The Effects of Steam-Curing on the Properties of Concrete

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Abstract-Worldwide, concrete is the most preferred construction material. The steam curing method is favored when there is a need for accelerating strength. This paper presents the study of the compressive and flexural tensile strength of concrete subjected to eight different steam cures. In addition, the stress-strain curve and the modulus of elasticity were determined at the age of 28 days. The compressive strength test results show that after treatment, strength increases with concrete maturity. A cycle with a pre-heating period gives better results than a cycle without a pre-heating period. The longer the duration of the maximum temperature period, the lower the strength drop compared to the control concrete. The best results were obtained for concrete treated according to the following cycle: a 3-hour pre-heating period at 20°C, a 2-hour increase of temperature from 20 to 70°C, and a 3 hour of maximum temperature of 70°C.

Keywords-steam curing; compressive strength; flexural tensile strength; modulus of elasticity; maturity

I. INTRODUCTION

Concrete is extensively used as a construction material and, globally, it is the second highest consumed material [1]. Ordinary Portland Cement (OPC) is usually used as the primary binder to make concrete and is one of the most energy-intensive construction materials. The primary reason for using steam in the curing of concrete is to produce high early strength, which is very desirable to the manufacturers of precast and pre-stressed concrete units [2]. There are many advantages in steam curing such as the production of concrete with high early strength, short production cycle, and superior economic benefits [3, 4]. The steam curing process includes the following four phases: the delay period, the isothermal period, the heating period, and the cooling period [5]. Heat treatment has been used to accelerate the development of the strength of concrete products, such as bricks and small concrete elements. By increasing temperature and duration, the strength of concrete is increased [6]. Authors in [7] showed that 85°C is the optimum temperature in order to obtain high early strength. Authors in [8] demonstrated the improved early-age strength of high performance concrete through steam curing. Authors in [9] showed that as the temperature increases, the compressive and flexural strength of concrete at early age increase. Authors in [5] reported that 65% of the strength of the control concrete at 28 days was obtained by thermal treatment within 24h after mixing. Similar results have also been reported in [6,10, 11]. The same results have been obtained for concrete with superplasticizers [12] and slag [5]. In order to obtain good final strength, it is not advisable to immediately heat the concrete. The faster the speed of temperature rising, the more the final strength of the treated concrete is weakened. Authors in [9] showed that the increase in temperature has significant impact on the compressive and flexural tensile strength of concrete. However, there is no effect on strength when hard concrete is exposed to 6-hour fire at 1000°C [13]. Authors in [5, 14] reported that the effect of heat treatment on the modulus of elasticity is the same as that on strength. Authors in [14] reported that the optimum rate of heating and preset period should be selected based on the maximum chamber temperature in use in order to secure the desired results. There was enhancement in the early compressive strength due to the effect of steam curing, however the delay period before steam curing is very essential for the early strength gain [2, 15]. Authors in [5] showed that the reduction in shrinkage of steam-cured concrete when compared to normal cured concrete is about 10%. Finally, steaming leads to a reduction of 20 to 30% of the creep compared to the same concrete, cured at room temperature and loaded with equal stress/strength ratio [16]. This reduction in creep has been confirmed by [5, 12].

II. MATERIALS AND EXPERIMENTAL DETAILS

Nine concrete mixtures were tested in this program. The concrete had an OPC content of 350kg/m^3. The total aggregate/ cement ratio was 5.41, the gravel/sand ratio was 1.61, and the

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water/cement ratio was 0.57. For all the mixtures, the coarse and fine aggregates were weighed in dry room conditions. The control OPC concrete was designed to develop a 28-day cube compressive strength of 35MPa. All the concrete mixtures were mixed for 2min in a laboratory mixer. All molded specimens were cured for 24h under wet hessian, then were demolded and cured in water at 20±2°C for 28 days. For each mixture, twelve 100mm cubes were made to determine the compressive strength and two 300×150mm diameter cylindrical specimens were used to determine the static modulus of elasticity. The flexure tensile strength was measured on 100×100×500mm prisms (Figure 1). The compressive strength was measured after 1, 3, 7, and 28 days (Figure 2). The flexural tensile strength, the stress-strain curve and the modulus of elasticity were determined at the age of 28 days.

Fig. 1. The concrete specimens.

Fig. 2. The cube compessive strength test.

The studied types of concrete were: A control concrete stored in water at an ambient temperature (20°C) and concretes subjected to 8 different steam curing cycles (Table I). The curing cycles necessarily include four distinct phases:

- Preheating period
- Heating period
- Maximum temperature period
- Cooling period

The molds were placed into the steam chamber, the latter being at the processing temperature. This steam chamber is equipped with a fan allowing the circulation of ambient air. A thermocouple was placed in the concrete in the middle of the central specimen of the cubic mold. After demolding, the concrete specimens were stored in water at 20°C

TABLE I. DIFFERENT TYPES OF CURING CYCLES

Cycle	Preheating period (h)	Heating period (h)	Max. Tem. period (h)	Initial Tem. (°C)	Max. Tem. (°C)	Maturity (°C.h)
A	0	2	3	20	70	350
B	1.5	2	3	20	70	395
C	3	2	3	20	70	440
D	3	2	1.5	20	70	320
E	3	2	0	20	70	200
F	1.5	2	3	20	50	315
G	1.5	2	3	24	70	405
H	1.5	2.5	3	24	70	433

III. RESULTS AND DISCUSSION

A. Influence of the Duration of the Pre-Heating Period on Compressive Strength

Figure 3 shows that the strength at the end of the treatment (0 days) and after 28 days of curing is minimal for zero preheating period. The decrease in final strength (28 days) compared to control concrete kept at 20°C is around 33%. For the cycles B and C, the fall is 26% and 15% respectively. So it is not advisable to heat the concrete immediately after pouring, which is in agreement with the results in [10]. The heating of fresh concrete causes the appearance of physical and chemical phenomena [17]. The physical order phenomena are essentially linked to the expansion of the various constituents of concrete under the effect of the rise in temperature. However, these various constituents have very different linear expansion coefficients. The rise in temperature causes the material to expand, which ultimately results in the appearance of pores. These pores indeed remain after the consolidation of the concrete structure. It is well known that the strength of concrete is inversely proportional to the number of pores in it. Chemical phenomena are linked to the appearance of insoluble, compact hydrate films, which oppose the subsequent penetration of water and somehow isolate the grains of cement [17].

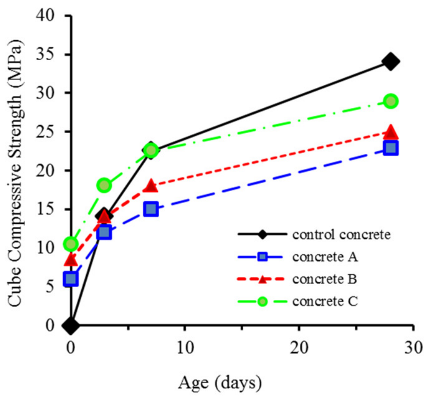

Fig. 3. The effect of the delay period on concrete strength.

B. Influence of the Speed of Temperature Rise on Compressive Strength

In order to study the influence of the speed of temperature rising, the evolution of the compressive strength for heating at 70°C with rise speeds of 18°C/h and 24.8°C/h are compared in Figure 4. It is observed that the best strength at 28 days is obtained for slowly heated concrete (18°C/h). However, the quality of treated concrete remains lower than that of control concrete. The drop in strength compared to control concrete is 13% and 15% for concrete heated to 18°C/h and 24°C/h respectively. This confirms the results of [5]. The physical cause of this alteration is known: it is the very significant expansion of the constituents of fresh concrete, water and air. A high rate of temperature rise causes disorders in the structure of concrete which can go as far as the appearance of micro-cracks.

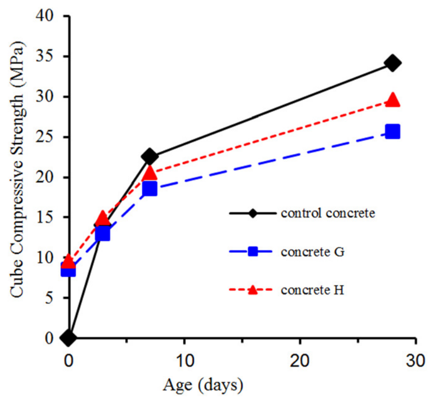

Fig. 4. The effect of heating period on concrete strength.

C. Influence of Maximum Temperature

When the temperature rises the compressive strength increases more rapidly at 0 days, whereas at 28 days, the strength of concrete treated at 50°C is greater than that of the concrete treated at 70°C (Figure 5). Authors in [7] found that the optimum maximum temperature of steam curing was near 60ºC. However, higher temperatures of 70ºC and 80ºC show a distinct reduction in strength after 28 days [7]. A significant increase of compressive strength for fly ash mortars has been found at the early age of 3 days when curing temperature was raised [18].

D. Influence of the Maximum Temperature Period Time

In order to study this phenomenon, three cycles of heat treatments (C, D and E) were considered, so the maximum temperature period varied from 0 to 3h. The three cycles had the same preheating period (3h), heating period (2h), and maximum temperature (70°C), however the maximum temperature period was 3, 1.5, and 0h respectively. It should be noted that the longer the maximum temperature period time, the higher the compressive strength in the short and long term is (Figure 6). Concrete maintained at a 3hour level presents, at 28 days, a reduction in strength around 15% compared to control. For 1.5h and 0h concrete, the strength drop is around 24% and 28%, respectively. Therefore, the greater the duration of the maximum temperature period, the smaller the drop in strength compared to control concrete at 28 days, which is in agreement with the results in [19].

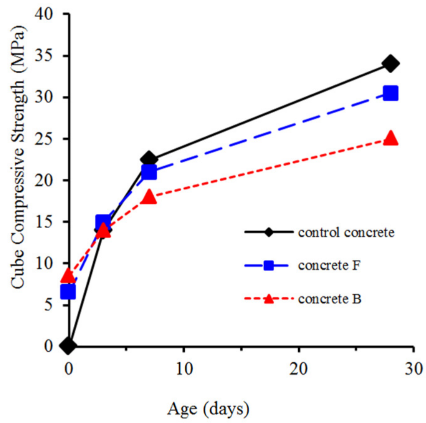

Fig. 5. The effect of maximum temperature on concrete strength.

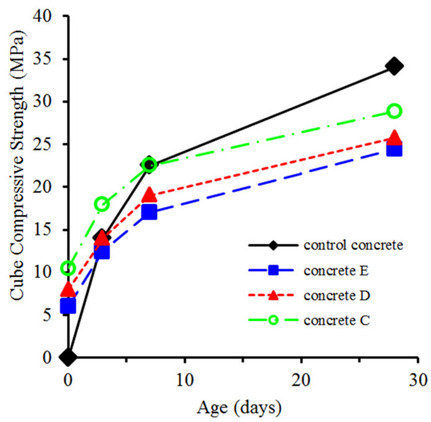

Fig. 6. Effect of maximum temperature holding time on concrete strength.

E. Maturity Factor

We can see that the compressive strength after treatment increases with maturity (Figure 7). The latter is the sum of the product of temperature and time:

$$Maturity = \sum\left(T + 10^{o}C\right) \times \Delta t \quad (1)$$

where T is the temperature in °C and Δt is the time interval (h).

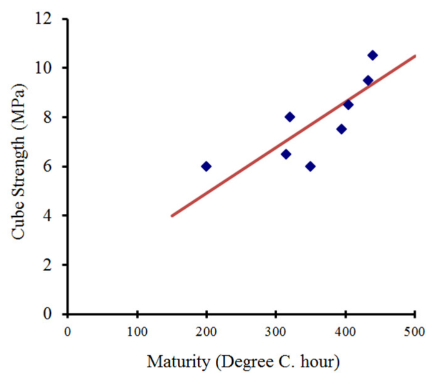

Fig. 7. Relationship between maturity and cube compressive strength.

F. Tensile Strength

The values of tensile strength are given in Table II. It can be seen that the maximum tensile strength (4.27MPa) is obtained by the control concrete. The tensile strength of all concrete mixtures was determined by the flexure test and is presented as a function of cube compressive strength in Figure 8. The European Concrete Committee (CEB) suggests that the axial tensile strength (f_t) can be related to the characteristic compressive strength (f_c) by:

$$f_t = 0.3 f_c^{2/3} \quad (2)$$

The flexural tensile strength of all the concrete mixtures ranged between 2.9 and 4.27MPa. For a given compressive strength, the values for flexural tensile strength for all concretes are slightly higher than to the curve proposed by the CEB in (2). The ratio of the flexural tensile strength to the compressive strength was about 0.13. The results of [21] showed that the steam-curing provides better performance at 3 days for flexural strength and the ratio of the flexural tensile strength to the compressive strength was about 0.10.

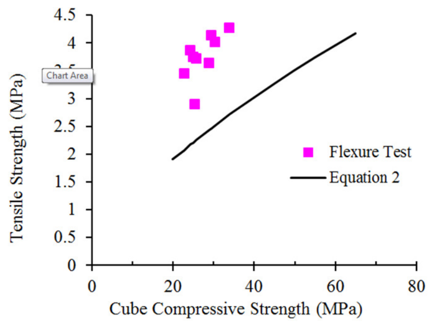

Fig. 8. Relationship between tensile and cube compressive strength.

TABLE II. FLEXURAL TENSILE STRENGTH

Cycle	Control	A	B	C	D	E	F	G	H
Tensile strength (MPa)	4.27	3.45	3.75	3.64	3.72	3.86	4.01	2.90	4.14

G. Stress-Strain Curve

The stress-strain curves in compression of the control and both B and C concretes are shown in Figure 9. It is clear that the shape of the curves is similar for all concretes. Moreover, it is worth mentioning that before failure, it is difficult to assess any value for limiting axial strain. However, comparison can be made on the basis of 95% of failure stress. The limiting axial strain for control concrete is about 1880 microstrains. However, for concretes B and C, these values are 1420 and 1596 microstrains respectively. These values are 24% and 15% lower than the control concrete's. The secant modulus of elasticity, as measured at a stress-strength ratio of 0.3 is shown in Table III. Compared with normal concrete, the values of concrete B and C are less by approximately 14% and 8% respectively. On the other hand, the value proposed by ACI [14] is 24.3GPa. This result is in agreement with the results in [20] for steam-cured slag concrete.

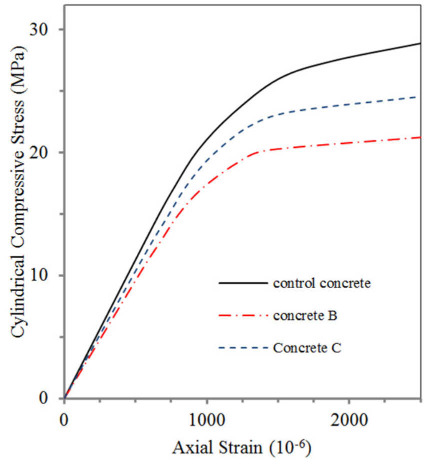

Fig. 9. Stress-strain curves for concretes in compression.

TABLE III. SECANT MODULUS OF ELASTICITY (GPA)

Age (days)	Control	B	C
28	26.5	22.8	24.4

IV. CONCLUSION

For the materials and test conditions reported in this study, it was found that:

- A decrease in the final strength of about 33% compared to that of the control concrete was observed for the cycle without pre-heating (Cycle A). However, for the cycles B and C (with pre-heating 1.5 and 3 hours), the decrease was 26% and 15% respectively.
- The greater the maximum temperature period time, the smaller the drop in compressive strength at 28 days compared to the control.
- The best result for the treated concrete is obtained according to the following cycle:
  - A 3-hour of pre-heating period at 20°C,
  - A 2-hour increase of temperature from 20°C to 70°C, and
  - A 3-hour heating at the maximum temperature of 70°C.

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