Concrete Physical Property Development at Early Ages: the Influence of Steam Curing

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Results of tests carried out to investigate the causes of early-age cracking reported in some precast, prestressed, steam-cured structural members are reported. Cracks have been observed at the fabrication site even before structures are put into use. An investigation was conducted into the development of concrete physical properties at early ages when the concrete is steam cured. Properties investigated were compressive strength, elastic modulus, splitting tensile strength, and Poisson's ratio. A prestressed concrete producer sample was used in the fabrication of conventional 6- × 12-in. cylinder test specimens. Test results were obtained for 8 hr, 14 hr, 1 day, 2 days, 3 days, 7 days, and 28 days. Tests were carried out on both steam-cured and companion standard moist-cured specimens for comparison. Steam curing was found to be beneficial to the development of all the physical properties only at early ages. The beneficial effect was found to be the least lasting on the tensile strength development in which the benefit appeared to have ceased even before steam curing was discontinued. This resulted in lower tensile strength values for the steam-cured specimens when compared with the values for their standard moist-cured companions. The observed low tensile strength developed in steam-cured specimens may be responsible, at least partially, for the cracking reported during strand release and form stripping at prestressing plants.

Steam curing is a relatively new curing method that is used mostly by the precast, prestressed concrete industry. The relatively recent introduction of precast, prestressed concrete into different areas of the concrete construction industry has brought pressure on the prestressing plants to produce concrete at a faster rate than can be accommodated by normal curing methods. This demand on the precast, prestressed plants has necessitated an economic daily turnaround of molds that can only be achieved through an accelerated curing procedure. The most commonly used method to achieve accelerated curing is the low-pressure steam-curing method in which concrete is cured with saturated steam at atmospheric pressure, necessarily at temperatures below 100°C (212°F). Its primary purpose is to accelerate concrete compressive strength development so that prestressing strands can be released, forms can be stripped and reused at frequent intervals, and concrete products can be stored or put to use at an early age. Since the use of steam curing at atmospheric pressure began about 60 years ago, considerable experimental work has been undertaken to investigate its effects on concrete strength development.

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Recently, it has been observed that some of the steam-cured prestressed structural members are developing cracks even before they are put into use. This early-age cracking has been reported by several researchers (*1–5*) and has been attributed to relatively low values of physical properties developed during the early ages. Cracking has also been reported during routine inspections at the prestressed concrete plant. In most cases, these cracks develop during prestressing at the time of form removal when concrete has not attained its specified design strength.

Although it is generally accepted by researchers (*6–9*) that steam curing accelerates compressive strength development, the effects of steam curing on the early-age development of other properties like elastic modulus, splitting tensile strength, and Poisson's ratio have not been precisely defined. Higginson (*7*) reported that elastic modulus increased with compressive strength and that Poisson's ratio showed nearly the same value for all ages and curing conditions. Hanson (*6*) pointed out that the optimum steam-curing conditions for modulus of elasticity and tensile strength would differ from those required for optimum compressive strength. The U.S. Bureau of Reclamation as well as many researchers (*6–10*) have observed that the greatest acceleration in compressive strength gain and minimum loss in ultimate strength were obtained at steam-curing temperatures between 120° and 165°F.

It has not been established that the stated optimum steam-curing condition for compressive strength development is equally beneficial to either elastic modulus development or tensile strength development at early ages. An understanding of elastic modulus development is required for the estimation of prestress losses and for calculation of immediate and long-term deformations due to early loading.

Although it is generally assumed that concrete performance is mostly governed by its compression capabilities, tensile strength (which directly influences cracking at prestress release) and shear capacity are important with respect to the appearance and durability of concrete structural members. Variation of tensile strength with time is an important factor in predicting concrete shear strength at different curing times. This study investigated the effects of the steam-curing conditions (as used by typical prestressing plants) on the development of the important physical properties at early ages.

EXPERIMENTAL INVESTIGATION PROCEDURE

Fabrication of Test Specimens

Test specimens were fabricated from a precast, prestressed concrete producer sample. The 28-day compressive strength of the concrete mix was approximately 6,000 psi. The specimens were cast from a single batch of concrete. Standard 6- × 12-in. molds were used in accordance with ASTM C 470, and molding was done according to the specifications of ASTM C 31. The coarse aggregate used was ASTM No. 67 with 100 percent of the crushed stone less than 1 in. (of this, 90 to 100 percent was about ¾ in.). Fine aggregate was crushed limestone. Concrete mix proportions were as follows (per cubic yard of mix):

- Type I portland cement, 752 lb;
- Coarse aggregate, 1,730 lb;
- Fine aggregate, 1,242 lb; and
- Water, 292 lb.

Curing Procedure

Wet burlap was used to cover the molds and specimens until the specimens were removed from the molds. A polyethylene sheet was placed over the burlap to minimize evaporation.

Both moist and steam curings were used for the precast, prestressed producer sample. Steam curing as practiced by typical prestressing plants was used. The presteaming period was 5 hr, and the rate of temperature rise was about 40°F per hour up to a maximum temperature of about 130°F. The total steaming period was 15 hr.

For comparison, companion specimens were moist cured at standard conditions. About 20 to 24 hr after casting, specimens were stripped and transferred to the standard moist room where curing continued at about 73°F (23°C) in accordance with ASTM C 192. Most of the test results on which strength design relations are based were performed on moist-cured concrete specimens; hence the choice of moist curing at 73°F in this study.

Testing Procedure

Three specimens from each mix were tested for each of the parameters investigated at 6 hr, 12 hr, 1 day, 2 days, 3 days, 7 days, and 28 days.

Compressive Strength, Elastic Modulus, and Poisson's Ratio Tests

The cylinders that were tested for compressive strength also provided the data for static elastic modulus and Poisson's ratio. Before testing, and to prevent stress concentration during testing, the specimens were capped with a proprietary compound containing sulfur in accordance with the specifications of ASTM C 617. Compressive strength testing was performed on a 300,000-lb capacity testing machine that is capable of loading at a rate of 20 to 50 psi/sec (ASTM C 39). Compressive strength tests were performed in uniaxial compression to failure.

Simultaneous with the compressive strength test, the longitudinal and lateral deformations were measured with the Structural Behavior Engineering Laboratories deformation jacket. This jacket is equipped with six linear variable differential transformer transducers (LVDTs). Three of these LVDTs measure the axial strain and the other three measure the lateral strain. These LVDTs provided an average of three readings for strains in each direction. This approach reduced the error in strain measurement and ensured a higher degree of accuracy of physical property evaluation. The strains in the two directions were computed using data acquisition software.

The compressive strength (S) was calculated from the relation

$$S = P/\pi r^2 \tag{1}$$

where P is load at failure and r is the radius of the specimen.

The static elastic modulus (Young's modulus) was calculated from the stress-strain diagram. The chord modulus is calculated from the relation

$$Ec = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005} \tag{2}$$

where S_2 is the stress corresponding to 40 percent of the ultimate stress, S_1 is the stress corresponding to a strain of 0.00005, and ε_2 is the longitudinal strain corresponding to S_2.

Poisson's ratio, the ratio of transverse strain to longitudinal strain, is determined from the relation

$$\mu = \frac{\varepsilon t_2 - \varepsilon t_1}{\varepsilon_2 - 0.00005} \tag{3}$$

where εt_2 and εt_1 are transverse strains at mid-height of the test specimen produced by S_2 and S_1, respectively. S_2, S_1, and ε_2 are the same as defined in Equation 2.

Splitting Tensile Strength

In general, three kinds of test methods are available for estimating the tensile strength of concrete: the direct tension test, the beam or modulus-of-rupture test, and the split-cylinder or Brazilian test.

Previous investigations (*11–15*) have indicated that the split-cylinder method is a more reliable measure of tensile strength than the modulus-of-rupture test. The most important advantage of the split-cylinder test is the approximate uniformity of tensile stress over the diametral area of the test cylinder. Moreover, its simplicity affords the opportunity to test a large number of specimens within a relatively shorter period of time.

The split-cylinder test was used in this study in accordance with the specifications of ASTM C 496. The tensile strength was computed from the relation

$$f_t = \frac{2P}{\pi DL} \tag{4}$$

where f_t is the tensile strength in pounds per square inch, P is the magnitude of load at failure in pounds, and D and L are the cylinder diameter and length, respectively, in inches.

PRESENTATION AND DISCUSSION OF TEST RESULTS

Tests were performed to investigate the influence of steam curing on the elastic modulus, the splitting tensile strength, Poisson's ratio, and the compressive strength developments at early ages. Test results are summarized in Table 1.

Figures 1 and 2 present a comparison of compressive strength development in steam- and moist-cured concretes. As expected, these figures indicate that steam curing significantly accelerated the strength development within the first day. At the end of the first day (when steam curing was discontinued), the rate of gain in strength in the steam-cured concrete diminished. In fact, there was little (184 psi) gain in strength between the end of the first day and the third day. Moist-cured concrete gained strength steadily and, by the third day, it developed more compressive strength than steam-cured concrete. At 7 and 28 days, moist-cured concrete continued to develop higher compressive strengths than steam-cured concrete. This result completely agrees with observations made by other researchers mentioned earlier.

Steam curing appears to have a more lasting effect on elastic modulus development than on development of the compressive strength. The results presented in Figures 3 and 4 show that steam curing was beneficial within the ages of 1 to 3 days. The greatest increase in the elastic modulus development was observed shortly after steam curing had been discontinued. Then, on the seventh day of curing, the moist-cured value of elastic modulus became slightly higher than the steam-cured value. Beyond the age of 7 days, the elastic modulus of moist-cured concrete developed faster than that of steam-cured concrete. This fact indicates that the benefit of steam curing to the elastic modulus development is limited to the first 3 days and that steam curing is detrimental to the elastic modulus development at ages above 3 days.

Tensile strength development benefits least. As presented in Figures 5 and 6, steam curing benefited tensile strength development only up to about 14 hr. Furthermore, it appears that the beneficial effect of steam curing on tensile strength ceased even before steam curing was discontinued. By the end of the first day (when strands are usually released), moist-cured concrete had developed more tensile strength than steam-cured concrete. Thereafter, and up to 28 days, moist-cured concrete consistently developed higher values of tensile strength than steam-cured concrete. As stated earlier, tensile strength controls resistance to cracking at prestress release. The relatively slow rate of tensile strength development in steam-cured concrete may be responsible, at least partially, for the

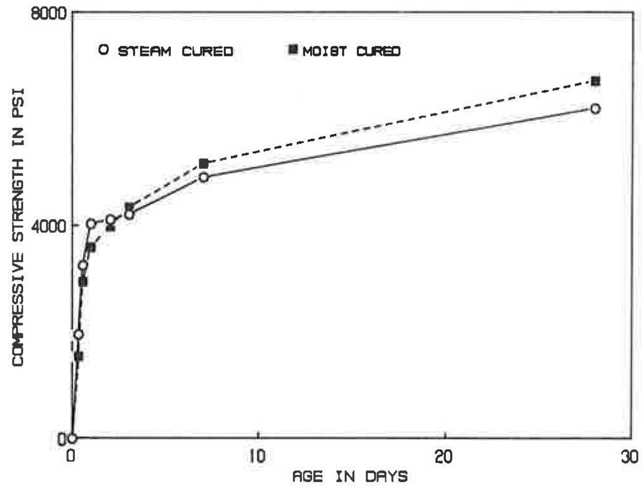

FIGURE 1 Comparison of compressive strength development in moist- and steam-cured concrete.

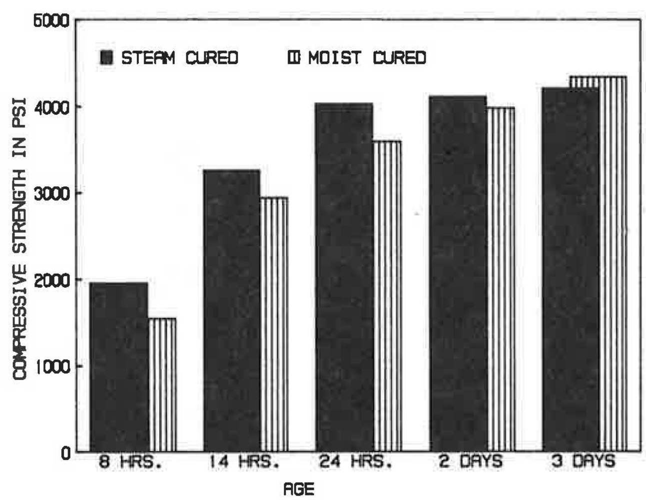

FIGURE 2 Compressive strength development in moist- and steam-cured concrete: first 3 days.

TABLE 1 SUMMARY OF TEST RESULTS

Age	Steam fc (psi)	Moist fc (psi)	Steam Ec (10^6 psi)	Moist Ec (10^6psi)	Steam ft (psi)	Moist ft (psi)	Steam ν	Moist ν
8 Hrs	1,957	1,548	2.4586	2.2677	243	177	0.1438	0.1374
14 Hrs	3,259	2,942	3.3438	3.2875	336	289	0.1841	0.1876
24 Hrs	4,025	3,596	4.2926	3.7994	346	366	0.1815	0.1839
2 Days	4,111	3,979	4.3537	4.0057	391	405	0.1805	0.1834
3 Days	4,029	4,339	4.4744	4.1840	398	420	0.1807	0.1862
7 Days	4,904	5,176	4.5816	4.5960	444	507	0.1906	0.1948
28 Days	6,198	6,720	4.7224	5.1316	534	597	0.1961	0.1875

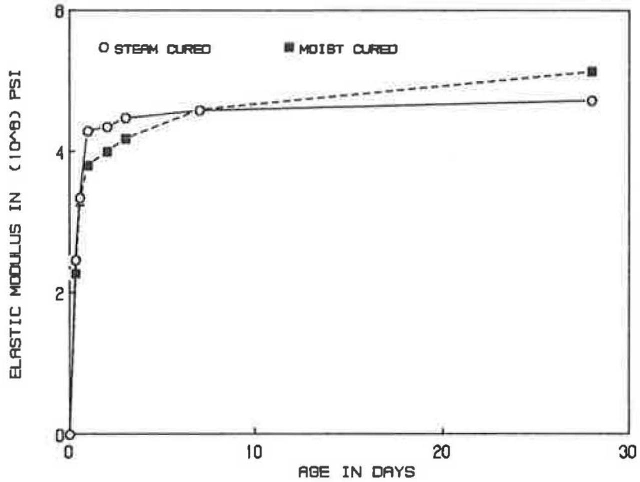

FIGURE 3 Comparison of elastic modulus development in moist- and steam-cured concrete.

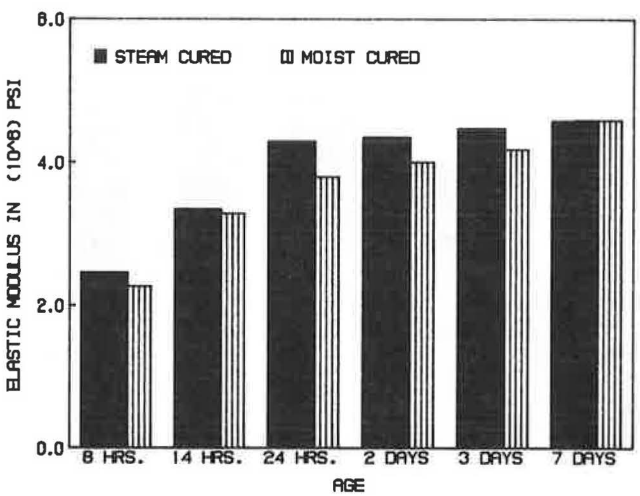

FIGURE 4 Elastic modulus development in moist- and steam-cured concrete: first 7 days.

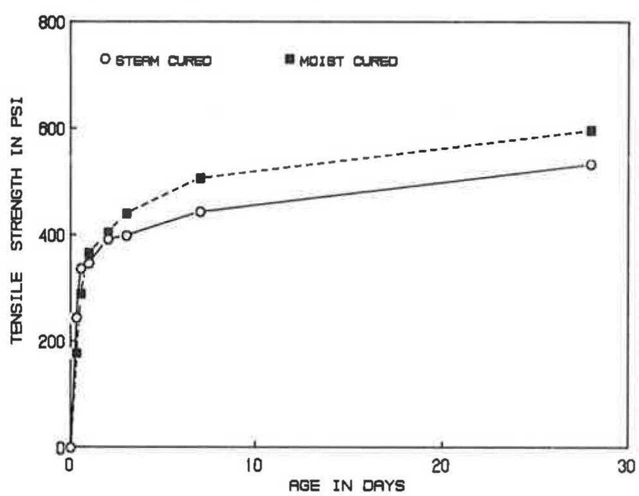

FIGURE 5 Comparison of tensile strength development in moist- and steam-cured concrete.

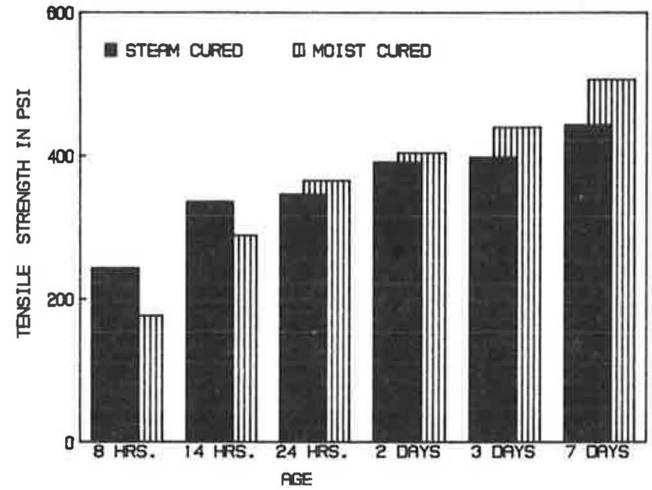

FIGURE 6 Tensile strength development in moist- and steam-cured concrete: first 7 days.

cracking that has been reported in precast, prestressed bridge deck panels during strand release and form removal. Although a difference of 20 psi in the tensile strength values at 1 day may not be statistically significant, it could be detrimental to the ability of concrete to resist cracking at this early age. Moreover, the steam-cured value was lower than that of moist-cured concrete.

Other factors arising from the defective detensioning procedures and improper handling of structures may contribute to early-age cracking. However, the properties of concrete that may contribute to cracking in steam-cured concrete are the concern in this paper.

Using the 28-day moist-cured values as standard, Table 2 presents the various physical properties developed at each testing age as percentages of the respective 28-day values. The detrimental effect of steam curing on physical property development is most pronounced with tensile strength, as evidenced by the percentage of the 28-day moist-cured values developed by each property.

Taking the moist-cured value for each variable at each testing age as an acceptable standard, the effect of steam curing on each property is depicted in Figures 7–9. Points above the reference line represent increases in property development due to steam curing, whereas points below the reference line indicate reductions in physical property development resulting from steam curing. Figure 10 presents the increase or decrease in property development caused by steam curing. The data presented in Figure 10 show that the higher the percentage increase in development of a property at early ages, the less lasting the beneficial effect of steam curing.

As can be seen in Table 3, Poisson's ratio was found to be insensitive to steam curing. Generally, the measured Poisson's ratio was virtually the same value for all ages and conditions of cure. This observation agrees with the previous observations of Hanson (*6*), Higginson (*7*), and Klink (*16*).

CONCLUSIONS

1. Steam curing as used by typical prestressing plants is not equally beneficial to the development of all the physical properties at early ages.

TABLE 2 INCREMENTAL PHYSICAL PROPERTY DEVELOPMENT (STEAM CURED)

	Compressive Strength			Elastic Modulus			Tensile Strength		
Age	Compressive Strength (psi)	fcx/fc (%)	Incremental fcx/fc (%)	Elastic Modulus (10^6 psi)	Ecx/Ec (%)	Incremental Ecx/Ec (%)	Tensile Strength (psi)	ftx/ft (%)	Incremental ftx/ft (%)
8 hrs	1,957	29.12	29.12	2.4586	47.91	47.91	243	40.70	40.70
14 hrs	3,259	48.50	19.38	3.6542	71.21	23.30	336	56.28	15.58
1 day	4,025	59.90	11.40	4.2926	83.65	12.44	346	57.96	1.68
2 days	4,112	61.19	1.29	4.3537	84.84	1.19	391	65.49	7.53
3 days	4,209	62.63	1.44	4.4744	87.19	2.35	398	66.67	1.18
7 days	4,904	72.98	10.35 (2.59/day)	4.5816	89.28	2.09 (0.52/day)	444	74.37	7.70 (1.93/day)
28 days	6,198	92.23	19.25 (0.92/day)	4.7224	92.03	2.75 (0.13/day)	534	89.45	15.08 (0.72/day)

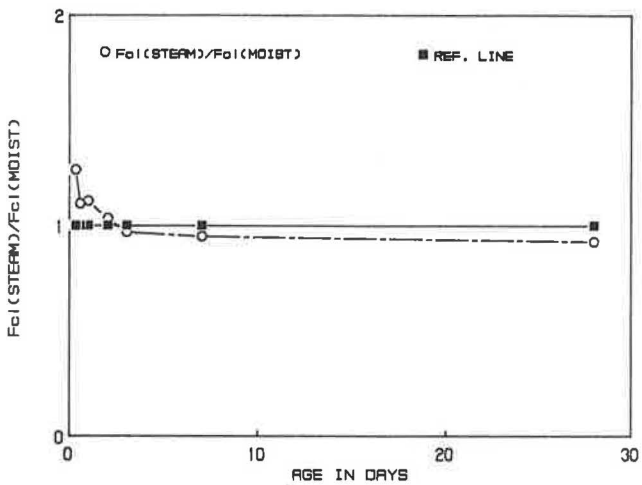

FIGURE 7 Normalized compressive strength for steam cure versus age.

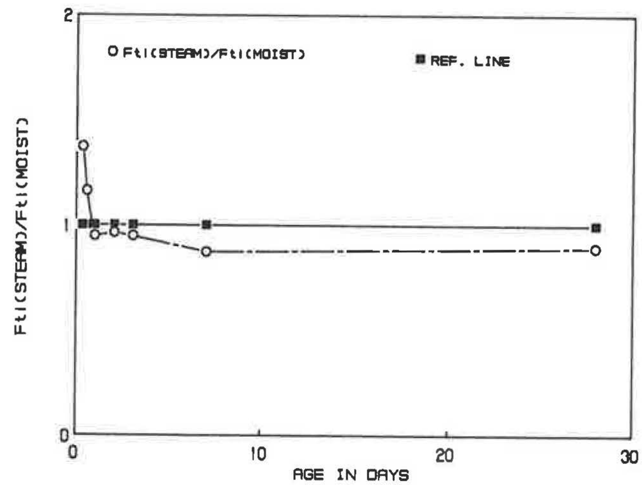

FIGURE 9 Normalized tensile strength for steam cure versus age.

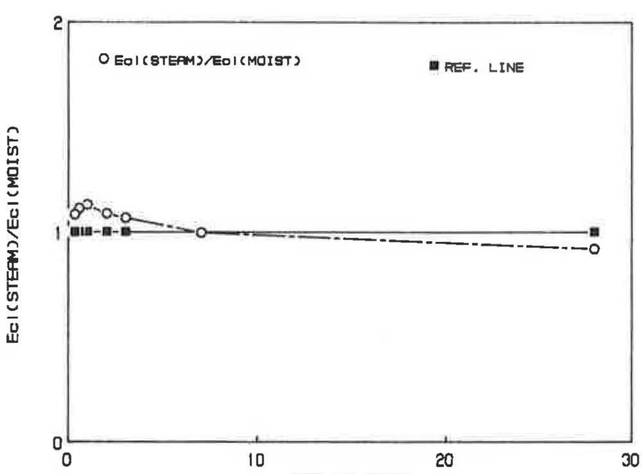

FIGURE 8 Normalized elastic modulus for steam cure versus age.

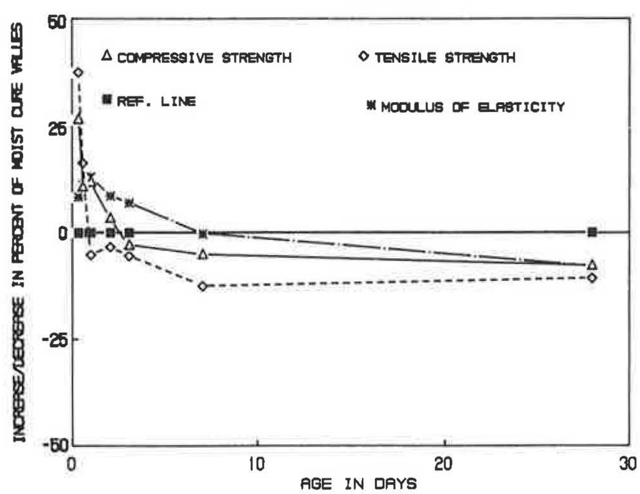

FIGURE 10 Increase or decrease in physical property development (moist-curing values) resulting from steam curing.

TABLE 3 INCREMENTAL PHYSICAL PROPERTY DEVELOPMENT (MOIST CURED)

	Compressive Strength			Elastic Modulus			Tensile Strength		
Age	Compressive Strength (psi)	fcx/fc (%)	Incremental fcx/fc (%)	Elastic Modulus (10^6 psi)	Ecx/Ec (%)	Incremental Ecx/Ec (%)	Tensile Strength (psi)	ftx/ft (%)	Incremental ftx/ft (%)
8 hrs	1,548	23.03	23.03	2.2677	44.19	44.19	177	29.63	29.63
14 hrs	2,942	43.78	20.75	3.2875	64.06	19.87	289	48.40	18.77
1 day	3,596	53.51	9.73	3.7994	74.04	9.98	366	61.24	12.84
2 days	3,979	59.21	5.70	4.0057	78.06	4.02	405	67.78	6.54
3 days	4,339	64.56	5.35	4.1840	81.53	3.47	420	70.37	2.59
7 days	5,176	77.02	12.46 (3.12/day)	4.5960	89.56	8.03 (2.01/day)	507	84.94	14.57 (3.64/day)
28 days	6,720	100.00	22.98 (1.09/day)	5.1316	100.00	10.44 (0.50/day)	597	100.00	15.06 (0.72/day)

2. Steam curing was found to be highly beneficial to the development of the elastic modulus and compressive strength but somewhat detrimental to the development of tensile strength at early ages. This detrimental effect may account for, at least partially, the early-age cracking that has been reported during strand release and form removal.

3. The optimum recommended steam-curing temperature for compressive strength development is not necessarily the optimum temperature for the development of either the elastic modulus or the splitting tensile strength. Investigations into the establishment of a possible optimum steam-curing temperature, which will equally benefit these three major physical properties, should be done. An optimum standard might mitigate the cracking and other serviceability problems associated with steam curing.

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