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Setting time: An important criterion to determine the length of the delay period before steam curing of concrete

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Abstract

Some precast concrete plants expose freshly made concrete elements to steam curing immediately after casting. This is detrimental to properties of the product; therefore, some delay prior to the steam curing process is beneficial. This paper contains the results of an investigation on the effects of various delay intervals selected based on initial setting time of concrete. Four different delay periods and two different steam curing periods at 80 °C (5 and 10 h) were used with two concrete types, namely C25 and C40. Compressive strength tests were performed at 1, 3, 7, 28, and 90 days. Setting time of the concrete was found to be an important criterion to determine the length of the delay periods.

Keywords: Compressive strength; Concrete; Curing

1. Introduction

Steam curing is widely used in the production of precast concrete members because it accelerates the rate of strength development. Some precast concrete plants apply steam curing immediately after casting the elements in the formwork in order to speed up the production rate. Although early application of steam curing is a common practice, many researchers have indicated that this is quite detrimental and that some delay prior to steam exposure is beneficial to concrete properties, such as strength and durability [1–5].

Soroka et al. [1] concluded that applying steam curing after short delay periods (30–60 min) were detrimental to compressive strength. Shideler and Chamberlin [2] showed that a delay of 2–6 h prior to steam curing, depending on the temperature, produced 15–40% higher strengths at 24 h than when steam curing was started immediately after the concrete was placed. Hanson [3] proved that as the delay period increased from 1 to 5 h, compressive strengths increased at all ages. Moreover, horizontal cracking was observed in all specimens steam-cured with only a 1-h delay period.

Mironov [4] concluded that the delay period should be determined in such a way that the steam curing operation should not cause expansions. It was stated that this period corresponds to the time needed for the concrete to have a compressive strength of 7–8 kgf/cm^2. Alexanderson [5] observed that the expansions can be neglected for delay periods of 4–7 h (depending on water–cement ratio) and no strength loss was observed at late ages. According to Alexanderson [5], lower quality of concrete due to shorter delay periods is the result of increased porosity and cracks caused by the tensile stresses formed by the internal pressure in the pores. Therefore, it was concluded that the concrete should have a critical tensile strength before the start of the steam curing operation.

Heinz and Ludwig [6] reported the significance of secondary ettringite formation on the deterioration of high temperature (>75 °C) steam-cured precast concrete. Delayed expansion in the concrete was attributed to the transformation of metastable monosulfate to ettringite when steam curing was followed by normal temperature moist curing at later ages [7]. Under such conditions, concrete may show abnormal expansion and associated microcracking, which may lead to failure in the long term [8]. Delayed ettringite formation (DEF) in non-steam-cured paste were studied by Odler and Gasser [9]. The factors that produce microcracks such as alkali–silica reaction [10,11], freezing–thawing

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[12,13], or mechanical damage [7] can promote DEF in the resulting cracks, which then induces the expansion. Taylor et al. [14] reviewed the literature on DEF very extensively. According to this review, the concrete or mortar microstructure determines how the material responds to the stress produced by ettringite formation. It was stated that anything that weakens the material would lower its ability to resist expansion. If curing temperature, heating and cooling rates, and delay periods are not chosen properly, thermal stresses can cause microcracks, and affect not only the strength, but also the liability of the concrete to all kinds of damaging processes such as DEF. The reason why DEF will be favored in such a case is that water penetrates into the concrete more easily and that paste–aggregate bonds become weaker [14].

In this paper, the effect of varying delay periods, based on initial setting time of the concrete, on the strength was investigated.

2. Experimental

2.1. Materials

Ordinary Portland cement, PC 42.5, corresponding to ASTM Type I cement, from a Turkish source was used in this study. Chemical composition and physical properties of the cement are presented in Tables 1 and 2, respectively.

Natural sand and crushed stone having different particle sizes were combined in the ratio of 55% fine aggregates and 45% coarse aggregates by mass. Maximum aggregate size of the coarse aggregate was 25 mm.

Municipal tap water was used as mixing water. A melamine-based, ASTM Type F superplasticizer was used to produce C40 type of concrete.

2.2. Concrete mixtures

Concrete mixture proportions were determined according to the procedure given by the American Concrete Institute Committee 211. The batch quantities for C25 and C40 types of concrete are shown in Table 3 (the designations C25 and C40 represent the minimum critical compressive strength at 28 days [in N/mm^2]). Both types of concrete were designed to obtain a 5-cm slump.

2.3. Experimental procedure

Concrete mixtures C25 and C40 were made at the laboratory temperature 23 °C. The reference specimens of C25 and C40 were continuously cured at 23 °C and 100% relative humidity until they were tested in compression at the end of 1, 3, 7, 28, and 90 days. For each type of concrete, three standard cylinder specimens (15 × 30 cm) were tested at each age and the average values were calculated to obtain the reference strength values.

Initial setting time (t) of each type of concrete was determined according to the procedure given in ASTM C 403. Initial setting times for C25 and C40 were 235 and 220 min, respectively. These setting times were taken as the basis of selecting the *delay periods*, defining the delay period as the period between the time that water is mixed with cement in the mixer and the time that the steam curing operation is started. The following four delay periods were investigated: t, $t-1$, $t-2$, and $t-3$ h. Table 4 lists the delay periods for each type of concrete.

During the delay period, the specimens were covered with a wet cloth and kept at 23 °C. At the end of the delay period, the temperature within the curing chamber was increased to 80 °C at a rate of approximately 21 °C/h For each one of the four delay periods, the specimens were subjected to steam curing at this constant temperature (80 °C) for either 5 or 10 h before they were allowed to cool down to the ambient temperature (23 °C) over a 5-h period. Then, the specimens were kept at 23 °C and 100% relative

Table 1
Chemical composition of Portland cement (%)

CaO	61.88
SiO_2	19.83
Al_2O_3	5.32
Fe_2O_3	3.47
MgO	1.78
SO_3	2.84
K_2O	0.82
Na_2O	0.20
LOI	3.06

Table 2
Physical properties of Portland cement

Specific gravity	3.11
Specific surface area (cm^2/g)	3250
Time of setting (min)	
Initial	70
Final	230
Compressive strength (MPa)	
7 days	32.6
28 days	45.3

Table 3
Concrete mixture proportions (slump = 5 cm)

Materials	C25	C40
Cement (kg/m^3)	300	375
Water (kg/m^3)	184	205
Natural sand (0–7) (kg/m^3)	462[a]	490[a]
Crushed stone (0–3 mm) (kg/m^3)	569[a]	450[a]
Crushed stone (3–9 mm) (kg/m^3)	678[a]	125[a]
Crushed stone (10–25 mm) (kg/m^3)	134[a]	660[a]
Superplasticizer (kg/m^3)	–	6.3
Water/cement	0.61	0.42

[a] Saturated surface dry condition.

Table 4
Delay periods for concrete mixtures C25 and C40

Concrete type	Delay period before steam curing (min)			
	t (initial setting time)	$t-1$ h	$t-2$ h	$t-3$ h
C25	235	175	115	55
C40	220	160	100	40

humidity until the testing age. For each steam curing condition, three standard cylinder specimens were tested in compression at the end of 1, 3, 7, 28, and 90 days, and the average values were computed.

3. Results and discussions

Compressive strength test results for C25 and C40 cured for 5 and 10 h at 80 °C are tabulated in Table 5. Compressive strength values of the reference concrete specimens are also given in the same table. The strengths of the steam-cured specimens, expressed as percentages of strength of the reference specimens at that age, are shown in Figs. 1–4.

Figs. 1–4 indicate that 1-day strengths of all steam-cured specimens were higher than those of the reference specimens, and the later age strengths were lower, as also reported in previous studies and in literature [15–19]. Significant strength losses at 3, 7, 28, and 90 days were observed for steam-cured specimens having delay periods of $t-3$, $t-2$, and $t-1$ h. However, there was no or little strength loss even at 3 days for the specimens having a delay period equal to the setting time (t).

Analysis of the test results given in Table 5 points out that 3-day strengths for a delay period of t were greater than 7-day strengths of the specimens having delay periods of $t-2$ and $t-3$ h. For example, for a hold time of 5 h, the 3-day strength of C40 having a delay period of t (32.7 MPa) was greater than the 7-day strengths of the specimens with delay periods of $t-2$ (28.8 MPa) and $t-3$ h (26.9 MPa). Similarly, when the delay periods was increased to t from $t-2$ or from $t-3$ h, the 1-day strengths were higher than the 3-day strengths with the exception of C25 with a hold time of 5 h.

It is apparent from Figs. 1–4 that the strength tends to increase with increasing delay intervals. When the delay period was increased to t from $t-3$ h, 1-day strengths improved appreciably. To illustrate, for a hold time of 10 h, 1-day strength of C25 was 17.9 MPa (equal to 130% of the reference) for a delay period of $t-3$ h, and it was 22.6 MPa (equal to 165% of the reference) when the delay period was t; the extra strength gain was 35%. This extra strength improvement was also noticed at 3, 7, 28, and 90 days for both C25 and C40, however, at these ages, the strength differences between t- and $t-3$-h delay periods were lower when compared to the 1-day strength differences. This extra strength improvement can be attributed to the reduction in crack propagation due to increased tensile strength as a result of increased delay period before steam curing process [5].

Various delay periods were investigated in the previous studies [1–5]. In this study, the delay periods were selected based on the setting time. The reason for this and the benefits of delay periods that are equal to the setting time can be explained as follows: during the temperature rise, the concrete temperature lags behind that of the curing chamber due to the time needed for the heat transfer to the inner parts. Therefore, if the steam application starts before the setting time of the concrete, the outer portions (or the faces) of a concrete specimen harden earlier while the inner concrete is still plastic. In other words, a rigid skeleton (or a hardened shell) is formed around the inner plastic concrete. As the internal temperature increases (due to steam application and heat of hydration), the inner fresh concrete will try to expand. Therefore, the exterior rigid shell can be damaged due to the tensile stresses induced by this expansion. Here, the authors suggest that the steam curing not be applied before the setting time of the concrete since there will no longer be inner plastic concrete (and its expansion) after setting.

Table 5
Compressive strength test results (MPa)

Concrete type	Age (days)	Reference	Steam curing hold time = 5 h				Steam curing hold time = 10 h			
			Delay period				Delay period			
			$t-3$ h	$t-2$ h	$t-1$ h	t[a]	$t-3$ h	$t-2$ h	$t-1$ h	t
C25	1	13.7	16.4	16.7	18.2	18.4	17.9	18.9	21.3	22.6
	3	23.4	18.5	19.6	22.3	22.7	19.8	21.1	23.2	24.8
	7	29.5	21.7	20.5	25.2	24.7	22.3	23.0	25.9	26.4
	28	34.1	27.5	28.0	28.7	30.2	28.5	29.5	30.6	32.3
	90	37.5	31.7	33.4	34.5	34.5	32.7	34.2	35.0	36.3
C40	1	22.6	23.5	24.1	27.4	30.2	26.3	27.7	30.7	34.1
	3	33.8	23.8	26.0	30.4	32.7	27.6	28.1	32.5	35.2
	7	40.9	26.9	28.8	34.6	36.7	29.2	31.2	35.7	38.4
	28	46.1	33.4	34.9	36.5	41.2	36.3	36.8	40.5	42.9
	90	49.2	39.9	42.2	43.0	43.5	42.2	43.4	45.5	46.5

[a] t is the initial setting time of the concrete. It is 235 min for C25 and 220 min for C40.

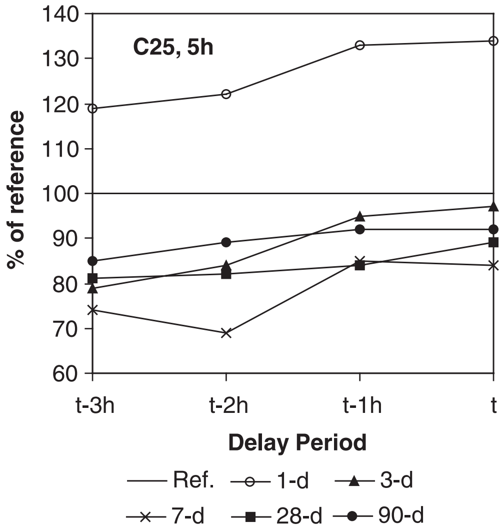

Fig. 1. Compressive strength of C25 as percentage of the strength of the reference concrete at the corresponding age (hold time = 5 h).

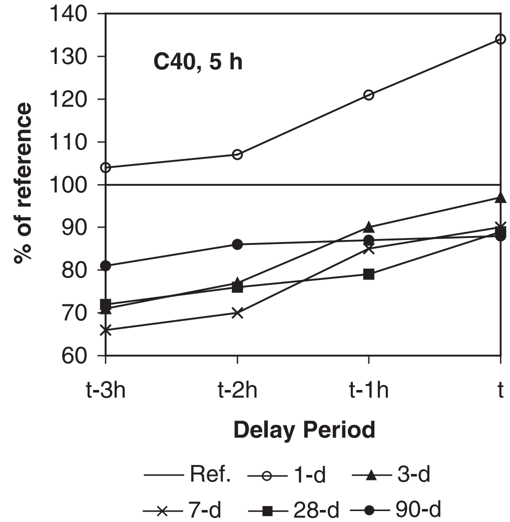

Fig. 3. Compressive strength of C40 as percentage of the strength of the reference concrete at the corresponding age (hold time = 5 h).

Moreover, during the heating stage, the differences in the thermal expansion coefficient of the concrete ingredients can lead to microcracking and increased porosity [5]. When the steam curing of the concrete begins after a delay period equal to its setting time, such a deleterious effect may be prevented to some extent by the increased resistance to expansions.

Test results show that higher strengths were obtained at all ages when the duration of hold time at the steam curing temperature was higher. Longer heat application was observed to be effective especially for 1-day strength. From Figs. 1 and 2, it can be seen that when the hold time period was increased from 5 to 10 h, the 1-day strength of C25 improved by 11%, 16%, 22%, and 31% for the delay periods of $t-3$, $t-2$, $t-1$, and t h, respectively. Similarly, from Figs. 3 and 4, the increase of hold time from 5 to 10 h improved the 1-day strength of C40 by 13%, 16%, 15%, and 17%, respectively, with increasing delay periods. On the other hand, for both C25 and C40, when the steam curing was prolonged from 5 to 10 h, the increases in strength at 3, 7, 28, and 90 days were much less than those at 1 day.

A comparison of the strength data between C25 and C40 shows that the 1-day strength gains of C25 due to steam curing are higher and its strength losses at later ages are lower than C40. Therefore, it was found that steam curing was more beneficial to C25 than C40. From the limited number of experiments of this study, the probable reason for this can be stated as follows: the accelerating effect of steam curing on the strength development is more pronounced when the water–cement ratio is higher. However, further research is required for more evidence to draw such a conclusion. At least, it can be said that for a given water–

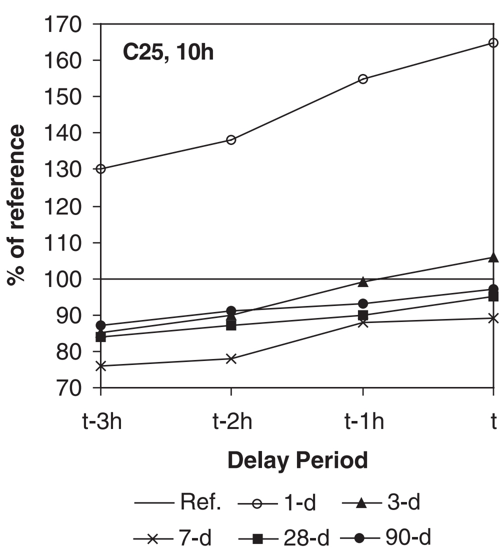

Fig. 2. Compressive strength of C25 as percentage of the strength of the reference concrete at the corresponding age (hold time = 10 h).

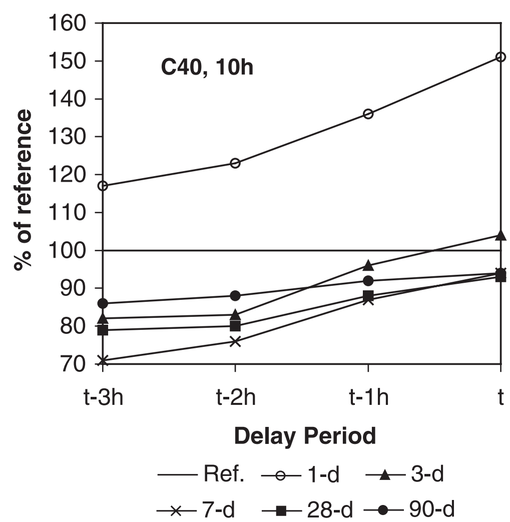

Fig. 4. Compressive strength of C40 as percentage of the strength of the reference concrete at the corresponding age (hold time = 10 h).

cement ratio, the detrimental effects of steam curing at later ages will be higher for the specimens with higher cement content. This is because higher heat of hydration will lead to higher temperature rise (and expansion) in the concrete during the heating stage of the steam curing cycle. In our case, it is suggested that applying longer delay periods can increase the efficiency of the steam curing of C40.

4. Conclusions

1. One-day compressive strengths of all steam-cured specimens were higher than the reference specimens. However, lower strengths were obtained at 3, 7, 28, and 90 days.
2. By delaying the steam curing operation by a period equal to the setting time of concrete, higher strengths were obtained in a shorter time. For the delay periods reported in this study, highest strength was obtained when the delay period was equal to the setting time.
3. Higher strengths were obtained when the duration of the steam curing operation at 80 °C was prolonged from 5 to 10 h.
4. Beneficial effects of steam curing were more pronounced for C25 when compared to C40. Delaying the steam curing by a period equal to the setting time of concrete was found to be more important for C40.

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