/m^3)	329
Fine aggregate (kg/m^3)	658
Coarse aggregate (kg/m^3)	1316
Water (kg/m^3)	181
Water-cement ratio (w/c)	0.55
All constituents (kg/m^3)	2484

C. Preparation and Casting of Concrete Cubes

A total of forty-two 150 mm concrete cube specimens were cast, cured and tested for compressive strength according to BS 1881 [20]. The compressive strengths of the specimens were determined from average of three sampled crushing loads of 150 mm cubes at 7 days, 14 days, 21 days, 28 days, 42 days, 56 days, 70 and 90 days. Concrete specimens were cast and then covered with thin polythene membrane to minimize moisture loss. The concretes were stored and tested in the laboratory under mean air temperature of 26±1˚C. The specimens were de-moulded after 24±½ hours and then transferred into a water-curing tank for the test periods.

D. Tests of Fresh and Hardened Concrete

The workability of the concrete mix in fresh state was determined through slump test carried out according to BS 1881 [21]. Compressive strength of the 150 mm concrete cube specimens of the five concrete mixtures was determined at the curing ages of 7 days, 14 days, 21 days, 28 days, 42 days, 56 days, 70 and 90 days in line with BS 1881 [22].

E. Heating Cycles

The industrial oven, which was effective for heating large specimens up to 750°C, was used for this study. The concrete specimens were subjected to five independent heating cycles with peak temperatures fixed at 100°C, 200°C, 300°C, 400°C, and 500°C. The first cycle consisted of three phases, while the subsequent cycles are accumulation of preceding cycles up to the fifth cycle at 500°C. The first phase of each cycle had heating-up at a rate of 1°C/min. The second was stabilization at constant temperature during one hour and finally cooling to the ambient temperature. The rate was used so that the thermal gradient inside the sample would be insufficient to create high internal stresses. Fig. 2 shows the thermal profile for the five temperature cycles and the heating system for concrete specimens are shown in Fig. 3.

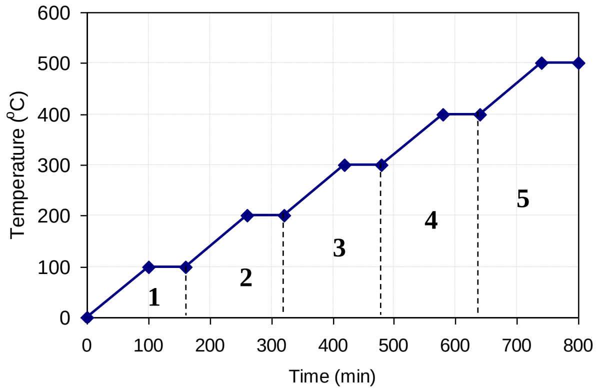

Fig. 2 Thermal profile of different heating cycles

Fig. 3 Heating test setup in an industrial oven

III. Results and Discussion

A. Physical appearance

The influence of heat on concrete specimens was characterized by four distinct stages namely, the incipient, growth, burning and decay. The most critical point when concrete began to lose its integrity was at the growth stage. The growth stage of fire is between 100ºC and 300ºC, within which concrete loses its residual properties. The effect of elevated temperature on concrete specimens was evident through visual observation. Changes in physical appearance were tracked in terms of colour change and subsequently by progressive cracking of the concrete. The original colour of concrete specimen prior to thermal exposure was greyish. However, there was a progressive change of colour immediately after the first cycle from dark grey to pink and later reddish pink at the outset of the third cycle to the end of the fifth cycle respectively. This could be attributed to the modification of the Fe_2O_3 constituents inside the aggregates that changed colour due to the heat. In addition, several microcracks were found on concrete surface most likely due to plastic shrinkage cracks and thermal dilatation strain. Popouts over quartz aggregate particles forming white-powdered particles and dehydrated paste were found on the surface of concrete cubes. At the end of the fifth cycle after 800 min, the colour was reddish, leaving specimens whose surface was easily breakable with the squeeze of a hand.

B. Compressive Strength

Unstressed residual compression strength test was conducted for the cube specimens. Uniaxial compression tests were performed with the aid of a hydraulic pressure. Three samples were tested and the average strength was obtained. Prior to this, the weight of each of the concrete cubes was obtained by means of a calibrated weighing balance. The test results of the compressive strength of the investigated concrete mixture are shown in Fig. 4.

The compressive strength of the concrete mixtures increased as the cement contents increased for all the test days. The compressive strength at the 7th day was 71.5% of the 28th day strength. The 28th day strength was 26.34 N/mm^2 and the rate at which the compressive strength increased was higher in concretes prior to the 28 days age, but later increased almost linearly at a decreasing rate from 28 days to 90 days, albeit at a decreasing rate. The latter being the period when considerable hydration of the cement ought to have been achieved [23].

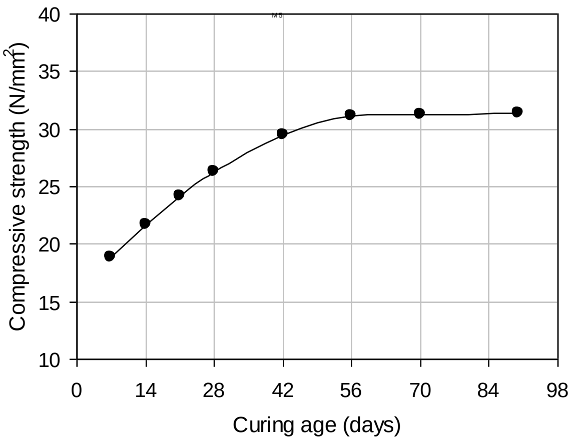

Fig. 4. Compressive strength of various concrete at varying curing ages

C. Mass Loss

Average mass of the specimen after each cycle of exposure of heat treatment was measured. The unheated concrete specimen under ambient exposure of laboratory temperature of 25°C served as control. The percentage mass loss with respect to the ambient specimen was calculated and plotted against the temperature exposure as presented in Fig. 5. It was evident that concrete loses weight at all temperature exposures. The best line of fit for the percentage mass loss of concrete in terms of temperature (with a coefficient of determination R^2 = 0.9678) is given by equation (1).

$$m = 0.0171t^{1.0761} \quad (1)$$

where

m is the percentage mass loss and *t* is the temperature exposure.

Mass loss increased with increase in temperature exposure could be attributed to damage mechanism which is primarily phase transformation taking place in the cement paste. As a result of this decomposition process, there was release of physically adsorbed water, gel destruction, and discharge of chemically and zeo-lithically bonded water. Between the ambient temperature 25°C and 100°C, concrete lost an average of 2.93% of its mass per °C to desorption or evaporation of physically absorbed water and the free water present in the voids and capillary pores [24]. After the evaporation of all free water further weight loss came from the removal of the adsorbed water in smaller pores, which took more energy. There was further loss of 3.95% of concrete mass per °C between 100°C and 200°C to evaporation of absorbed water and gel destruction. This study has further corroborated the claim of Noumowe *et al*. [25] that the total concrete mass loss to heat at 100°C was about three and four times lower than those measured after exposure to heat at 200°C and 300°C. This study also established that there was smaller portion of free water in concrete compared to hydrated water.

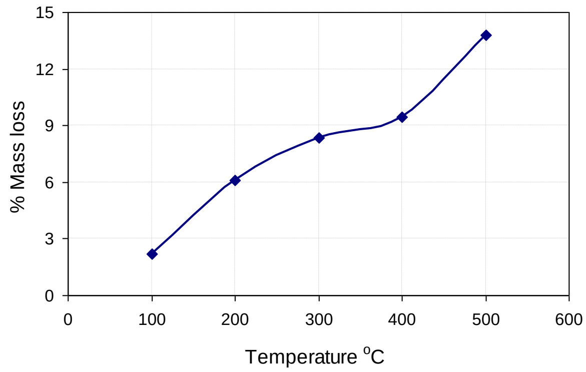

Fig. 5 Mass loss of cubes at varying temperature exposure

Mass loss, however, reduced from 200 - 300°C and 300 - 400°C by 2.20% and 1.10% respectively of original concrete mass. These respective values accounted for the primary dehydration stage when existing gel was completely destroyed and chemically absorbed or zeo-lithically bonded water was released. The huge loss of 4.23% of concrete mass between 400°C and 500°C could be attributed to the decomposition of Portland cement which exceeded initial loss to desorption of physically absorbed water. Moreover, at higher temperatures, some phase transformations usually take place and a certain amount of chemically bound water is released and evaporated. The amount of adsorbed water and chemically bound water released due to the phase transformation was less than the free water in the concrete specimens. The mass loss could be partly attributed to loss of both the gel water and capillary water. The cumulative loss of concrete mass at the end of each of the five cycles at 100°C, 200°C, 300°C, 400°C and 500°C were 2.2%, 6.12%, 8.35%, 9.43% and 13.79% respectively. Mass loss in concrete at high temperature was reported by authors such as Lee *et al*. [26] and Noumowe *et al*. [25]. This change in density of concrete when subjected to heat should be given special attention in the design and construction of nuclear power plants and chemical containment applications. This is also key to ensure durability of reinforced concrete structural systems especially when specifying nominal cover of concrete to reinforcing bars.

D. Residual Compressive Strength

The 28th day strength of 26.35 N/mm^2 was obtained for concrete specimens under ambient exposure at 25°C. The experimental results of compressive strength after each cycle of temperature exposure are plotted as shown in Fig. 6. Similar to mass loss, the residual compressive strength of concrete as a function of temperature exposure followed a quadratic trend (with R^2 =0.9618) as given by equation (2).

$$f_c = 0.004t^2 - 0.0387t + 27.806 \quad (2)$$

where

f_c is the compressive strength and t is the temperature exposure.

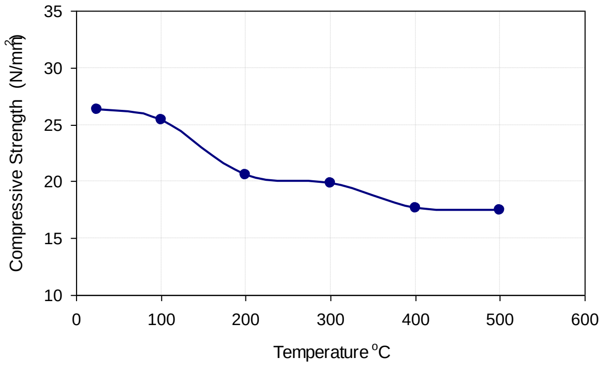

Fig. 6. Average compressive strength for concrete cube at elevated temperature

A progressive loss of strength of concrete was observed with temperature rise. As exposure temperature increased, the bond between the concrete constituent broke down. There was an escape of gel water, which was the main chemical components that contributed to concrete strength. The total loss of compressive strength at the end of each of the five cycles at 100°C, 200°C, 300°C, 400°C and 500°C were 3.48%, 21.97%, 24.56%, 33.06% and 33.81%, respectively. Between ambient temperature of 25°C and 100°C, concrete lost an average of 1.23% of its original strength per °C rise in temperature. The strength loss of 4.87% per °C between 100°C and 200°C was the highest among the five cycles. Since the aggregates, essentially crushed igneous rock and washed river sand, accounted for over 70% of concrete mass and volume, it may be concluded that the loss of absorbed water and gel destruction in concrete accounted for huge loss of compressive strength. This is in agreement with Noumowe *et al*. [25] that the elastic modulus concrete decreased by 5-10% within a temperature range of 100 – 300°C, and much faster beyond 300°C.

It is evident from the study that there is a correlation between mass loss and strength loss in concrete at elevated temperature. For instance, strength loss in the range 200 - 300°C was 0.68% of its original strength per every degree Celsius rise in temperature is comparable to the trend in mass loss relationship. Between 300°C and 400°C, the loss of chemically absorbed or zeo-lithically bonded water resulted in average loss of 2.24% of original strength within this range. Unexpectedly, loss rate in compressive strength was a meager 0.2% of original concrete strength per every degree rise in temperature between 400°C and 500°C. It was unexpected because decomposition of Portland cement was expected to have taken place within this cycle.

Fig. 7 shows the trend of residual strength loss of concrete specimens under the various exposure conditions. About 18.49% of the control strength was lost in the second cycle, while only 2.59% was lost in cycle 3. Within cycles 4 and 5, 8.50% and 0.74%, respectively, of the residual strength were lost to elevated heat. It is noteworthy that the experiments were performed on unstressed concrete specimens and temperature rise further reduced the strength values because of internal pore pressures were easily expelled at high temperature under this condition. These findings agree with several others who have also reported reduction in residual compressive strength of concrete at high temperatures ([13], [10], [9], [27]).

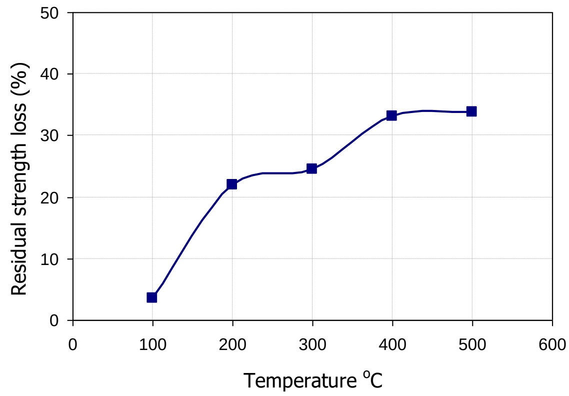

Fig. 7 Residual compressive strength loss for concrete at elevated temperature

IV. CONCLUSIONS

The article presents the behavior of concrete under a step-wise temperatures cycles of 100°C, 200°C, 300°C, 400°C, 500°C at a heating rate of 1°C/min. The influence of heat on concrete specimens was characterized by four distinct stages namely, the incipient, growth, burning and decay. To analyse this effect, deterioration of concrete structure to heat was evaluated in relations to mass loss and change in compressive strength. Evolution of cracks at each temprature level of exposure was studied. The following conclusions were drawn from the study:

1. Mild deterioration was observed in the physical and mechanical properties of the concrete up to 100^{0}C. This could be alluded to the dehydration of chemically bound water from the calcium silicate hydrate in concrete becomes significant above 100^{o}C.
2. The relationships of mass loss and strength loss as a function of temperature were power and quadratic respectively. A marked relationship between mass or density and the compressive strength of concrete was established when exposed to heat.
3. Although decomposition of Portland cement contributed significantly to loss of mass of concrete, the influence on compressive strength appeared to be questionably mild within temperature range 400 - 500°C.
4. High grade concrete with reduced water-cement ratio is recommended for concrete that are vulnerable to elevated temperature as deterioration is often traceable to loss of absorbed water and pore water pressure in concrete matrix.

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