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Influence of cement composition on the early age flexural strength of heat-treated mortar prisms

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Abstract

Heat treatment is extensively used to accelerate the process of the strength development of concrete for prefabrication purposes. This study was conducted to determine the effect of cement composition on the improvement of the one-day flexural strength of heat-treated mortar prisms. Considering the strength gain at the end of one day of heat treatment application, it can be concluded that a treatment temperature of 80 °C seems to be appropriate for CÇ 32.5 cement while it is 65 °C for the other cements tested. It is also concluded that an initial curing of 4 h is suitable in view of the technical success of heat treatment application. However, it may be shorter for blended cements for economic reasons.

Keywords: Heat treatment; Flexural strength; Strength gain; Cement type and composition

1. Introduction

Strength development of concrete at early age is often inadequate for prefabrication purposes since the hardening process and strength-gaining rate of concrete under normal curing conditions are rather slow. Keeping track of mould rotation as fast as possible is of great importance, particularly for the prefabrication industry in order to maintain low-cost production by accelerating the hardening and strength-gaining process of concrete [1]. So far, various strength-accelerating procedures have been adopted to accomplish this. Currently, heat treatment is the most extensively applied method [2,3].

Cement has a profound effect on heat treatment application due to its governing role in hardening and strength-gaining process of concrete [4,5]. In this context, the composition of cement and its fineness, along with curing conditions are the primary factors [6,7]. Type and amount of cement replacement for blended cements [8], aggregate [9], water to cement ratio [10], and mineral additives [11] are the secondary factors. Regardless of the composition of cement, cycle parameters of heat treatment application have to be also taken into account [12]. Although the effect of such parameters on heat treatment application is known roughly, there is a need of evaluate their optimum values.

The ultimate strength of concrete subjected to heat treatment is also lower with respect to those cured normally [13]. This is because higher curing temperatures affect the physical characteristics of the cementitious system by altering the dormant period of hydration process. Heat treatment does also alter the crystal morphology and the amount of ettringite formed in the cementitious system. This formation apparently increases the porosity and the gel/space ratio of the cement paste and gives rise to a non-uniform distribution of the hydrated products since the time available for complete hydration is not sufficient. Cases of expansion and crack formation in concrete cured at temperatures over 70 °C

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have also been reported due to the delayed formation of ettringite in the hydrated cement paste [14].

2. Experimental study

2.1. Objective and scope

The aim of this investigation is to ascertain the most efficient cement for heat treatment application considering its early flexural strength and to determine the parameters of heat treatment cycle suitable to such cement for optimum strength gain both at early and later ages.

2.2. Materials and program layout

Five cements of different type and composition that are commonly produced in most countries were studied. PÇ 42.5 and PÇ 32.5 represent a rapid-hardening Portland cement and an ordinary Portland cement, respectively. CÇ 32.5 is a Portland blast-furnace (slag) cement; KÇ 32.5 and TÇ 32.5 represent a Portland composite cement and a Portland-pozzolan cement, respectively. The heat treatment cycle used in this study is shown in Fig. 1. The total duration of the heat treatment cycle is 22 h with a constant post curing period of 2 h. The heating and cooling rates were kept constant as 15 °C per hour. In this study, therefore, only the treatment temperature and its duration, along with preheating duration were determined.

A preliminary test was performed to determine an optimum preheating duration for the heat treatment cycle. Considering one-day flexural strengths, a preheating duration of 2–4 h was found to be appropriate. To keep morphological and physical changes of hydration products to a minimum level, a 4 h preheating duration was then adopted to determine the heat treatment temperature suitable to cements for flexural strengths as high as possible at early age. The program layout pursued is given in Table 1.

A treatment temperature ranging from 50 to 95 °C was used to simulate the temperatures used in practice.

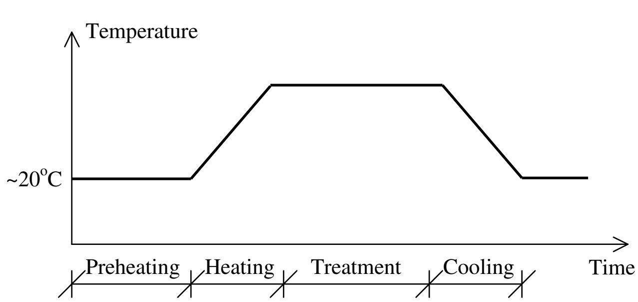

Fig. 1. Schematic sketch of typical heat treatment cycle.

Table 1
Heat treatment cycles applied in the program

Cycle no.	Treatment temperature (°C)	Preheating duration (h)	Heating duration (h)	Treatment duration (h)	Cooling duration (h)
1	50	4	2	14	2
2	65	4	3	12	3
3	80	4	4	10	4
4	95	4	5	8	5
5	80	0	4	14	4
6	80	2	4	12	4
7	80	6	4	8	4

Starting with 50 °C, five different treatment temperatures with 15 °C increments were tried. For each treatment temperature, preheating duration of 0, 2, 4, and 6 h were then tried for each cement. Considering the heat-treated one-day and 28-day flexural strengths, the optimum heat treatment cycle and the cement suitable to such treatment were decided. Cements studied with their physical properties and oxide analyses along with the potential compounds of Portland cements only are given in Table 2.

2.3. Specimen preparation and experimental conditions

The investigation was carried out at 20 ± 2 °C. The standard cured specimens were kept in the same room in a water tank at 20 °C until the testing age. The specimens to be subjected to heat treatment at the end of the preheating duration were immediately placed in a water tank with a temperature of 20 °C prior to heat treatment. A temperature programmer unit appropriate for the desired cycle adjusting the water temperature of the tank and the temperature was continuously controlled using a platinum resistance thermostat. The specimens were stripped off the moulds 2 h after the cooling period and then tested at the end of 24 h. The moulds were then cleaned and prepared for the next production in 2 h; thus, the program was permitted the moulds to be used once a day. The specimens to be tested at the end of 28 days were kept in water at 20 °C.

Three standard mortar prisms measuring 40 × 40 × 160 mm for each cycle were produced in accordance with TS EN 196-1 [15]. A standard sand rich in quartz was used in preparing the mixture for mortar prisms. According to the procedure described in the associated standard, one unit of water, two units of cement, and three units of sand in mass were used so that a water to cement ratio of 0.5 was adopted. Following the heat treatment application, the prisms were subjected to bend testing at the end of 1 day and 28 days; thus, the flexural strength obtained was as an average of three measurements. To determine the standard flexural strength, two series of mixtures were prepared and tested so that the standard flexural strength obtained was an average

Table 2
Physical and mechanical properties along with chemical analysis of cements

Cement type	Turkish designation (TS EN 197-1)	PÇ 42.5 (CEM I)	PÇ 32.5 (CEM I)	CÇ 32.5 (CEM III)	KÇ 32.5 (CEM II)	TÇ 32.5 (CEM IV)
Physical properties	Specific gravity, g/cm^3	3.04	3.09	3.02	3.05	3.05
	Fineness					
	200 μm (retained), %	0.17	0.22	0.12	0.23	0.26
	75 μm (retained), %	2.71	12.71	10.17	9.72	12.18
	Specific surface					
	(Blaine), m^2/kg	381	275	298	386	395
	Water demand, %	29.5	25.0	27.0	26.5	26.5
Mechanical properties	*Flexural strength, MPa*					
	1-day	2.7	1.4	1.5	1.7	1.5
	28-day	7.3	6.3	6.2	6.6	5.8
	Compressive strength, MPa					
	1-day	8.0	5.0	5.4	7.1	5.5
	28-day	47.0	39.8	34.1	41.9	31.7
Potential compounds (%)	C_2S	7.1	47.9	–	–	–
	C_3S	63.2	22.2	–	–	–
	C_3A	6.6	14.1	–	–	–
	C_4AF	10.0	7.9	–	–	–
Chemical composition (%)	Silica (SiO_2)	19.09	22.54	25.16	19.41	10.08
	Alumina (Al_2O_3)	4.60	6.98	9.41	5.50	7.64
	Ferric oxide (Fe_2O_3)	3.28	2.60	2.24	4.08	4.36
	Lime (CaO), total	63.19	61.40	52.84	57.30	49.27
	Magnesia (MgO)	1.79	1.40	4.46	0.77	1.40
	Sulphur trioxide (SO_3)	2.79	1.75	1.95	2.88	1.81
	Loss on ignition	2.67	1.32	0.45	2.26	3.83
	Insoluble residue	1.01	0.64	0.74	6.90	19.04
	Lime (CaO), free	1.33	0.21	0.35	0.28	0.35

of six measurements. The flexural strength was determined by the center-point loading. In the testing, the prisms were tested turned on their sides with respect to their mould face by applying the load at mid point over a span of 10 cm.

3. Results and discussion

Fig. 2 shows the variation of the one-day flexural strength of the prisms heat-treated with a 4 h preheating duration in relation to treatment temperature. The one-day flexural strengths of the standard cured specimens are also included in the same plot. Except for CÇ 32.5, a treatment temperature of 65 °C seems to be appropriate for all cements as the one-day flexural strength is maximum at that temperature. Concerning CÇ 32.5, a treatment temperature of 80 °C is relevant since the one-day flexural strength is maximum at that temperature. This may be attributed to the strength-contribution effect of slag that is present in CÇ 32.5 cement [8]. However, concerning the one-day flexural strength of prisms, it can be concluded that treatment temperatures ranging from 50 °C to 80 °C seem to be quite relevant for prefabrication purposes. Regardless of cement type and composition, heat treatment with higher temperatures does not seem to contribute much to flexural strength; on the contrary, it does obviously decrease over 80 °C. It may also be seen from Fig. 2 that PÇ 42.5 and KÇ 32.5 indicate relatively better performance under heat

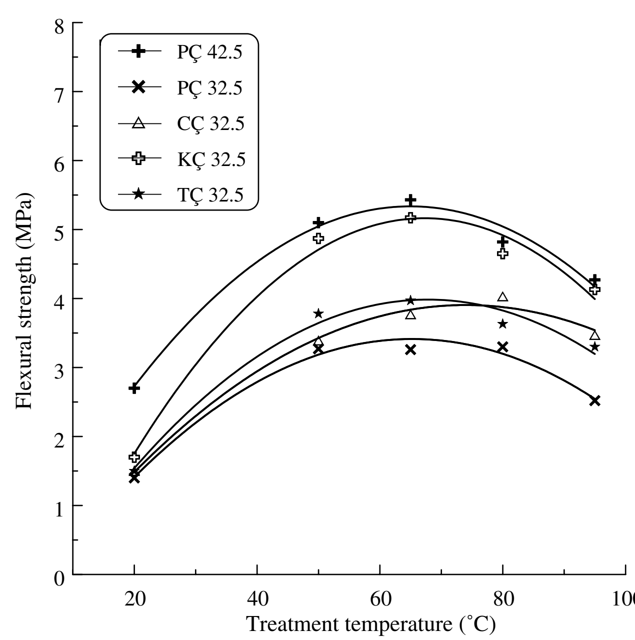

Fig. 2. One-day heat-treated flexural strength with respect to treatment temperature.

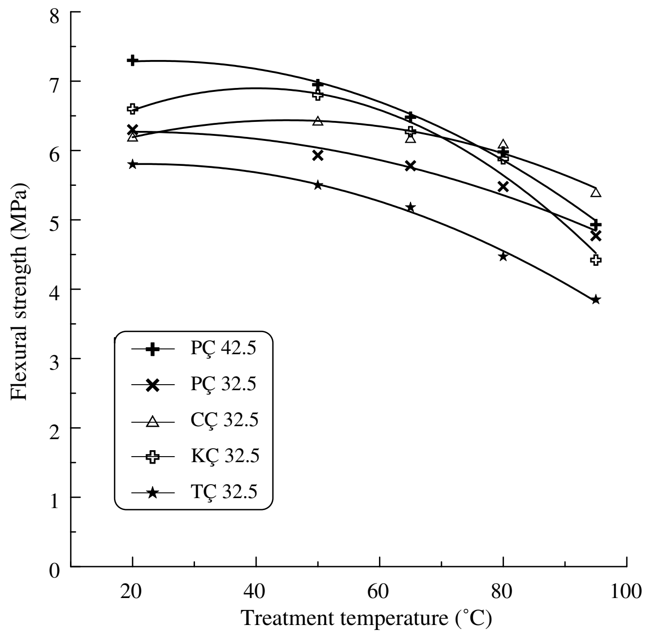

Fig. 3. Twenty-eight-day flexural strength with respect to treatment temperature.

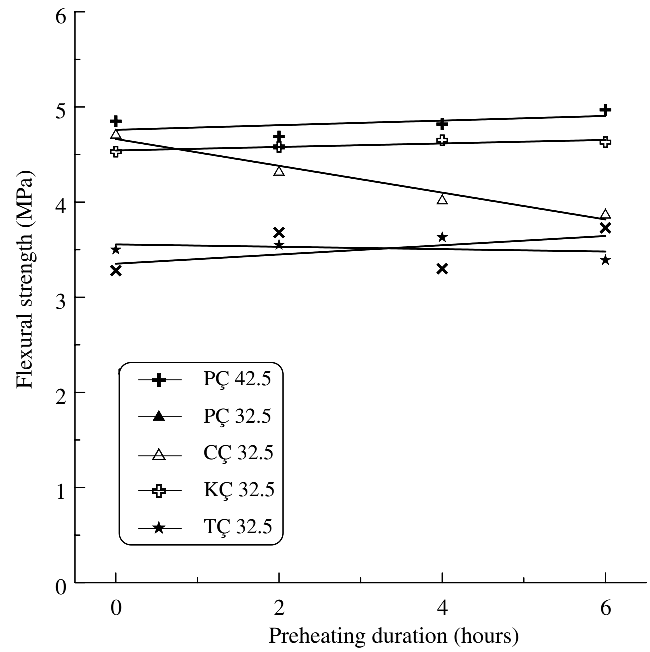

Fig. 4. One-day flexural strength with respect to preheating duration.

treatment application compared to the other cements tested. This might be attributed to their quite similar composition and their high fineness with very close values of 381 m^2/kg and 386 m^2/kg, respectively. The potential compound of KÇ 32.5 cement could not be determined by Bogue formula since it is a composite cement. The PÇ 32.5 cement indicated relatively poor performance compared to CÇ 32.5 and TÇ 32.5 cements. This might be attributed to its rather low fineness with a value of 275 m^2/kg.

Fig. 3 presents the variation of the 28-day flexural strength of the prisms heat-treated with a 4 h preheating duration with regard to treatment temperature. This graph shows that the 28-day strength decreases with respect to the treatment temperature, regardless of the type of cement used. In view of the drop observed in strengths as the temperature increases, CÇ 32.5 seems to be more suitable to heat treatment compared to the other cements. This might be attributed to the contribution of slag present in the cement to the strength gain at higher temperatures. Overall, regardless of cement type, heat treatment with a temperature over 65 °C seems to be detrimental since the flexural strengths start to decrease over this temperature. This indicates once more that the technical optimum treatment temperature for cement under testing is below 80 °C. If lower early flexural strength is satisfactory, heat treatment temperatures in the range of 40–80 °C may be applicable for all cements tested for better economy.

Fig. 4 shows the variation of the one-day flexural strength of the prisms heat-treated at 80 °C with respect to the preheating duration. As can be seen from the figure, depending on the preheating duration, while the flexural strengths of PÇ 42.5, PÇ 32.5 and KÇ 32.5 indicate a statistically insignificant increase, the flexural strength of CÇ 32.5 decreases. On the other hand, there is almost no change in the flexural strength of TÇ 32.5, depending on preheating duration. Overall, Fig. 4 clearly shows that a preheating duration between 0 and 6 h may be found appropriate for all cements. However, a preheating duration between 2 and 4 h may be recommended to be appropriate for minimizing the possible physical damage that occurs due to residual volume increase of the concrete by extending the duration prior to application of heat treatment. To be more precise, a preheating duration of 2 h can be said to be suitable for economic and practical reasons.

Overall, the temperature at which the early flexural strength gain is the highest is 80 °C for CÇ 32.5, and 65 °C for the other cements tested. This indicates that a treatment temperature of 65 °C is optimum for maximum flexural strength gain at the end of 1 day of heat treatment. The cycle parameters determined here as appropriate for heat treatment application do not necessarily mean that they are also suitable to any cement with a composition different from those tested in this study. Obviously, heat treatment temperature can be adjusted in accordance with the targeted one-day strength. It is clear that heat treatment application with a lower treatment temperature is economic and energy saving. Therefore, in choosing heat treatment cycle, the technical and economic priorities should be taken into account, and it is of vital importance to choose treatment temperature suitable to the cement to be used.

4. Concluding remarks

The main conclusions derived from the study are as follows:

(i) The cements studied all responded well to heat treatment application concerning the flexural strength level reached at one-day. The strength level that reached at 24 h is over 60% of their respective the 28-day standard flexural strengths.
(ii) Except for CÇ 32.5, the heat treatment temperature at which the one-day strength becomes maximum is 65 °C. A treatment temperature of 80 °C seems to be suitable for CÇ 32.5 cement. Treatment temperatures over 80 °C seem to be detrimental because of the adverse effects on both early and long-term strengths. If the target strength level is sufficient, lower temperatures in the range of 50–70 °C may be economical.
(iii) Based on the results, it can be seen that a preheating duration of 2–4 h is appropriate. A shorter duration may be chosen for CÇ 32.5 since a considerable decrease in strength is obvious as the preheating duration increases.
(iv) Overall, cement type and composition is of great importance concerning both the short and long-term flexural strength gains.

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