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SELF-STRESSED CONCRETE FOR PRECAST BUILDING UNITS

K. L. Benuska
Stressed Structures, Inc.
Denver, Colorado

V. V. Bertero
University of California
Berkeley, California

M. Polivka
University of California
Berkeley, California

Since the development of an expansive type of cement for chemical prestressing by Alexander Klein(1), extensive research has been carried out on this material at the University of California at Berkeley. During the past 12 years many studies of the expansion characteristics and the mechanical behavior of expansive cement concretes have clearly indicated that expansive cement concrete can be successfully used for prefabrication of self-stressed building elements. However, for such structural applications not only must a concrete mix be selected that will produce the desired properties but the structural elements must be specifically designed for chemical prestressing. Also, the precasting technique, including the type of formwork and type of curing, must be appropriate to chemically prestressed concrete.

The expansive cement used in all of the investigations carried out at the University of California at Berkeley contained an expansive anhydrous calcium sulfoaluminate compound. This type of cement is designated as Type K cement by ACI Committee 223(2).

Expansive cement concretes are generally classified in two categories: (1) shrinkage compensating; and (2) self-stressing. Shrinkage compensating concrete is intended for use principally to minimize the development of cracks due to drying shrinkage. Self-stressing or chemical prestressing of concrete is accomplished by producing a large enough expansion in a concrete properly restrained with steel reinforcement so as to produce the desired level of prestress. Since there will be a loss of prestress due to shrinkage and creep, the final stabilized stress level achieved is of prime interest to the designer.

In the United States the use of the shrinkage compensating concrete for various types of construction is well established. However, the use of the self-stressing type of expansive cement concrete is still quite limited.

The technology and mechanical behavior of self-stressing expansive cement concretes and their potential application to fabrication of structural elements and structural systems are summarized. Test specimens of lightweight aggregate concrete with expansive cement, and reinforced with 0.67 percent steel in each direction, developed compressive strengths above 5000 psi (350 kg/cm²), final stabilized self-stress about 300 psi (21 kg/cm²), and a modulus of rupture that exceeded $11\sqrt{f'_c}$.

The application of the self-stressing type of concrete requires a careful investigation not only of the mechanical behavior of the concrete but also its structural use, both of which are interrelated.

PREVIOUS RESEARCH

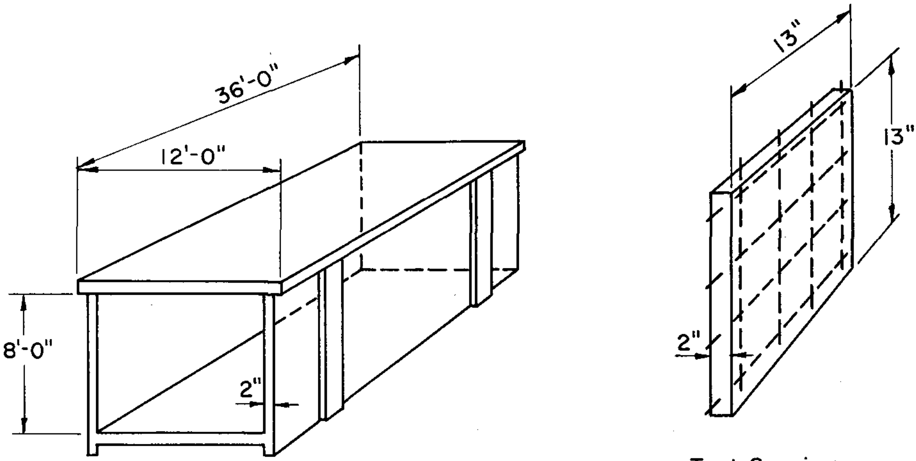
Most of the research carried out at the University of California was on the self-stressing type expansive cement concretes. Much of this research up to 1966 is summarized in a report by Aroni, Polivka and Bresler(3). The material and structural problems of self-stressing expansive cement concrete are presented in a paper by Aroni, Bertero and Polivka(4). Other studies focused on the effect of degree of restraint(5), the effect of curing(6), the effect of lightweight aggregate(7), and many other factors influencing the properties of self-stressed concrete(8). Structural elements found to be suitable for chemical prestressing included pipes, thin walls and slabs(9), shells(10), folded plates, composite columns(4), and precast beams and columns(11).

From these results, it appears that only certain types of structural elements are suitable for chemical prestressing(4). Prefabrication must be used because of the high degree of control required. The amount of prestress as well as the mechanical characteristics of the concrete are sensitive to the curing conditions. Furthermore, misalignment of reinforcement can lead to undesirable distortions.

Chemical prestressing is applicable to structural elements and systems in which the optimum amount of prestress is relatively low. It will not replace mechanical prestressing where a high percentage of steel and a high level of prestress are required.

DESIRABLE CHARACTERISTICS FOR PRECAST BUILDING UNITS

To gain maximum efficiency from factory production of building units, it is desirable to precast full modules containing floors, ceilings and walls.



Test Specimen

Fig. 1. Typical precast building unit with test specimen (right) to simulate wall behavior

Fig. 1 shows a building unit concept with thin walls and structural floor and ceiling slabs. Thickened areas may be provided to carry vertical loads, particularly when units are stacked for multi-story construction.

Building units should be lightweight to facilitate transportation and erection. Thus lightweight aggregate is desirable. Previous investigations(7) show that water stored in soaked expanded shale aggregate aids the curing of self-stressed concrete.

Monolithic three-dimensional casting of building units using self-stressed concrete will produce rigid structures due to connection continuity at the intersection of floor, wall and ceiling slabs. It is desirable to use continuous reinforcing steel through these intersections to create a continuous prestress through the joint. Welded wire mesh is convenient for such reinforcement. It provides the biaxial restraint needed to create a biaxial prestress in each slab and may be bent around slab intersections to create the desired prestress continuity. This is not possible with mechanical prestressing.

Each structural element must provide an ultimate load carrying capacity to resist applied loads with an adequate factor of safety against collapse. Failure in flexure must be ductile; that is, increased deflections must occur after significant overload to warn of impending failures.

The precast building unit will experience stresses due to handling, transportation, erection, and volume changes due to temperature, creep and shrinkage which are difficult to predict by analytical methods. Experience with conventional prestressed construction indicates the need for minimum concrete compression of 250 to 300 psi (18 to 21 kg/cm^2) to prevent cracking due to unexpected stress concentrations.

Welded wire mesh with a reinforcement percentage of 0.67 produces a restrained concrete compression of 300 psi (21 kg/cm^2) while limiting the steel tension stress to 60 percent of its ultimate strength of 80,000 psi (5620 kg/cm^2).

$$f_s = f_c/p = 300/0.0067 = 45{,}000 \text{ psi } (3160 \text{ kg/cm}^2)$$
$$f_s \leqq 0.60\, f'_s = 0.60\,(80{,}000) = 48{,}000 \text{ psi } (3370 \text{ kg/cm}^2)$$

where f_s = tension stress in steel reinforcement
f_c = compression stress in concrete
f'_s = ultimate strength of steel
p = ratio of steel area to concrete area

Many of the loads on precast building units will be resisted by bending moments causing fiber tension in zones of precompressed concrete. Thus, a high modulus of rupture is very desirable to prevent cracking.

EXPERIMENTAL INVESTIGATION

Objectives. The main objective of the experimental investigation was to select the proper concrete materials, mix proportions, and curing conditions to produce a self-stressing concrete for use in production of precast building units, similar to that shown in Fig. 1, which would satisfy the following requirements:

1. The concrete mix should be of a consistency and workability suitable for complex castings
2. The concrete units when properly reinforced should expand enough to develop a final stabilized prestress of about 300 psi (21 kg/cm^2)
3. The total expansion should be developed in the shortest time to facilitate earliest possible transportation of units and thus avoid problems of storage.

A slab test specimen was designed to represent a middle segment of a self-stressed wall 2 in. (5.1 cm) thick, as shown in Fig. 1.

Materials. The expansive cement was Type K with three levels of expansion: low (S-7830), intermediate (S-8162) and high (S-8106). Fine aggregate was Felton "O" sand from Felton, California. Coarse aggregate was a lightweight expanded shale in the size range ⅜ in. to No. 4 (9.51 to 4.76 mm) with a specific gravity of 1.43 (SSD) and SSD moisture of about 20 percent.

The reinforcement used for all test slab specimens was the same as that to be used in the building units, i.e. a welded wire mesh with 4-in. (10.2 cm) spacing in both directions. This welded wire mesh was placed at mid-depth of the slab. The mechanical characteristics of the steel are shown in Fig. 2. The wire used had an elastic limit of about 55 ksi (3870 kg/cm^2), ultimate strength of about 80 ksi (5620 kg/cm^2), and modulus of elasticity of 26×10^6 psi (1.83×10^6 kg/cm^2). Tests conducted on pieces including the welds showed no significant reduction in strength at the welds.

Test specimens. The test specimens selected for evaluation of the mechanical characteristics of self-

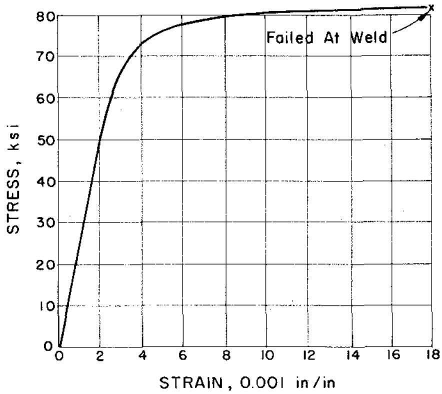


Fig. 2. Stress-strain diagram for welded wire mesh reinforcement

stressed concrete walls were biaxially reinforced 13 x 13-in. slabs (33 x 33 cm), 2-in. (5.1 cm) thick, with 0.67 percent steel reinforcement in each direction. The plan dimensions of the test slab were considered large enough to avoid boundary effects at the center and at the same time small enough to permit easy handling and the cutting out of specimens which could be tested as beams having a 1-ft. (31 cm) span to determine the flexural characteristics of the slab.

To provide good anchorage, the steel mesh was welded to channels that formed the edges of each slab specimen. Each channel was free to move relative to adjacent channels thus allowing biaxial expansion of the slab.

Face plates were affixed to the channels surrounding the slab specimen prior to placement of concrete. The plates, which simulated steel forms used in casting building units, were removed after the concrete cylinder strength reached 1000 psi (70 kg/cm^2).

Compressive strength of the concrete was determined on 3 x 6-in. (7.62 x 15.25 cm) cylinders tested at different ages. Thus the proper time for removal of the forms could be estimated, and the test specimens could be handled without danger of damage. Heavy cast iron molds were used. They offered considerable restraint to the concrete expansion. The molds were removed just before compression strength testing.

Concrete. After several trial batches, the concrete mix selected had a nominal water-cement ratio of 0.43 by weight. The slump of the concrete was 7±1 in. (17.8±2.5 cm). The aggregate consisted of a blend of 73 percent Felton sand and 27 percent of ⅜-in. to No. 4 (9.51 to 4.76 mm) lightweight aggregate by weight. Concrete mix data are shown in Table 1.

A 2-cu. ft. (0.057 m^3) pan-type mixer was used for mixing the concrete. The concrete was mixed 3 minutes, left still for 3 minutes, then mixed again for 2 minutes.

Instrumentation. To obtain the expansion history of slab specimens, electrical wire strain gages were affixed to the welded wire mesh. A pair of gages was located on each of the two cross-wires closest to the center of the slab. Slab expansion was measured using a Whittemore type gage between brass gage points cast into the concrete surface at the nodal points of a square grid spaced at 5 in. (12.7 cm) on both slab faces.

Modulus of rupture was deter-

Table 1. Properties of concrete mixes

	Series I	Series II	Series III
Cement used	S-7830	S-8162	S-8106
Cement content, sacks*/cubic yard (kg/m^3)	8.73 (488)	8.25 (462)	8.73 (488)
Sand/cement by weight	1.92	1.92	1.92
Gravel/cement by weight	0.695	0.650	0.650
Water/cement by weight	0.412	0.435	0.412
Unit weight, lb./cu. ft. (kg/m^3)	122.5 (1962)	121.0 (1940)	122.5 (1962)
Slump, in. (cm)	7.5 (19.1)	7 (17.8)	7 (17.8)

*1 sack = 94 lb. (43 kg)

Table 2. Curing condition after initial air curing at 140 F (60 C)

Series	Specimen Number	Curing Condition
I	1 2 3	110 hrs. water at 120 F (49 C) 110 hrs. water at 120 F 2 mos. water at 120 F
II	4 5	16 hrs. water at 140 F (60 C) 40 hrs. water at 140 F
III	6 7 8	48 hrs. water at 140 F 48 hrs. water at 140 F 4 wks. water at 140 F

mined from flexural tests conducted on slab strips either 5 in. (12.7 cm) or 8 in. (20.3 cm) wide, which were cut out along the midspan of the slab specimen and then tested as simple beams having a 1-ft. (31 cm) span and loaded at their midpoints. Two electrical wire strain gages were epoxied to each face of the concrete strip midway along its length at the third points of its width.

Curing. Immediately after casting, all specimens were stored in air at 140 F (60 C). Test cylinders were tested at intervals beginning at age 5 hr. As soon as the cylinder strength reached 1000 psi (70 kg/cm^2) (usually this occurred within the first 8 hr.) the slabs were demolded and the second stage of curing started. Test cylinders were kept in their molds until they were tested.

After the forms were removed from slab specimens, all the specimens were cured in water at 120 F (49 C) and 140 F (60 C) for periods specified by the curing schedule. (Table 2). The curing period was varied to determine the effect of this parameter on concrete expansion.

Some specimens were transferred from the 140 F (60 C) water to 70 F (21 C) water or were stored at normal ambient temperature (at 70 F) and humidity (at 60 percent) to determine the effect of a service environment on concrete expansion. The curing condition is noted on subsequent graphs of expansion history.

TEST RESULTS

History of slab expansion. The recording of each slab specimen's expansion history was terminated by a strength test whose results are presented in a later section.

Series I: Type K cement designated S-7830 was used to cast specimens 1, 2 and 3. Their history of expansion is presented in Fig. 3. The specimens expanded at a high rate to 290 psi (20 kg/cm^2) prestress at 24 hr., after which expansion took place at a lower rate up to about 320 psi (23 kg/cm^2) at 50 hr.

No appreciable variation in the expansion was observed from 50 hr. to about 118 hr., after which Specimen 1 was removed from the hot water and tested. At this stage Specimen 2 was transferred to room temperature and humidity where it gained about 20 psi (1.4 kg/cm^2) prestress and then began to shrink to about 310 psi (22 kg/cm^2) at the age of 3 weeks. Specimen 3 was left in 120 F (49 C) water for 2 months and then transferred to room temperature and humidity. Both specimens were tested at 3½ months. Because of the poor functioning of the

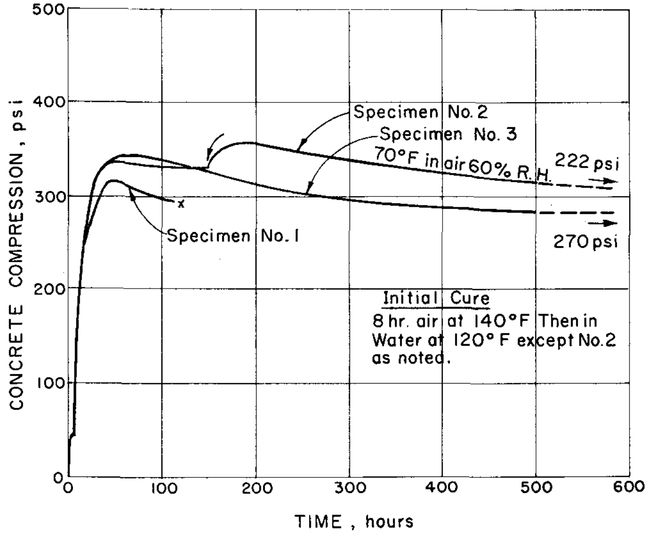


Fig. 3. Expansion history for Slabs 1, 2, and 3, Series I

strain gages and Whittemore gage, no reliable data were obtained after three weeks. It was possible to determine the total amount of prestress retained by Specimens 2 and 3 by measuring the release in prestress after removing (by cutting) the concrete around the wire where the gages were placed. Slab 2 had 222 psi (16 kg/cm^2) prestress remaining, and Slab 3 had 270 psi (19 kg/cm^2) prestress.

Series II: Type K cement designated S-8162 was used to cast Specimens 4 and 5. This cement had a higher expansion potential than the S-7830. The history of expansion is presented in Fig. 4.

Specimens 4 and 5 at 24 hr. both reached about 280 psi (20 kg/cm^2). After 24 hr. Specimen 4 continued expanding slowly when placed in water at 70 F (21 C) to about 365 psi (26 kg/cm^2) prestress at 14 days and 430 psi (30 kg/cm^2) at 46 days. Two days after its removal from water it started to shrink very slowly, but the rate of shrinkage increased considerably after approximately 10 days. At time of test the net prestress was about 290 psi (20 kg/cm^2).

Specimen 5 cured in water at 140 F (60 C) up to 48 hr. had a total prestress of 353 psi (25 kg/cm^2) at this age. Upon transfer to room temperature and humidity, shrinkage reduced the prestress to 200 psi (14 kg/cm^2) at an age of about 5½ months, remaining stable thereafter.

From the results of Series I and II it is clear that while 24 hr. of hot water curing is not enough to permit the completion of the expansion reaction, 48 hr. of this type of curing is enough for the development of a large percentage of the expansive reaction.

Series III: Specimens 6, 7 and 8 were cast using Type K cement designated S-8106. This cement had the

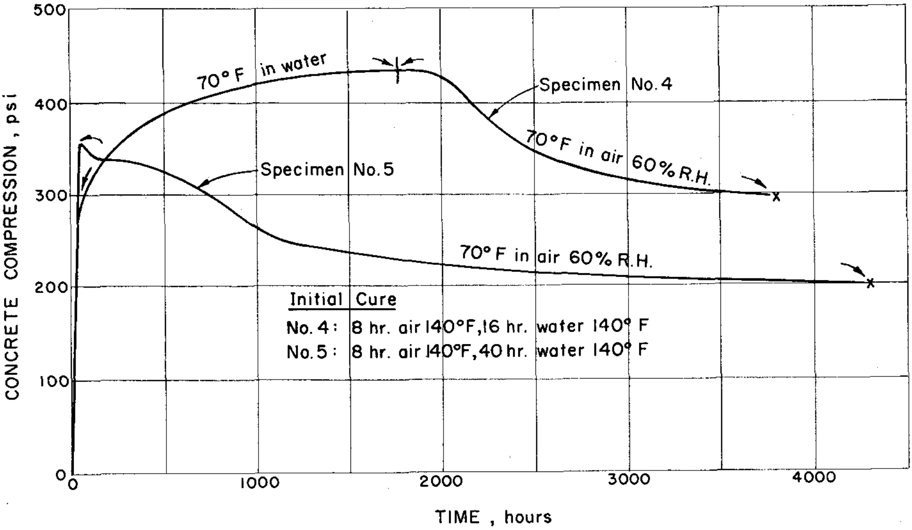


Fig. 4. Expansion history for Slabs 4 and 5, Series II

highest expansion potential of the series of three cements. Fig. 5 presents the history of expansion.

The steel formwork restricted almost completely the expansion of the specimens during the initial 8-hr. heating period, after which they expanded upon removal of the formwork to a net prestress of about 90 psi (6 kg/cm^2).

As soon as the specimens were subjected to water at 140 F (60 C), they expanded rapidly to a prestress of about 300 psi (21 kg/cm^2) at 24 hr. After this age, expansion took place at a slower rate, and at 56 hr. the total prestress was about 340 psi (24 kg/cm^2). The history of Specimen 8 shows that by extending treatment in hot water the overall expansion increases very little.

Specimen 6 was transferred at 56 hr. to water at 70 F (21 C), resulting in an increase in prestress from 342 psi (24 kg/cm^2) at 56 hours to 450 psi (32 kg/cm^2) at 49 days. After this age no significant increase in expansion was detected. Two days after the slab was removed from water (age 66 days) it started to shrink and reached a stable state at about 6 months, at which time the net prestress was approximately 280 psi (20 kg/cm^2).

Specimen 7 was transferred at 56 hr. to room temperature and humidity. It continued to expand, increasing prestress by 50 psi (3 kg/cm^2) within 24 hr., thus reaching a total prestress of about 390 psi (27 kg/cm^2) at 3 days. Thereafter this specimen started shrinking, reaching 340 psi (24 kg/cm^2) again at 7 weeks. Upon exposure to water at 70 F (21 C) the specimen again expanded, increasing prestress about 80 psi (6 kg/cm^2) within 2 days, and remaining practically constant while in water. After removal from water the specimen shrank, stabilizing at a prestress of 300 psi (21 kg/cm^2) at age of about 6½ months.

Comparing the expansion history

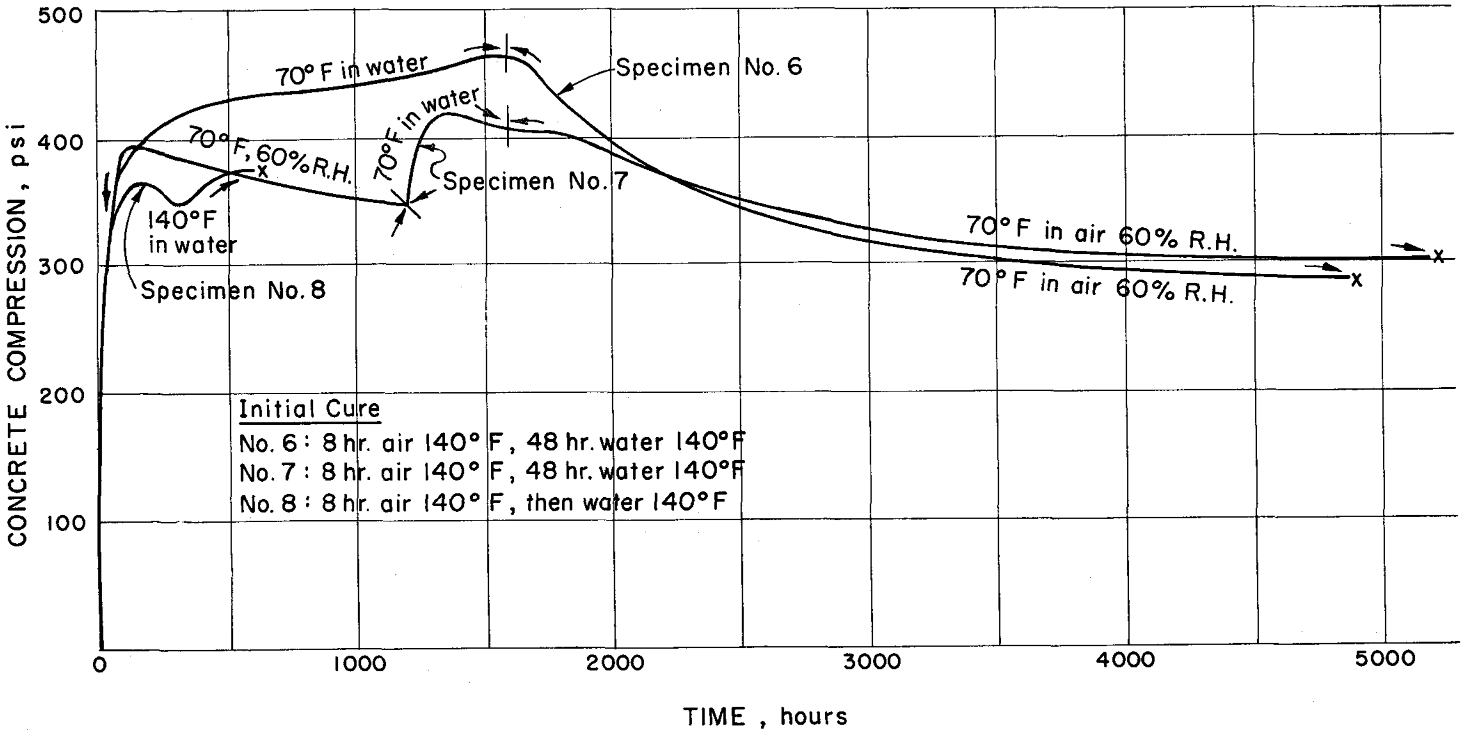


Fig. 5. Expansion history for Slabs 6, 7 and 8, Series III

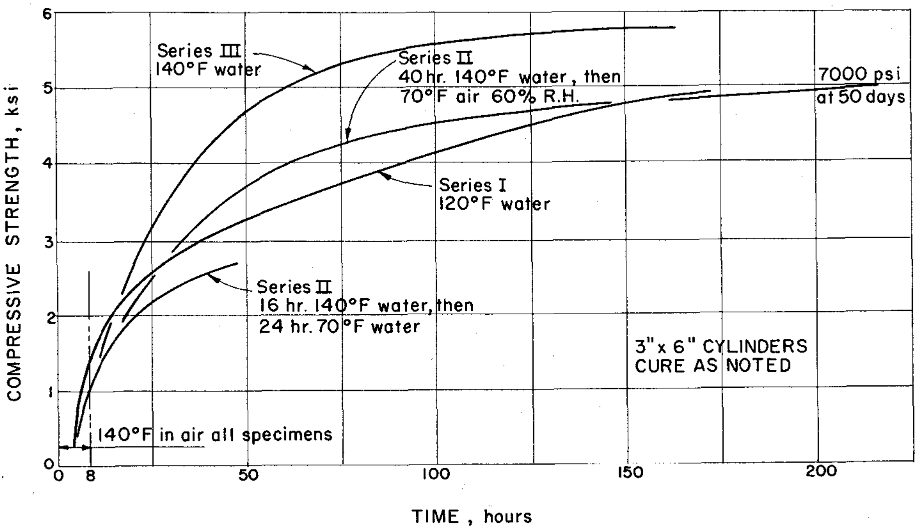


Fig. 6. Cylinder strength history, Series I, II and III

of Specimens 6, 7 and 8, it is clear that not very much gain in prestress is obtained by keeping specimens in water after 56 hr., and that it is better not to continue the exposure at high temperature, i.e. 140 F (60 C).

Comparing Specimens 6 and 7 shows that the final stabilized prestress is little affected by the previous history of wetting and drying as long as the initial cure (56 hours) adequately develops the expansion potential of the concrete. In this light, a review of the expansion history of Slabs 4 and 5 indicates that Slab 4 would have approached the stabilized value of 200 psi (14 kg/cm^2) exhibited by Slab 5 if given time (more than 6 months) to shrink fully.

History of cylinder strength gain. The cylinder strength history for Series I, II and III is shown in Fig. 6. All specimens tested had a compressive strength in excess of 1000 psi (70 kg/cm^2) at 8 hr. and 3000 psi (210 kg/cm^2) before the age of 48 hr. At 8 hr. it was possible to remove slab forms safely in all cases.

The concrete strength development is dependent on the curing environment and period of curing rather than on the type of cement used.

Slab specimen strength. Two kinds of strength specimens were cut out of each slab at termination of the expansion test:

1. Prisms 3 x 2 in. (7.6 x 5.1 cm) in section, and 2 to 5.5 in. (5.1 to 14 cm) high for compression tests.
2. Longitudinal strips 5 or 8 in. (13 or 20 cm) wide for testing as a beam with a 12-in. (31 cm) span and loaded at midspan. This test was conducted to determine cracking and ultimate strengths as well as stiffness and ductility of the slabs.

The results of these test series are summarized in Table 3. Series II data

Table 3. Mechanical properties of slabs

Series No.	Specimen No.	Testing Age	Self stress psi		Cracking		Tensile strength psi	Ultimate flexural strength in.-lb. per 1 in. wide strip	Stiffness of the uncracked section-EI in.^{2}-lb. per 1 in. wide strip	Compressive strength on 2 x 3-in. prisms psi	
			(1)	(2)	Moment in.-lb. per 1 in. wide strip	Maximum tensile stress psi				2 in. high	3 to 5½ in. high
I	1	118 hr.	293		720	1080	787	1130	1.82×10^6	5000	—
	2	3.5 mos.	—	222	675	1015	793	1000	2.05×10^6	—	5380
	3	3.5 mos.	—	270	945	1418	1146	1256	3.03×10^6	—	6670
II	4	5.4 mos.	290	278	962	1440	1150	1160(3)	1.98×10^6	6070	—
	5	6.0 mos.	200	232	660	990	790	1240	1.95×10^6	5130	—
III	6	6.8 mos.	282	282	745	1120	838	970(3)	2.18×10^6	6050	—
	7	7.5 mos.	300		1020	1533	1233	1310	2.17×10^6	—	6450
	8	0.9 mos.	370		954	1430	1060	1440	2.04×10^6	6040	—

(1) Values obtained from history of expansion
(2) Values obtained from strain release in reinforcing steel after its removal from concrete
(3) Test interrupted before reaching ultimate strength

Note: 1000 psi = 70 kg/cm^2
1000 in.-lb. = 1150 cm-kg
2.0×10^6 in.^{2}-lb = 5.87×10^6 cm^2-kg

are reported on the basis of a 1 in. (2.5 cm) wide strip. The initial stiffness, cracking and ultimate strengths and ductility at failure are important to the serviceability and safe design of self-stressed slabs, possibly more important than the value of stabilized prestress.

Initial stiffness: The uncracked section of the slabs shows a minimum stiffness of 1.82×10^6 in.^{2}-lb. (5.33×10^6 cm^2-kg) per 1-in. (2.5 cm) wide section. If it is considered that the I of the 1-in. (2.5 cm) wide section is $\frac{2}{3}$ in.^{4} (27.7 cm^4) the minimum value for E_c is computed to be 2.73×10^6 psi (0.19×10^6 kg/cm^2), which agrees very closely with the value obtained by using the ACI Building Code equation for E_c.

Cracking strength: The data of Table 3 are too limited to permit a probabilistic prediction of tensile flexural strength. However, no cracking occurred below a loading tensile stress of 990 psi (70 kg/cm^2). Inspection of specimens cut from Slab 5 reveals that too much vibration applied to this slab caused segregation with most of the lightweight aggregate rising toward the top edge of the slab as it was cast upright. The first crack occurred in this section away from midspan where the load was applied to the flexural test specimen. This result clearly points out the importance of carefully controlling the vibration of the slabs.

For Series III slabs, the first cracking occurred under a tensile stress—due to external load—equal to or larger than 1120 psi (79 kg/cm^2), corresponding to a modulus of rupture of concrete of 838 psi (59 kg/cm^2), which is approximately $11\sqrt{f'_c}$ in which f'_c is the compressive strength obtained from prism tests.

Ultimate strength: Flexural tests carried out up to the maximum load that the specimens were able to resist, show that the minimum value for the ultimate resisting moment of the slab section was 1000 in.-lb. (1150 cm-kg) per 1-in. (2.5 cm) wide strip, and for the slabs of Series III this minimum value was 1310 in.-lb. (1510 cm-kg). Furthermore, the minimum ratio of ultimate resisting moment to cracking moment was 1.28.

In a few tests, the displacement ductility was also measured. For all tests the ratio of displacement at failure to displacement at cracking was larger than 7.

SUMMARY AND CONCLUSIONS

The data, although limited, support the conclusion that safe and serviceable thin slab building units can be produced using self-stressed concrete.

1. A specimen cured for a prolonged period in water at 140F (60C) —after being cured in air for 8 hr. at 140F (60C) prior to demolding—gained 75 percent of the maximum possible prestress in 24 hr., 90 percent in 48 hr., and 99 percent after 70 hr.

2. For the specimens that were transferred from the water at 140F (60C) to the laboratory air (70F) earlier than 48 hr., the expansion process seems to stop. However, if the transfer age was 48 hr. or more, there was actually a gain in prestress. When the specimens were transferred from water at 140F (60C) to water at room temperature at 56 hr. or earlier, the expansion continued but at a very slow rate.

3. Specimens cured in water 48 hr. at 140F (60C) could gain an extra 30 percent of the 48-hr. prestress obtained by exposure to moisture (100 percent R.H.) at room temperature (70F). However, when these specimens are then exposed to a 70F (21C) and 60 percent R.H. en-

vironment, there is a contraction which reduces the level of prestress to approximately that experienced by a specimen placed in the 70F (21C) and 60 percent R.H. environment. This contraction is the result of shrinkage and creep.

4. For samples kept at room conditions (approximately 70F and 60 percent R.H.) after being cured in water at 140F (60C) for 48 hr., the maximum observed reduction in the gained prestress due to shrinkage and creep was about 44 percent. The contraction starts soon after removal from water and takes approximately 5½ months to reach a condition which may be considered stable for practical purposes.

5. It appears that 48 hr. of 140F (60C) water curing is the optimum curing treatment for the expansive concrete used in the specimens investigated.

6. All specimens tested had a compressive strength in excess of 1000 psi (70 kg/cm^2) at 8 hr. and 3000 psi (210 kg/cm^2) before the age of 48 hr. At 8 hr. it was possible in all cases to remove the forms safely. Even at 6 hr., the concrete was strong enough to allow careful handling. The concrete strength developed was dependent on the curing environment and period of curing rather than on type of cement used.

7. The flexural tests carried out on specimens obtained from the slabs reveal that first cracking occurs under a modulus of rupture of at least $11\sqrt{f'_c}$, in which f'_c is the compressive strength obtained from testing concrete prisms.

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