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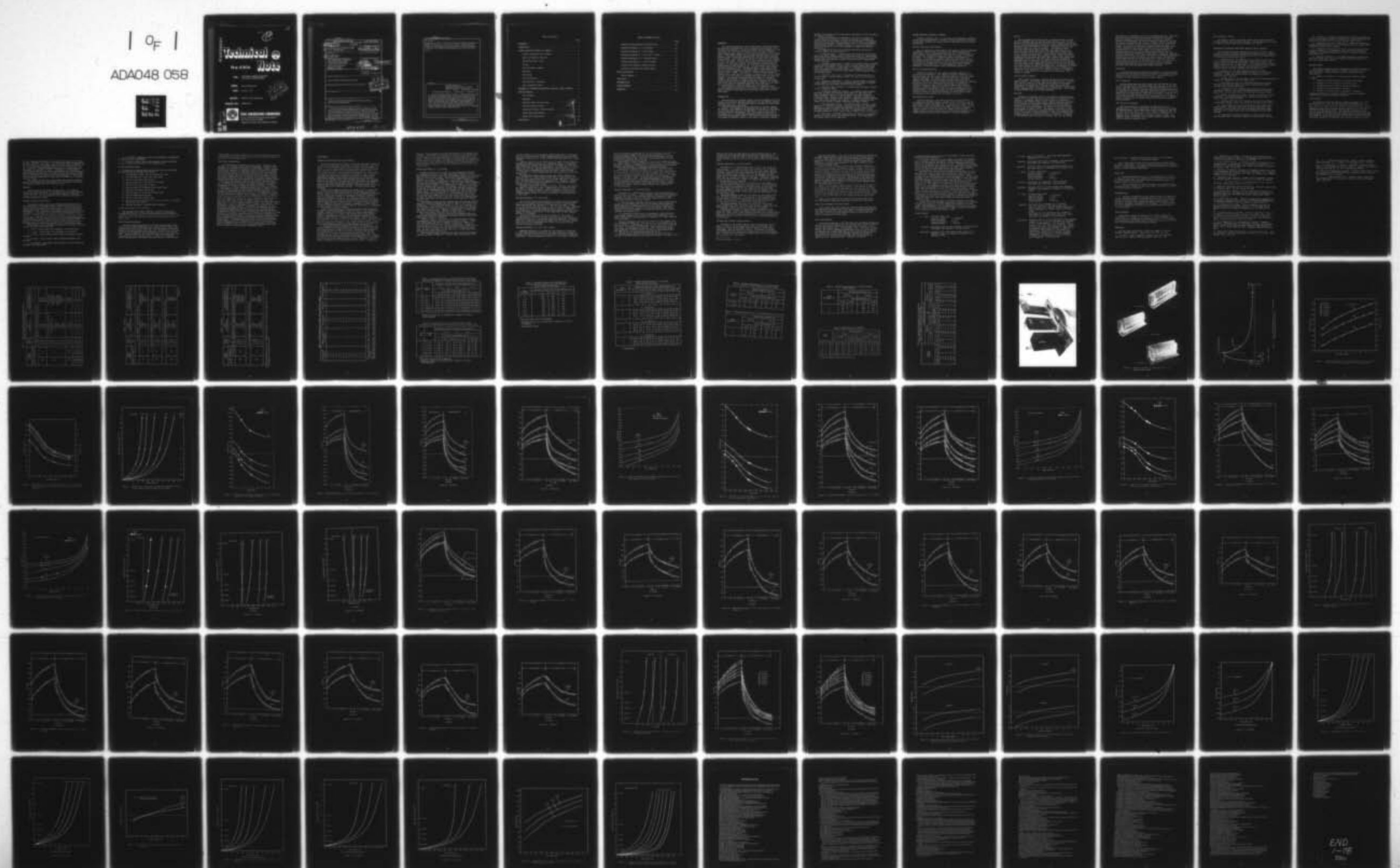

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Expansion and subsequent shrinkage characteristics of shrinkage-compensating concrete were determined in mesh-reinforced prisms. The prisms were cured in fog for 14 days and then subjected to drying in either 25%, 50%, or 75% relative humidity (all at 73F). The concretes were made with four different aggregate types: (1) moderate quality river aggregate, (2) moderate quality limestone aggregate, (3) light-weight coarse aggregate and river sand, and (4) lightweight coarse and fine aggregates. Maximum

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BACKGROUND

The industrial manufacture of portland cement involves pulverizing raw materials containing lime, silica, alumina, and iron oxide, [1,2] (properly proportioned) to obtain the desired chemical composition. The ingredients are then heated at 2,600F (1,427C) to 3,000F (1,649C) to form portland cement clinker, which is later pulverized to form portland cement. The products formed are tricalcium silicates (C_3S), dicalcium silicates (C_2S), tricalcium aluminate (C_3A), and tetracalcium alumino-ferrite (C_4AF). The setting of C_3S and C_2S is fairly slow, but setting of C_3A if very rapid. Not much C_3A is found in modern portland cements, but the finer nature of these cements makes flash setting of C_3A more probable. It was found, however, that addition of small amounts of gypsum prevents flash setting of C_3A. For this reason, very carefully controlled amounts (±0.10%) of gypsum are added to the cement during the final pulverizing step. The gypsum ($CaSO_4 \cdot 2H_2O$) combines with the C_3A to form a needle-like insoluble compound called calcium sulfoaluminate ($C_6A\overline{S}_3 \cdot 32H_2O$). This product, called ettringite because it resembles the natural mineral ettringite, occupies a fairly large volume; too much of it could result in damaging expansions after the cement has hardened. Under normal conditions the small amount of ettringite formed by the addition of a slight amount of gypsum to prevent flash setting does not result in damaging expansions. However, the recognition of the potential expansions resulting from formation of ettringite led to development of expansive cements as we now know them.

This technical note is the final report on a research study at the Civil Engineering Laboratory (CEL) directed toward use of expansive cement concretes in thin-shell and conventional construction at Navy shore bases.

INTRODUCTION

The development of expansive cements has been documented by several authors [3,4,5] and by Technical Committee 223 of the American Concrete Institute (ACI).[6,7] The following remarks regarding this development were taken from these references.

The motivating stimulus behind development of expansive cements was twofold: (1) elimination of shrinkage cracking and (2) inducement of relatively high levels of precompression in the concrete, much as is done by mechanical prestressing. The twofold objective resulted in development of (1) a shrinkage-compensating expansive cement and (2) a self-stressing expansive cement. The principal difference between the two classes of expansive cements is the amount of expansive component provided for reaction with portland cement ingredients to form ettringite, the expansion producer.

Purposeful research and development on the use of ettringite to produce expansions intended to overcome the effects of shrinkage and to self-stress concrete began in France in the mid-1930's. An expansive cement for repairs and for waterproofing as well as for self-stressing was developed in Russia. Studies by Klein, et al, at the University of California (Berkeley) led to the development of commercial expansive cements.[3,4]

ACI Committee 223 lists the following definitions pertinent to expansive cements and concretes:[6,7]

1. Expansive cement - A cement which when mixed with water forms a paste that, after setting, tends to increase in volume to a significantly greater degree than portland cement paste; used to compensate for volume decrease due to shrinkage or to induce tensile stress in reinforcement (post-tensioning).

2. Expansive cement Type K - A mixture of portland cement, anhydrous tetracalcium trialuminate sulfate ($C_4A_3\overline{S}$), calcium sulfate ($CaSO_4$) and lime (CaO). The $C_4A_3\overline{S}$ is a constituent of a separately burned clinker that is interground with portland cement; or, alternately, it may be formed simultaneously with the portland cement clinker compounds during the burning process.

3. Expansive cement Type M - Interground or blended mixtures of portland cement, calcium aluminate cement, and calcium sulfate suitably proportioned.

4. Expansive cement Type S - A type of portland cement containing a large computed C_3A content and interground with an amount of calcium sulfate above the usual amount found in portland cement.

5. Expansive cement concrete - a concrete made with Type K, Type M, or Type S expansive cement.

6. Shrinkage-compensating concrete - An expansive cement concrete which when properly restrained by reinforcement or other means will expand an amount equal to or slightly greater than the anticipated drying shrinkage. Because of the restraint, compressive stresses will be induced in the concrete during expansion. Subsequent drying shrinkage will reduce these stresses; but, ideally, a residual compression will remain in the concrete, thereby eliminating shrinkage cracking.

7. Self-stressing concrete - An expansive cement concrete in which expansion, if restrained, induces compressive stresses of a high enough magnitude to result in significant compression in the concrete after drying shrinkage has occurred. The level of precompression in self-stressing concrete is in the range of 300 to 1,000 psi (21 to 70.3 kg/cm^2).

8. Ettringite - The phase formed during the hydration of expansive cements; it is the source of the expansive force. It is comparable to the natural mineral of the same name.

FACTORS AFFECTING EXPANSION OF CEMENTS

Purposeful expansion is one of the features distinguishing expansive cements from portland cements. As shown by other researchers, the amount of achievable expansion for a given cement is dependent upon the factors listed below.

Chemical Composition and Fineness

Rate of expansion is proportional to the amount of readily hydratable aluminates so long as $CaSO_4$ is available.[6] The aluminates may be $C_4A_3\overline{S}$ (Type K), calcium aluminate cement (Type M), or C_3A (Type S). As the fineness of an expansive cement increases, the amount of expansion decreases. The increase in fineness accelerates the formation of ettringite. If the bulk of expansion takes place before the concrete has achieved sufficient strength, it will be wasted; on the other hand, if the bulk of the expansion occurs after the concrete has reached a relatively high strength level, internal damage may result from the expansions. A Blaine fineness of about 2800 seems optimum.[8]

Amount of Expansive Material

Generally speaking, the more expansive material present, the more will be the expansion. The essential expansion ingredients can be proportioned into all types of expansive cements to cover the entire range of expansions. The commercially available Type K shrinkage-compensating cements are proportioned to produce relatively low expansions. The Type K cements contain from 10% to 15% expansive components having from 25% to 50% calculated $C_4A_3\overline{S}$ (calcium sulfoaluminate). Laboratory studies on Type K self-stressing cements have utilized contents of expansive component from 10% to 50%. Expansion of self-stressing cements is related to amount of expansive component but not proportionately. Polivka and Bertero [9] have recommended that the influence of amount of expansive component in self-stressing cements be evaluated in the specific type of concrete to be used.

Water/Cement Ratio (W/C)

Generally speaking, it has been found that the lower the W/C, the higher the expansion; however, changes in W/C also affect relative proportions of other ingredients.[6] For instance, concretes with the same cement content can be made with a range of values of W/C. In this case, all the concretes would have the same potential for expansion (cement content); but the more pervious, higher slump concretes (higher W/C) will take up curing water more readily and therefore will expand somewhat more (see below on effects of curing on expansion).

Curing

The requirements for proper curing of expansive cement concretes are more stringent than for portland cement concrete. [6,7] The formation of the strength-producing calcium silicate hydrates (C_3S and C_2S) and the expansion-producing ettringite are affected differently by curing temperature and by availability of water. Inadequate curing can substantially reduce the level of expansion. All expansive cement concretes expand significantly more when cured under water or in a moist room than they do when cured in an environment in which water is not available to the concrete. Curing under a polyethylene sheet greatly reduces expansions when compared to water curing. Steam-cured expansive concretes expand only about 80% as much as when water-cured. Lightweight concretes, in which the highly absorptive lightweight aggregates give off water and thus provide a form of internal curing, have been shown to have higher expansion characteristics than concrete made with normal weight aggregates, especially in larger sections where a moisture gradient is usually established.[10] The presence of internal water also reduces the potentially damaging effects of differential expansions in the larger sections. Results of tests to determine the effects of curing temperature on expansion are conflicting. More research is needed.

Size and Shape of Member

Other things being equal, expansion decreases as the size of the member increases. In addition, the exterior can expand at a different rate from the interior of large moist-cured members and when these differences are significant, mechanical properties are adversely affected.[6] As stated above, internal curing achieved by using lightweight aggregate tends to alleviate these differentials. The influence of shape of member has not yet been determined.

Restraint

Successful utilization of any of the expansive cement concretes depends upon the amount and type of resistance to the expansion of the concrete. An expansive cement concrete in which no resistance is provided to the expansion shows greatly reduced mechanical properties. In the language of the expansive cement industry the resistance to expansion is called "restraint." Restraint can be either external, as in the case of rigid framework, or internal in the form of reinforcing steel or mesh.[5,6,7,11] Some degree of restraint can also be provided by such forces as subgrade friction and by abutting structures. In the case of reinforcing steel or mesh, the developing bond strength provides the necessary restraint to expansion. Resistance to the expansion places the steel in tension; this, in turn, places the concrete in compression, much as in prestressed concrete. Most tests have been made on specimens using uniaxial (longitudinal) restraint. Generally speaking, it has been found that the more the restraint (percent of reinforcement) the less the measured expansion and the more the induced compression in the concrete. However, since the expansion potential for a given concrete is the same regardless of degree of restraint, an increase in longitudinal restraint (uniaxial) might cause lateral expansions large enough to adversely affect the mechanical properties.[11] For this reason, there is an optimum amount of uniaxial restraint for a given expansive cement concrete that will produce adequate prestress forces, minimum lateral expansions, and best mechanical properties. Most field installations of shrinkage-compensating concretes have utilized successfully the amount, kind, and position of reinforcement required for the given structure. Some tests made with biaxial restraint have shown improvements in uniformity of expansion and in mechanical properties. Due to their higher level of expansion, self-stressing concretes may require triaxial restraint, although successful tests have been made with biaxial restraint.

Mixing Time

Increasing mixing time decreases the expansion of a given expansive cement concrete.[6] Mixing accelerates formation of ettringite and thus depletes its availability for later expansion. Continued mixing also increases the water required to obtain a given slump.[7]

Use of Admixtures

Air-entraining admixtures which comply with ASTM C260 may be used for the same purpose with shrinkage-compensating concretes as with other types of portland cement concrete.[7] Some ASTM C494 Types A, B, and D water-reducing, retarding, and water-reducing/retarding admixtures are not compatible with certain shrinkage-compensating cements. It is recommended that such admixtures be tested before acceptance, using the particular cement and other materials selected for the job.[7] Calcium chloride (accelerator) is generally not recommended for use in expansive cement concrete because it reduces expansion and increases subsequent drying shrinkage.

Type and Size of Aggregate

Both rate and amount of expansion are affected by type of aggregate.[6,10] Of three types tested (crushed granite, river gravel, and expanded shale), the expanded shale concrete expanded the most and the river gravel the least. Data on the effects of aggregate size are limited. For a given workability, yield, and W/C, an increase in aggregate size is accompanied by a decrease in cement content. This change in cement content may cause a greater change in expansion than would the change in aggregate size.

Age of Expansive Cement

The length of storage of expansive cement after manufacture tends to reduce slightly the restrained expansion. The best practice is to keep the cement in sealed drums, away from exposure to air.[6]

PROPERTIES OF SHRINKAGE-COMPENSATING EXPANSIVE CEMENT CONCRETES

The following statements regarding properties of expansive cement concretes are based on previous research data obtained by other researchers together with observations made during and after field installations of full-size structures.[5,6,7,12,13]

1. Workability.[6] The workability of concretes made with Type K, Type S, and Type M shrinkage-compensating cements is the same as for portland cement concrete of equal slump. Type K cement seems to require slightly more water for the same slump, but the additional water probably combines with the expansive component and thus does not appear to adversely affect the other properties (W/C, strength, etc.).

2. Bleeding.[6] All three expansive cements have shown a consistent decrease in bleeding compared with similar portland cement concretes. In some cases there has been no bleeding at all with expansive cement concretes.

3. Setting time.[6] Setting times of all three shrinkage-compensating cements are comparable to Type I portland cement.

4. Unit weight and yield.[6] Shrinkage-compensating concretes have about the same unit weight and yield as does portland cement concrete (other things being equal).

5. Strengths.[6,7.12] Shrinkage-compensating concretes develop compressive, tensile, and flexural strengths equivalent in rate and magnitude to concretes made with Type I and Type II portland cements.

6. Modulus of elasticity (E).[6,7] Moduli of elasticity - static and dynamic - of shrinkage-compensating concretes are comparable to those in portland cement concretes.

7. Shrinkage and creep.[6,7] Shrinkage and creep of shrinkage-compensating concrete is about the same as in portland cement concrete.

8. Bond Strength.[6] Very few comparative bond strength tests have been made. Those tests which have been made showed that bond strengths of concrete made with Type K shrinkage-compensating cement were equal to or greater than those in the companion portland cement concrete.

9. Coefficient of thermal expansion.[6] The few tests which have been made show a coefficient similar to portland cement concrete.

10. Resistance to freezing and thawing.[13] Shrinkage-compensating concretes can be made resistant to damage from freezing and thawing with proper air entrainment and with relatively high cement content.

11. Resistance to de-icer scaling.[12,13] Shrinkage-compensating concretes showed resistance to de-icer scaling equal to or greater than comparable portland cement concrete.

12. Resistance to sulfate attack.[6,12] Very few tests have been conducted. Results are contradictory, with some showing favorable resistance of shrinkage-compensating concretes to sulfate attack and some unfavorable.

13. Abrasion resistance.[6] Shrinkage-compensating concrete made with Type K cement was found to have abrasion resistance superior to that of portland cement concrete.

RESEARCH PROGRAM

The research program at CEL was designed to determine the efficacy of using expansive cement concretes for Naval construction of thin-shell structures. Listed below are the major factors which were investigated:

1. Amounts of expansion to be expected with different cement contents
2. Effects of different amounts of restraint on expansion
3. Expansion of test specimens of different sizes
4. Shrinkage effects in different drying environments
5. Effects of air-entrainment on expansion
6. Effects of type and weight of aggregate on expansion

A detailed listing of the research program involving the expansive cement concrete prisms is presented in Table 1.

Test Specimens

To simulate concrete thin shells, prismatic specimens 5 in. (12.7 cm) wide and 12 in. (30.5 cm) long were made in thicknesses of 1, 2, and 4 in. (2.5, 5.1, and 10.2 cm). Figure 1 shows one of each of these prism sizes. The edges of the prisms were sealed to water vapor, so that subsequent drying of the concrete occurred only from the 5- by 12-in. (12.7 by 30.5 cm) opposite faces. This was done to simulate a continuous thin-shell structure in which drying would be from the upper and lower surfaces. The first prisms were reinforced with galvanized welded wire fabric of the following spacing and wire sizes: 2 by 2 in. (5.1 by 5.1 cm) No. 14 and No. 12 and 1 by 1 in. (2.5 by 2.5 cm), No. 14 and

No. 12. Examples of placement of the fabric with respect to the forms is shown in Figures 2a, b, and c. To obtain lower steel percentages for the 1-in.-thick (2.5 cm) prisms, some of them were made in widths of 10 in. In these prisms, welded wire fabric 4 by 4 in. (10.2 by 10.2 cm) No. 14 was used. Several different percentages of reinforcement were obtainable, as indicated in Table 2. Computation of reinforcement percentage was based on the total cross-sectional area of the horizontal wires viewed from either end. The vertical wires completing the fabric were not considered in computing the steel-percentage. In this report, reinforcement is designated by a lower case p followed by a percentage, e.g., p = 0.15%.

Also visible in Figure 2 are the screws which served as reference points for measurement of length changes with a mechanical strain gage. The reference screws were 5 in. (12.17 cm) apart.

Aggregate

Concretes used in this study were made with: (1) a moderate quality river sand and gravel, (2) a moderate quality crushed limestone (coarse and fine), and (3) an expanded shale lightweight aggregate (coarse and fine). All aggregates were dried prior to use but were not screened into separate sizes.

Expansive Cement Concrete Mixes

The expansive cement used was the shrinkage-compensating Type K sold commercially as "ChemComp Cement." Mixes were made over a wide range of cement contents (590 to 1,034 lb/yd^3 - 350 to 613 kg/m^3) and water/cement ratios (0.376 to 0.596 by weight), both with and without entrained air. For comparsion, a few mixes were made with portland Type II cements. In this report the concrete mixes are designated by the number of equivalent bags per cubic yard followed by the type of cement used, e.g., 7.5 SCA means 7.5 $bags/yd^3$, shrinkage-compensating cement, air entrained. The vast majority of the mixes of shrinkage-compensating concrete were made with 7.5 bags (705 lb) of cement per cubic yard because, at the time, this mix was typical of those being used in the Los Angeles area for structural purposes (other than slabs-on-grade).

The different types of shrinkage-compensating (SC) cement concretes used in this study are listed below.

1. 7.5 SC - normal weight river aggregate, non-air-entrained

2. 7.5 SCA - normal weight river aggregate, air-entrained

3. 7.5 SC-L - normal weight crushed limestone aggregate, non-air-entrained

4. 7.5 SCA-L - normal weight crushed limestone aggregate, air-entrained

5. 7.5 SCA-SLW - lightweight coarse aggregate and river sand, air-entrained (sand-lightweight)

6. 7.5 SCA-LW - lightweight coarse and lightweight fine aggregate, air-entrained (all-lightweight)

7. SC mixes - normal weight river aggregate, non-air-entrained 6.3 SC, 7.5 SC, 8.25 SC, 9.1 SC, 10.25 SC, and 11.0 SC

Concrete Mixing Procedure

To simulate the average mixing and hauling time of truck mixers, the following mixing procedure was adopted:

1. Mix aggregate, cement, and 3/4 of water for 3 min
2. Stop the mixer for 5 min (total time 8 min)
3. Mix for 2 min (total time 10 min)
4. Stop the mixer for 5 min (total time 15 min)
5. Mix for 2 min (total time 17 min)
6. Stop the mixer for 5 minutes (total time 22 min)
7. Mix for 2 min (total time 24 min)
8. Stop the mixer for 5 min (total time 29 min)
9. Add the remaining mixing water
10. Mix for 2 min (total time 31 min)
11. Measure the slump, seeking 4 in. (10.2 cm), adjust if necessary and measure air content.
12. Cast the specimens, consolidating by vibration.

Curing and Storage of Test Specimens

The specimens were cured in 100% R.H. (fog) for 14 days prior to being placed in one of three controlled temperature and humidity environments (25% R.H., 50% R.H., or 75% R.H., all at 73F). The curing period of 14 days was found to be typical for job-curing in the Los Angeles area.

Length Change Measurements

All length change measurements on the test specimens began about 6 hours after casting, immediately after removal from the molds. The specimens were then placed in 100% R.H., and measurements of expansion during the curing period were made daily for 7 days and then at 14 days, at which time the specimens were transferred to one of the controlled rooms. Drying shrinkage in the controlled rooms was measured daily for 1 wk, weekly for 3 mo, then monthly for at least 1 yr. Expansion strains and subsequent shrinkage strains were obtained by dividing the length change by the gage length of 5 in. (12.7 cm); strains are reported as microstrain (μ in./in.) or as strain in percent, where 1% strain is equivalent to 10,000 microstrain.

Theoretical Consideration

As unreinforced and unstressed concrete dries, it shrinks (compresses), and no damage results from the shrinkage. However, if the shrinkage is resisted or restrained by reinforcement, tensile stresses of sufficient magnitude to cause the concrete to crack can be induced. These cracks, refered to as shrinkage cracks, are not only unsightly but often allow ingress of water and other particles, which can cause more severe damage. When the concrete portion of reinforced concrete is placed in compression prior to drying, the tensile stresses resulting from shrinkage must first overcome the compressive stresses already present before the concrete itself can crack due to tensile stress.

Shrinkage-compensating concrete expands during the curing period, and if this expansion is properly restrained (resisted), the steel reinforcing is stretched, placing the concrete to which it is bonded in compression. An ideal expansion-shrinkage curve is shown in Figure 3. The expansion during the curing period (origin to point A) is resisted by reinforcing, and the concrete is being compressed. As the concrete enters the drying period A to B (i.e., is placed in service), the concrete begins to shrink. This shrinkage is actually, in terms of strain, tensile in direction, but this tension must first overcome the "built-in" compression before the concrete undergoes a tensile stress; i.e., the strain curve as shown in Figure 3 from A to B must drop below the "zero" line to enter the tensile stress zone where the concrete might crack. For the conditions shown in Figure 3, the concrete, after shrinkage, is still in compression; therefore the concrete will not crack due to shrinkage stresses. The problem in designing a structure of shrinkage-compensating concrete, then, is that of providing the required restrained expansion to overcome the shrinkage the structure is expected to undergo. The amount of shrinkage to be expected in a given structure is principally dependent upon the localized environment and the thickness of the structure. Obtaining the required restrained expansion is dependent upon the interplay between shrinkage-compensating cement content, the percentage of reinforcing steel, and the thickness of the member. It should be emphasized that the concrete begins to "shrink" immediately after removal from fog curing, but the important aspect is whether or not-and to what extent-the shrinkage drops below the zero strain line into the zone of negative strain.

TEST RESULTS

Expansion Strains During the Curing Period

Expansion strains after 14 days of fog curing are shown in Tables 3, 4, and 5 for various mixes containing 7.5 bags of cement per cubic yard and for steel percentages of 0%, 0.15% and 0.30%. The only results in Tables 3, 4, and 5 which might have been considered predictable are the higher expansions found in the lightweight mixes (lines 5 and 6). If other things are equal, the longer the curing period (i.e., the longer the cement is exposed to liquid water), the higher is the expansion. It has been shown that some of the water absorbed by the highly porous lightweight aggregate during mixing later returns to the concrete matrix as the concrete dries, thus furnishing more water for continued hydration of cement.[14] The effects of air-entrainment upon expansion vary, in some cases showing lower expansion and in some cases higher expansion than non-air-entrained concrete. Expansion strains for p = 0% should represent the "expansion potential" of a given mix and prism thickness.

Table 4 shows expansion strains for prisms 1 and 2 in. thick made with concretes containing various amounts of shrinkage-compensating cement. Since it is the cement that, in the end, provides the expansion, it then follows that the more the cement, the higher the expansion. This is corroborated in Table 4. The effects of cement content on expansion of prisms 1 inch thick are illustrated in Figure 4 for three steel percentages. Note that the left ordinate is shown in microstrain and the right ordinate in percent strain. As cement content increases from 6.3 bags/yd^3, the rate of increase in expansion is rather high up to cement contents between 7.5 and 8 bags/yd^3; then there is a decreasing rate of increase up to 11.0 bags/yd^3.

Table 5 shows expansions of prisms with various steel percentages. As expected, expansion decreased as the resistance to the expansion increased. Figure 5 illustrates the effects of steel reinforcement on expansion of prisms 1 in. thick. With curves such as those shown in Figure 5, expansions at any amount of reinforcement between 0% and 0.78% is easily obtained. As indicated in Table 2, some of the welded wire fabric was 1 by 1 in (2.5 by 2.5 cm), some 2 by 2 in. (5.1 by 5.1 cm), and some 4 by 4 in. (10.2 by 10.2 cm). Curves shown in Figure 5 reveal that this difference in spacing of wires does not affect the smoothness of the relationship between percent reinforcement and expansion.

A convenient means for determing the effects of specimen size upon certain properties of concrete is on the basis of the ratio of the exposed surface area to volume (S/V).[15,16] Exposed drying surfaces of the prisms were the 5 by 12-in. (10.2 by 30.5 cm) or 10 by 12-inch (25.4 by 30.5 cm) faces, the edge surfaces being sealed. Only the thickness affects the S/V, since widths and lengths cancel out. Figure 6 illustrates the relationship between 14-day expansion of 7.5 SC prisms and S/V for steel percentages from 0% to 0.78%. Expansions for intermediate thicknesses can be interpolated from the curves. As shown in

Figure 6, 14-day expansions decrease substantially as the specimen size increases. S/V values for thicknesses of 6 and 12 in., beyond the scope of this study, are also shown on Figure 6 along the lower right side. However, expansion for these thicknesses can be determined by extension of the curves to the origin of the graph as indicated by the dashed lines. An S/V value of zero would mean no specimen at all, and therefore the expansion would also be zero. S/V for a thickness of 3 ft is 0.67, and 6 ft is 0.33.

Expansion-Shrinkage of 7.5 SC Prisms

Residual strains of 1-in.-thick (2.5 cm) prisms after 365 days are presented as a function of steel percentage in Figure 7 and are also included in Table 6, along with corresponding values for 2- and 4-in.-thick (5.1 and 10.2 cm) prisms. Strain-time relationships are shown in Figures 8 a, b, and c for prisms 1 in. (2.5 cm) thick in 25% R.H., 50% R.H., and 75% R.H., respectively. Curves shown in Figure 8a for various steel percentages reveal that in 25% R.H. none of them approaches the ideal curve of Figure 3. Shrinkage rate of prisms 1 in. (2.5 cm) thick is extermely high in such a low humidity. The curve for 0% steel is included for general interest; as indicated previously, expansive cements are not recommended unless the concrete has some reinforcement, however slight. Data in Figure 8b for prisms 1 in. (2.5 cm) thick in 50% R.H. reveal that the curve for p = 0.15% approaches the ideal in that it falls only slightly below the zero strain line after 1 year. In Figure 8c, data for 75% R.H., the curve for p = 0.15% remains above the zero strain line, and the curve for p = 0.30% falls only slightly below at 1 yr.

Relationships between residual strains after 365 days and relative humidity of drying environment are shown in Figure 9 for various steel percentages. For the conditions given i.e., for 7.5 SC concrete 1 in. (2.5 cm) thick, concrete with p = 0.15% could be used in any exposure from 100% R.H. down to about 56% R.H. and remain above or at the zero strain line after 365 days. Likewise, concrete with p = 0.30% could be used in any exposure from 100% R.H. to about 78% R.H.

Data interpolations shown in previous and subsequent tables and figures were obtained by harmonizing curvilinear relationships such as those shown in Figures 7 through 9.

Residual strains of 2-in.-thick (5.1 cm) prisms after 365 days are presented in Figure 10 and are also included in Table 6. Strain-time relationships are shown in Figures 11a and b for prisms 2 in. (5.1 cm) thick in 50% R.H. and 75% R.H., respectively. Figure 11a reveals that the curve for p = 0.15% barely goes below the zero line at 1 yr. In 75% R.H., Figure 11b, the curve for p = 0.15% stays well above the zero strain line, and the curve for p = 0.30% barely drops below the zero strain line at 1 yr.

Relationships between residual strain after 365 days and relative humidity are shown in Figure 12. Study of these curves reveals that

7.5 SC concrete 2 in. (5.1 cm) thick could be used with p = 0.15% from 100% R.H. to about 54% R.H. without dropping below the zero strain/line. Similarly, concrete with p = 0.30% could be used from 100% R.H. to about 76% R.H.

Residual strains of 4-in.-thick (10.2 cm) prisms after 365 days are presented in Figure 13 and are also included in Table 6. Time-strain relationships are shown in Figure 14a and b for prisms 4-in. (10.2 cm) thick in 50% R.H. and 75% R.H. respectively. The curve for p = 0.15% in Figure 14a, 50% R.H., remained above the zero strain line until 1 yr, at which time its residual strain value was zero. Curves for both p = 0.15% and p = 0.30% remained above the zero strain line in 75% R.H. (Figure 14b).

Relationships between residual strain and relative humidity are shown in Figure 15. These curves indicate that 7.5 SC concrete 4-in. (10.2 cm) thick could be used with p ≈ 0.15% from 100% R.H. to about 50% R.H. without dropping below zero residual strain. Similarly, concrete with p = 0.30% could be used from 100% R.H. to about 73% R.H. without dropping below zero residual strain.

Residual strains after 365 days in 25% R.H., 50% R.H., and 75% R.H. are shown in Figure 16a, b, and c, respectively, as a function of S/V. The effects of member thickness is readily apparent in each of these figures. Use of Figures 16a, b, and c in conjunction with others, to establish design factors for given job conditions, is discussed later in this report.

Expansion-Shrinkage of 7.5 SCA Prisms

The 7.5 SCA concrete mix was identical to that of the 7.5 SC except for the air-entrainment and the necessary correction for mixing water; cement content was held constant at 7.5 bags per cubic yard. Prisms of 7.5 SCA concrete were made only in 1-in. (2.5 cm) thickness. Expansion strains after 14 days of fog curing are given in Table 3. Expansion for prisms with p = 0.15% showed about 9% less expansion than the 7.5 SC prisms, but those prisms with p = 0.30% showed about 2% more expansion than the 7.5 SC prisms.

Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms of 7.5 SCA concrete in 75% R.H. are shown in Figure 17, along with corresponding curves for 7.5 SC concrete taken from Figure 8c. Effectively, there are no significant differences between the two concretes, meaning that after 1 yr, air entrainment has little or no effect on the net expansion-shrinkage performance.

Expansion-Shrinkage of 7.5 SC-L and 7.5 SCA-L

Expansion strains of 1-in.-thick (2.5 cm) prisms of 7.5 SC-L and 7.5 SCA-L concretes after 14 days of fog curing are listed in Table 3. As found with the 7.5 SC and 7.5 SCA concretes, there are no significant differences. Expansion-shrinkage curves for p = 0.15% and p = 0.30% in

50% R.H. are shown in Figure 18a for 7.5 SC-L concretes. The curve for p = 0.15% dropped slightly below the zero strain line after 1 yr. Expansion-shrinkage curves for the same steel percentages in 75% R.H. are presented in Figure 18b. Both the curves remained above the zero strain line through the 365-day period.

Comparisons of residual strains of 7.5 SC-L and 7.5 SCA-L concretes are shown in Table 7. As noted before for the 7.5 SC and 7.5 SCA concretes, there are no significant differences, so air-entrainment does not appear to affect the performance of shrinkage-compensating concretes.

Comparisons of expansion-shrinkage data for 7.5 SC and 7.5 SC-L (Tables 3 through 7) show that expansion of 7.5 SC prisms 1-in.-thick (2.5 cm) with p = 0.15% (845) is considerably higher than similar prisms of 7.5 SC-L (705); on the other hand, the shrinkage from 14 to 365 days for the 7.5 SC prisms in 50% R.H. is -880 [845 - (-35)] and for 7.5 SC-L prisms is -750 [705 - (-45)]. Corresponding figures for shrinkage in 75% R.H. are -680 and -450. With these relationships for 1-in.-thick (2.5 cm) prisms and the logical assumption that the effects of prism thickness and steel percentage will be same for both types of concrete (7.5 SC and 7.5 SC-L), data for design purposes can be obtained for 7.5 SC-L concretes.

Expansion-Shrinkage of 7.5 SCA-SLW Prisms

Expansions of 7.5 SCA-SLW prisms after 14 days of fog curing are listed in line 5 of Table 3. These expansion values represent significant increases over those in the previously reported concretes of lines 1-4. Lightweight concretes, such as 7.5 SCA-SLW, expand more than normal weight concretes for at least two reasons:

(1) The lightweight aggregate (in this case, coarse expanded shale) absorbs much more mixing water than does the normal weight aggregate. This mixing water is later drawn back into the concrete matrix as the cement hydrates and the interior of the concrete dries. This water increases the humidity inside the concrete and provides more favorable conditions for expansion.[17]

(2) Lightweight concrete gains in strength at a slower rate than normal weight concrete, due to the basically weaker aggregate; this weaker strength means less resistance to expansion (i.e., more expansion in a given time).

Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms in 50% R.H. are shown in Figure 19a. The curve for p = 0.15% remains above the zero strain line. Corresponding curves for 1-in.-thick (2.5 cm) prisms in 75% R.H. are presented in Figure 19b. Both curves remain in the plus strain zone throughout the 365-day period. Similar performances are observed for 2- and 4-in.-thick (5.1 and 10.2 cm) prisms in 50% R.H. and 75% R.H., as indicated in Figures 20 and 21.

Residual strains after 365 days are shown in Table 8 and the effects of specimen thickness are presented in Figure 22 in terms of S/V.

Shape of the curves is quite similar to those in Figures 16a, b, and c. It should be noted that although thickness affects the magnitude of residual strain, in 50% R.H. the p = 0.15% curve remains above the zero strain line and in 75% R.H. both of the curves are above the zero strain line.

Expansion-Shrinkage of 7.5 SCA-LW Prisms

Expansions of 7.5 SCA-LW prisms after 14 days of fog curing are shown in Table 3. As noted previously with regard to the 7.5 SCA-SLW concrete, these expansions are higher than the normal weight aggregate concretes. Causes of the higher expansions are the same as stated for the 7.5 SCA-SLW concrete; in this case, all the aggregate is lightweight and is thus highly absorptive, eventually contributing even more water into the concrete for curing of the cement. Generally, expansions of the 7.5 SCA-LW concrete in Table 3 are higher than those for the 7.5 SCA-SLW concrete, as expected.

Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms in 50% R.H. are shown in Figure 23a. The curve for p = 0.15% stayed above the zero strain line throughout the 365-day period, and the curve for p = 0.30% dipped just below the line toward the end of the period. Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms in 75% R.H. are presented in Figure 23b. Both curves remained substantially above the zero strain line.

Expansion-shrinkage curves for 2-in-thick (5.1 cm) prisms in 50% R.H. are shown in Figure 24a. The curve for p = 0.15% stayed above the zero strain line, while the curve for p = 0.30% reached the zero strain line at 365 days. As indicated in Figure 24b, both curves in 75% R.H. stayed substantially above the zero strain line.

Expansion-shrinkage curves for 4-in.-thick (10.2 cm) prisms, shown in Figure 25a and b for 50% R.H. and 75% R.H., respectively, are quite similar to those for the 2-in.-thick (5.1 cm) prisms.

Residual strains after 365 days are given in Table 9 for all three thicknesses. Effects of prism thickness upon S/V are shown in Figure 26. These curves, quite similar to previous ones, furnish a ready means for prediction of expected performance of 7.5 SCA-LW concretes in thicknesses from 1 to 12 in. (2.5 to 30.5 cm) for steel percentages of 0.15 and 0.30.

SC Mixes With Different Cement Contents

Expansions of the prisms made with these concretes are shown in Table 4. Since it is the cement which causes the expansion, one would expect that the more cement the more expansion, other things being equal. This is verified in Table 4. As expected, the higher the reinforcement, the lower is the expansion for a given prism thickness. Figure 4 shows the effects of cement content on 14-day expansion for 1-in.-thick (2.5 cm) prisms.*

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*Steel percentage p = 0.15%.

Expansion-shrinkage of 1-in.-thick (2.5 cm) prisms of SC mixes with different cement contents in 50% R.H. is presented in Figure 27a for p = 0.15%. Note that the rather significant differences in expansion between the 6.3 SC and 11.0 SC at 14 days is greatly reduced after 365 days; i.e., much of the advantage of the higher expansion is lost during the shrinkage period.

Reasons for this are shown in Table 10 which reports shrinkage strains for the SC mixes with different cement contents. Table 10 verifies the long-established axiom that shrinkage increases as the cement content increases. Referring to Figure 27a, the optimum cement content to obtain a residual strain of zero after 365 days would be about 8.5 bags/yd^3; 9.1 bags/yd^3 would be conservative for the conditions shown (1-in.-thick prisms with p = 0.15%). Figure 27b gives the same curves for 75% R.H. As noted in Figure 27a, the advantage of the higher expansions at higher cement contents is reduced after 365 days but not quite so dramatically as in 50% R.H. All of the curves remained above the zero strain line in 75% R.H.

Table 11 lists residual strains after 365 days for all prisms of the SC mixes with different cement contents. Also included in Table 11 are the pounds per cubic yard equivalents for the bags per cubic yard. Curvilinear relationships for the 1-in.-thick (2.5 cm) prisms are shown in Figure 28. As noted in almost all other concretes in 50% R.H., prisms with p = 0.30% dropped below the zero strain line after 365 days, while at least some of those with p = 0.15% remained above the zero strain line.

Table 11 also lists residual strains for the same mixes in 75% R.H., and Figure 29 shown the curves for 2-in-thick (5.1 cm) prisms.

Compressive Strengths and Young's Moduli

In an earlier CEL report, data were presented which indicated that both compressive strengths and Young's moduli of shrinkage-compensating concretes are equal to or greater than those of portland cement concrete.[18] Further tests have shown that this is true for all the types of concrete used in this study.

DESIGN APPLICATIONS

Structurally speaking, it has been shown that shrinkage-compensating concrete can be safely substituted for portland cement concrete, utilizing the same design factors as for portland cement concrete: cement content, water/cement ratio, air-entrainment, steel percentage, etc.[6,7] However, the value of shrinkage-compensating concrete is in its ability to compensate for expected shrinkage and thus avoid shrinkage cracking. Test results make it plain that shrinkage-compensating concrete is effective for its stated purpose only when the steel percentage is fairly low (i.e., less than 0.30%). Effective utilization of shrinkage-compensating concrete is thus limited to those structures which are lightly reinforced.

For a given structure, once the designer has chosen the thickness, steel percentage, and minimum cement content required for structural safety, he can determine the efficacy of using shrinkage-compensating concrete by determining the following factors: shrinkage to be expected (to be compensated for) and expansion he can expect from different cement contents at the steel percentage chosen, with both factors dependent upon the thickness of the structure and upon environment.

Shrinkage to be expected can be determined from Figures 30 and 31. Shrinkage values used to derive these curves were taken from test data in this report; averages were used to simplify the curves. Since shrinkage is not much different for steel percentages of 0.15% and 0.30%, shrinkage curves in Figures 30 and 31 are independent of steel percentage. Where one shrinkage was slightly higher than the other, as in line 2 of Table 10, the higher value was plotted, thus making these figures conservative. For example, for a structure 6 in. thick made with normal weight 7.5 SC river aggregate concrete to be placed in an environment where the average humidity is 65%, Figure 30a shows shrinkage values of -780, -655, and -540 for 1, 2, and 4 in. thick, respectively. These values, plotted on Figure 31a, result in the dashed curve shown. Shrinkage of a 6-in.-thick structure in 65% R.H. can be expected to be -460 microstrain. If the cement content is higher or lower than 7.5 bags/yd^3, a multiplication factor for the shrinkage can be obtained from Figure 32 (taken from Table 10), which shows factors for steel percentages of 0.15% and 0.30%.

Having established the amount of expected shrinkage, the design and analysis for use of shrinkage-compensating concrete can be completed by utilizing Figures 33a, b, and c which shows expansion for normal weight, sand-lightweight, and all-lightweight 7.5 SC concretes, respectively. Figures 34 and 35 show effects of cement content on expansions in SC concretes with steel percentage = 0.15%.

Design Examples

1. Given: SC normal weight river
   Aggregate concrete = 7.5 bags/yd^3
   Steel percentage = 0.15%
   Concrete thickness = 6 in.
   Average humidity = 65% R.H.

   Analysis: From Figures 30a and 31a, shrinkage = -460 microstrain
   From Figure 33a, expansion = 530 microstrain

   Conclusion: Expansion (530) of SC normal weight concrete at 7.5 bags/yd^3 is more than adequate to compensate for shrinkage (-460)

2. Given:	Same as for Example 1, except that sand-lightweight aggregates are to be used	
Analysis:	From Figures 30b and 31b, shrinkage = -380 microstrain From Figure 33b, expansion = 565 microstrain	
Conclusion:	Fxpansion (565) of SC sand-lightweight concrete is more than adequate to compensate for shrinkage (-380).	
3. Given:	SC normal weight river	
	Aggregate concrete	= 7.5 bags/yd^3
	Steel percentage	= 0.15%
	Concrete thickness	= 3 in.
	Average humidity	= 50% R.H.
Analysis:	From Figure 31a, shrinkage = -665 microstrain From Figure 33a, expansion = 660 microstrain	
Conclusion:	Expansion (660) of SC normal weight river aggregate concrete is just adequate to compensate for shrinkage (-665)	
4. Given:	SC normal weight river	
	Aggregate concrete	= 7.0 bags/yd^3
	Steel percentage	= 0.15%
	Concrete thickness	= 2 in.
	Average humidity	= 50% R.H.
Analysis:	From Figure 31a, shrinkage for 7.5 bags/yd^3 and 2 in. thickness = -740 microstrain; since cement content is 7.0 bags/yd^3, obtain multiplication factor from Figure 32: 0.96 x (-740) = -710 microstrain From Figure 34, plot expansions for 7.0 bags/yd^3 onto Figure 35, as shown by the dashed line; expansion for 2 in. thickness = 675 microstrain	
Conclusion:	Expansion (675) of 7.0 SC normal weight river aggregate concrete is not adequate to compensate for shrinkage (-710). Alternatives are: (1) use higher cement content or (2) use lower steel percentage. Assuming the steel percentage to be minimum for code, adjust by obtaining proper cement content to compensate for shrinkage of -710 microstrain. From Figure 34, adjust cement content to 7.5 bags/yd^3, providing expansion of 730 microstrain. To check adequacy of expansion, see Figure 31a to obtain shrinkage for 7.5 bags/yd^3 = -740 microstrain.	

Final Conclusion: Expansion (730) is close enough to the shrinkage (-740) to be considered adequate.

Other combinations of data for use in design can be prepared from the data in this report. The example designs were presented to illustrate methods. Similar design relationships can be developed for SC concretes made with crushed limestone aggregates.

CONCLUSIONS

1. Shrinkage-compensating concrete can be designed and utilized to adequately compensate for shrinkage; due consideration must be given to cement content, steel percentage, thickness, adequate curing, and ambient humidity at the structure.

2. Steel percentages less than 0.30% seem to be optimum for most design situations, although in some cases cement content can be increased to overcome deficient expansion.

RECOMMENDATIONS

1. Shrinkage-compensating concrete should be used to eliminate or minimize shrinkage cracking in designs which incorporate low steel percentages (less than 0.30%). Tables and figures in this report should be used to determine interrelationships between cement content, steel percentage, thickness, environment, and shrinkage. It should be noted that this recommendation applies only to structural applications, not to slabs-on-grade.

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Table 1. Thin Shell Prisms of Shrinkage-Compensating Concrete Used in Research Program

Cement Content		Prism Size[a]	Mesh Reinforcement	Relative Humidity in Storage Environment at 73F
lb/yd^3	$bags/yd^3$	in.	%	%
A. River Aggregate, Non-Air-Entrained Concrete				
592	6.3	1 x 5	0.30	50,75
		1 x 10	0.15	50,75
		2 x 5	0.15	50,75
		2 x 5	0.30	50,75
705	7.5	1 x 5	0.0,0.30,0.47,0.503,0.785	25,50,75,100
		1 x 10	0.15	50,75
		2 x 5	0.30,0.503,0.785	25,50,75,100
		2 x 5	0.0	50,75,100
		2 x 5	0.15,0.44	50,75
		4 x 5	0.30	25,50,75,100
		4 x 5	0.785	25,50,100
		4 x 5	0.0	50,75,100
		4 x 5	0.15,0.44	50,75
		4 x 5	0.503	75
776	8.25	1 x 5	0.30	50,75
		1 x 10	0.15	50,75
		2 x 5	0.15,0.30	50,75
855	9.1	1 x 5	0.30	50
964	10.25	1 x 5	0.30	50
1,034	11.0	1 x 5	0.30	50

continued

Table 1 (Cont'd)

Cement Content		Prism Size[a]	Mesh Reinforcement	Relative Humidity in Storage Environment of 73F
lb/yd^3	$bags/yd^3$	in.	%	%
B. River Aggregate, Air-Entrained[b] Concrete				
705	7.5	1 x 5	0.30,0.47	25,50,75,100
		1 x 5	0.503	25,50,100
		1 x 5	0.0	100
		1 x 10	0.15	50,75
C. Crushed Limestone Aggregate, Non-Air-Entrained Concrete				
705	7.5	1 x 5	0.30,0.47	50,75
		1 x 5	0.0	75
		1 x 10	0.15	50,75
		2 x 5	0.0,0.15,0.30	50,75
D. Crushed Limestone Aggregate, Air-Entrained[b] Concrete				
705	7.5	1 x 5	0.30,0.47	50,75
		1 x 5	0.0	100
		1 x 10	0.15	50,75
		2 x 5	0.15,0.30	50,75
		2 x 5	0.0	100

continued

Table 1 (Cont'd)

Cement Content		Prism Size[a]	Mesh Reinforcement	Relative Humidity in Storage Environment of 73F
lb/yd^3	$bags/yd^3$	in.	%	%
E. River Sand and Lightweight Coarse Aggregate, Air-Entrained[b] Concrete				
705	7.5	1 x 5	0.30	50,75,100
		1 x 10	0.15	50,75,100
		2 x 5	0.15	50,75
		2 x 5	0.30	50,75,100
		4 x 5	0.15,0.30	50,75
F. All Lightweight Aggregate, Air-Entrained[b] Concrete				
705	7.5	1 x 5	0.30	50,75
		1 x 10	0.15	50,75
		1 x 10	0.0	75
		2 x 5	0.15	50,75
		2 x 5	0.30	50,75,100
		4 x 5	0.15,0.30	50,75

[a] Prism measurements refer to thickness and width; all thin-shell prisms were 12 in. long.

[b] Entrained air content was 6 to 8%.

Table 2. Reinforcement Percentages Using Welded Wire Fabric

Prism Size[a] (in.)	Number of Pieces of Fabric	Mesh Spacing, (in.)	Wire Gage No.	Reinforcement[b] (%)
1 x 10	1	4 x 4	14	0.15
1 x 5	1	2 x 2	14	0.30
1 x 5	1	2 x 2	12	0.47
1 x 5	1	1 x 1	14	0.50
1 x 5	1	1 x 1	12	0.78
2 x 5	1	2 x 2	14	0.15
2 x 5	2	2 x 2	14	0.30
2 x 5	2	2 x 2	12	0.44
2 x 5	2	1 x 1	14	0.50
2 x 5	2	1 x 1	12	0.78
4 x 5	2	2 x 2	14	0.15
4 x 5	4	2 x 2	14	0.30
4 x 5	4	2 x 2	12	0.44
4 x 5	4	1 x 1	14	0.50
4 x 5	4	1 x 1	12	0.78

[a] Prism measurements shown refer to thickness and width; all thin-shell prisms were 12 in. long

[b] Reinforcement percentage = the total cross-sectional area of the horizontal wires at the end of the prism ÷ the total cross-sectional area of the prism, viewed from the end.

Table 3. Expansion Strains of Prisms Made With Concrete Mixes Containing 7.5 Bags/yd^3 of Cement, After 14 Days of Fog Curing

Line. No.	Concrete Mix	Expansion Strains[a] With Prism Thicknesses of--								
		1 in.			2 in.			4 in.		
		With Steel Reinforcement (%) of--								
		0	0.15	0.30	0	0.15	0.30	0	0.15	0.30
1	7.5 SC	1,010	845	630	860	730	560	705	610	555
2	7.5 SCA	925	775	645	None	None	None	None	None	None
3	7.5 SC-L	830	705	550	None	None	None	None	None	None
4	7.5 SCA-L	865	705	510	None	None	None	None	None	None
5	7.5 SCA-SLW	1,115	930	725	None	815	630	None	670	525
6	7.5 SCA-LW	1,205	980	710	None	860	665	None	745	610

[a]Expansion strains are in microstrain, average of at least three specimens

Table 4. Expansion Strains of Prisms Made With SC Mixes Containing Different Amounts of Cement,[a] After 14 Days of Fog Curing

Line No.	Concrete Mix	Expansion Strains[b] With Prism Thicknesses of--					
		1 in.			2 in.		
		With Steel Reinforcement (%) of --					
		0	0.15	0.30	0	0.15	0.30
1	6.3 SC	835	710	505	None	565	380
2	7.5 SC	1,010	845	630	None	730	560
3	8.25 SC	1,090	915	700	None	810	625
4	9.1 SC	1,160	985	765	None	885	685
5	10.25 SC	1,245	1,075	850	None	975	745
6	11.0 SC	1,295	1,125	905	None	1,025	775

[a]All mixes made with river aggregate.
[b]Expansion strains are in microstrain, averages of at least three specimens.

Table 5. Expansion Strains of Prisms Made With 7.5 SC Mixes With Different Steel Percentages[a], After 14 Days of Fog Curing

Steel Percentage	Expansion Strains[b] With Prism Thickness of--		
	1 in.	2 in.	4 in.
0	1,010	860	705
0.15	845	730	610
0.22	750[c]	645[c]	555[c]
0.30	630	560	485
0.44	515[c]	470[c]	385
0.47	495	455[c]	370[c]
0.50	480	440	355
0.78	390	340	265

[a]All mixes made with river aggregate.

[b]Expansion Strains are in microstrain, averages of at least 3 specimens.

[c]Interpolated values.

Table 6. Residual Microstrains in 7.5 SC Prisms After 365 Days of Drying

Prism Thickness, in.	Residual Strains With Steel Reinforcement of--							
	0%	0.15%	0.22%	0.30%	0.44%	0.47%	0.50%	0.78%
A. In 25% R.H.								
1	60	-140[a]	-270[a]	-360	-495[a]	-515	-535	-680
2	35[a]	-95[a]	-175[a]	-280	-440[a]	-460[a]	-480	-600
4	10[a]	-60[a]	-120[a]	-230	-390[a]	-415[a]	-435[a]	-545
B. In 50% R.H.								
1	150	-35	-135[a]	-220	-335[a]	-355	-375	-500
2	110	-10	-70	-170	-305	-325[a]	-350	-480
4	70	0	-50[a]	-130	-285	-310[a]	-330[a]	-455
C. In 75% R.H.								
1	300	165	55[a]	-30	-145[a]	-165	-180	-290
2	240	135	80	-10	-120	-130[a]	-150	-250
4	180	110	75[a]	15	-100	-115[a]	-130	-215
D. In 100% R.H.								
1	1,095	920	820[a]	695	565[a]	545	525	420
2	980	830	745[a]	655	540[a]	520[a]	500	390
4	875	765[a]	705[a]	625	510[a]	490[a]	470[a]	365

[a] Interpolated

Table 7. Residual Microstrains of 1-in.-Thick Prisms of 7.5 SC-L and 7.5 SCA-L Concretes After 365 days.

Concrete Mix	Residual Microstrains in--			
	50% R.H.		75% R.H.	
	With Steel Reinforcement of--			
	0.15%	0.30%	0.15%	0.30%
7.5 SC-L	-45	-180	255	65
7.5 SCA-L	-25	-210	255	30

Table 8. Residual Microstrains in 7.5 SCA-SLW Prisms After 365 Days

Prism Thickness, in.	Residual Microstrains in--			
	50% R.H.		75% R.H.	
	Steel Reinforcement of--			
	0.15%	0.30%	0.15%	0.30%
1	50	-155	265	85
2	75	-110	285	115
4	115	- 60	315	150

Table 9. Residual Microstrains in 7.5 SCA-LW Prisms After 365 Days

Prism Thickness, in.	Residual Microstrain in-- 50% R.H. Steel Reinforcement of-- 0.15%	50% R.H. 0.30%	75% R.H. 0.15%	75% R.H. 0.30%
1	120	- 40	345	120
2	165	0	360	150
4	215	40	390	185

Table 10. Shrinkage Strains of SC Mixes With Different Cement Contents (14 Days to 365 Days)

Cement Content		Shrinkage Strains[a] in--							
		50% R.H.				75% R.H.			
		1 in. Thick		2 in. Thick		1 in. Thick		2 in. Thick	
		at Steel Reinforcement of--							
bags/yd^3	lb/yd^3	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%
6.3	592	-830	-815	-650	-635	-650	-635	-505	-480
7.5	705	-880	-850	-740	-730	-680	-660	-595	-570
8.25	776	-920	-885	-785	-760	-715	-680	-640	-595
9.1	855	-965	-920	-825	-785	-750	-700	-685	-620
10.25	964	-1,030	-965	-890	-805	-800	-735	-740	-645
11.0	1,034	-1,070	-1,005	-925	-815	-830	-765	-770	-645

[a]Microstrain, shown as negative to indicate direction.

Table 11. Residual Microstrains in SC Mixes With Different Cement Contents After 365 Days

Cement Content		Residual Microstrains in--							
		50% R.H.				75% R.H.			
		1 in. Thick		2 in. Thick		1 in. Thick		2 in. Thick	
		Steel Reinforcement of--							
bags/cu yd	lb/cu yd	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%
6.3	592	-120	-310	-85	-255	60	-130	60	-100
7.5	705	- 35	-220	-10	-170	165	- 30	135	- 10
8.25	776	- 5	-185	25	-135	200	20	170	30
9.1	855	20	-150	60	-100	235	65	200	65
10.25	964	45	-115	85	- 60	275	115	235	100
11.0	1,034	55	-100	100	- 40	295	140	255	120

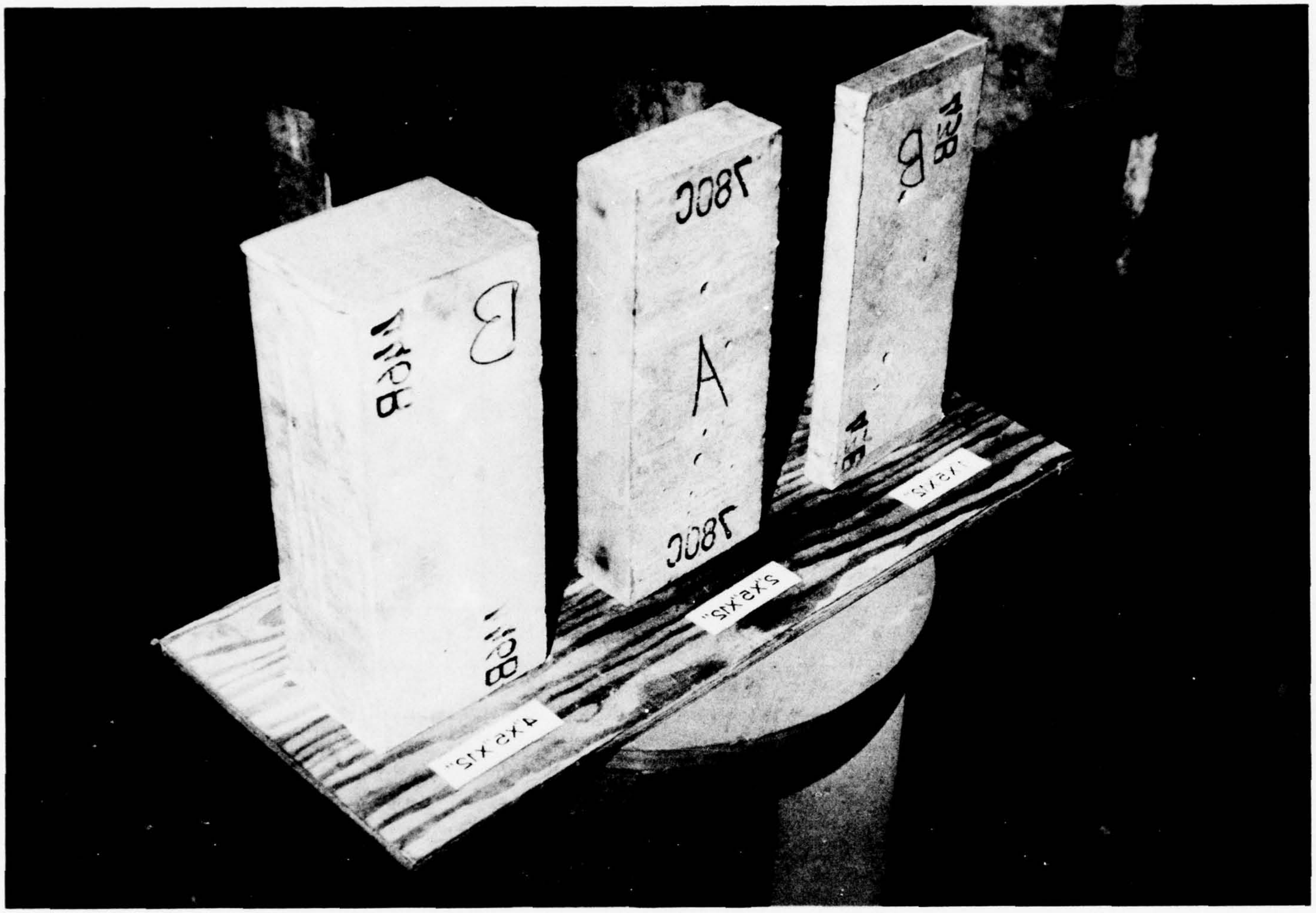
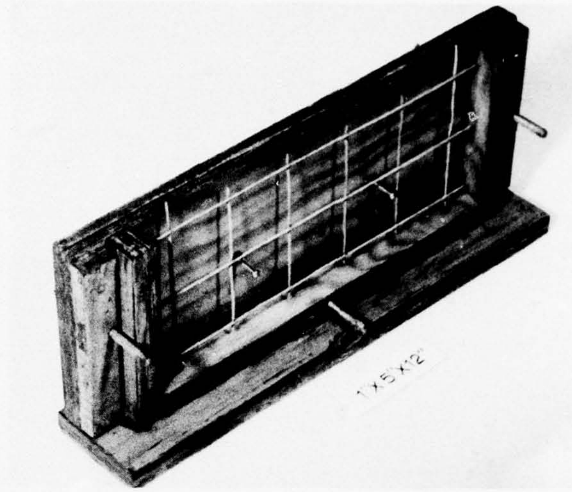
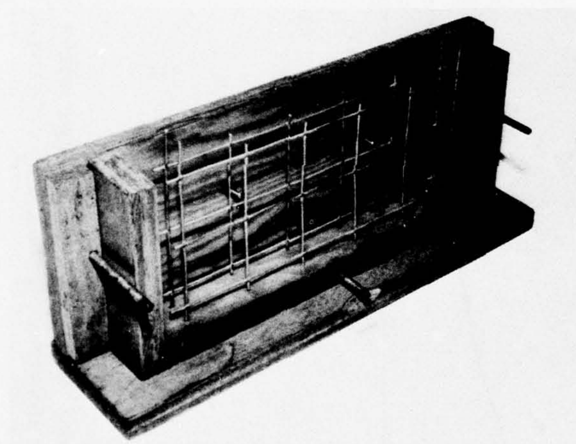


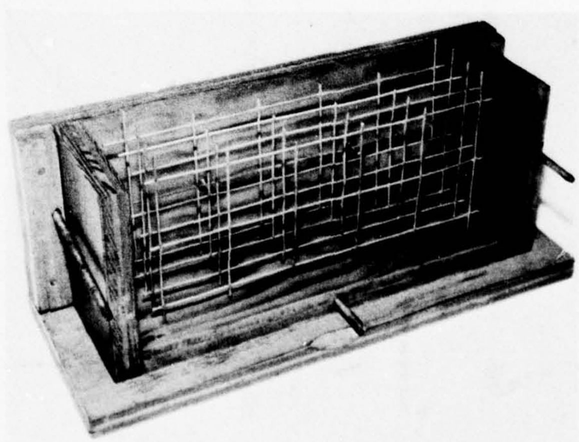
Figure 1. Prismatic test specimens.



(a) 1 in. thick.



(b) 2 in. thick.



(c) 4 in. thick.

Figure 2. Forms for prisms 5 in. wide and 12 in. long, showing reinforcement.

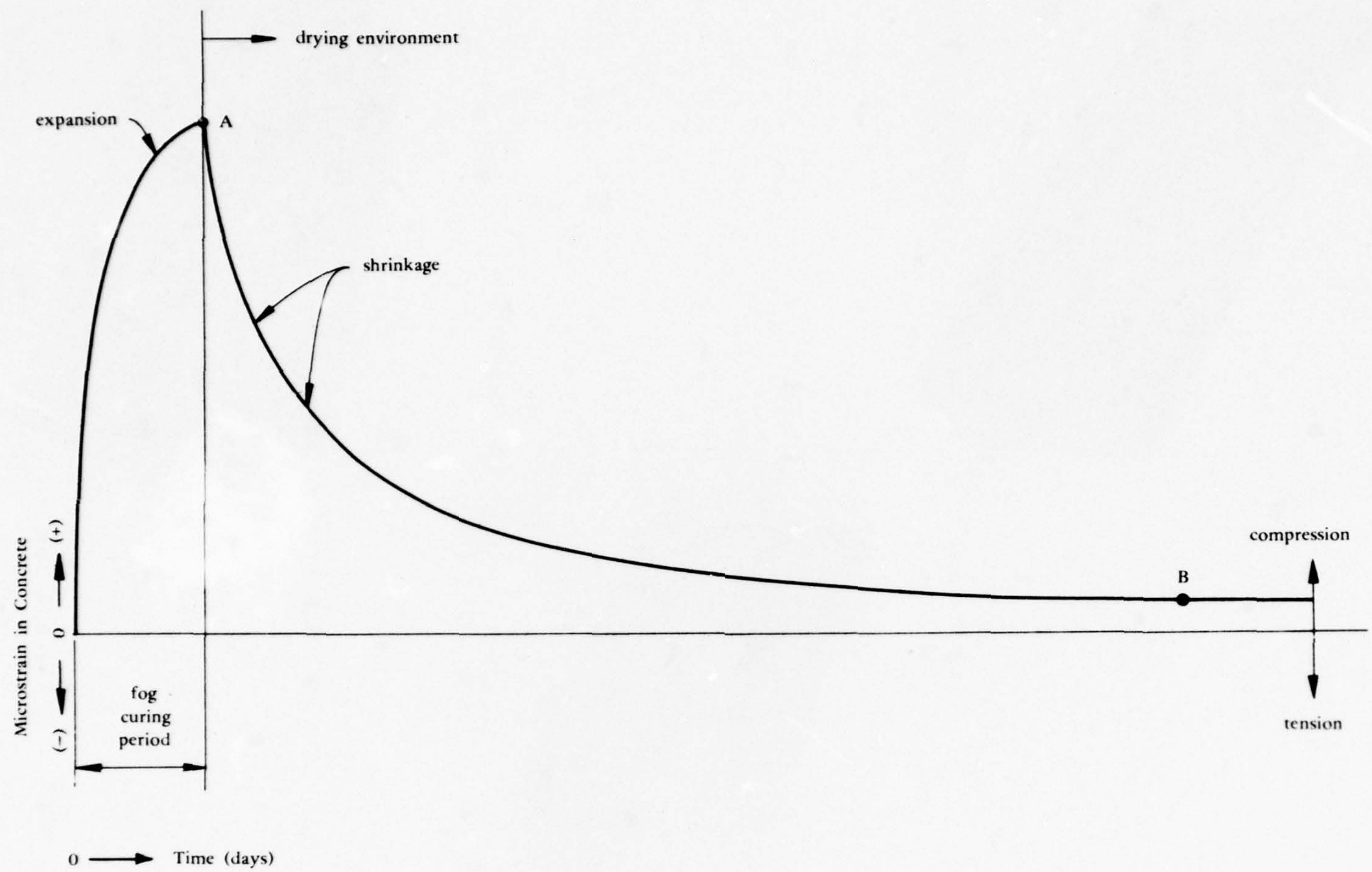


Figure 3. Ideal expansion-shrinkage curve for restrained shrinkage-compensating concrete.

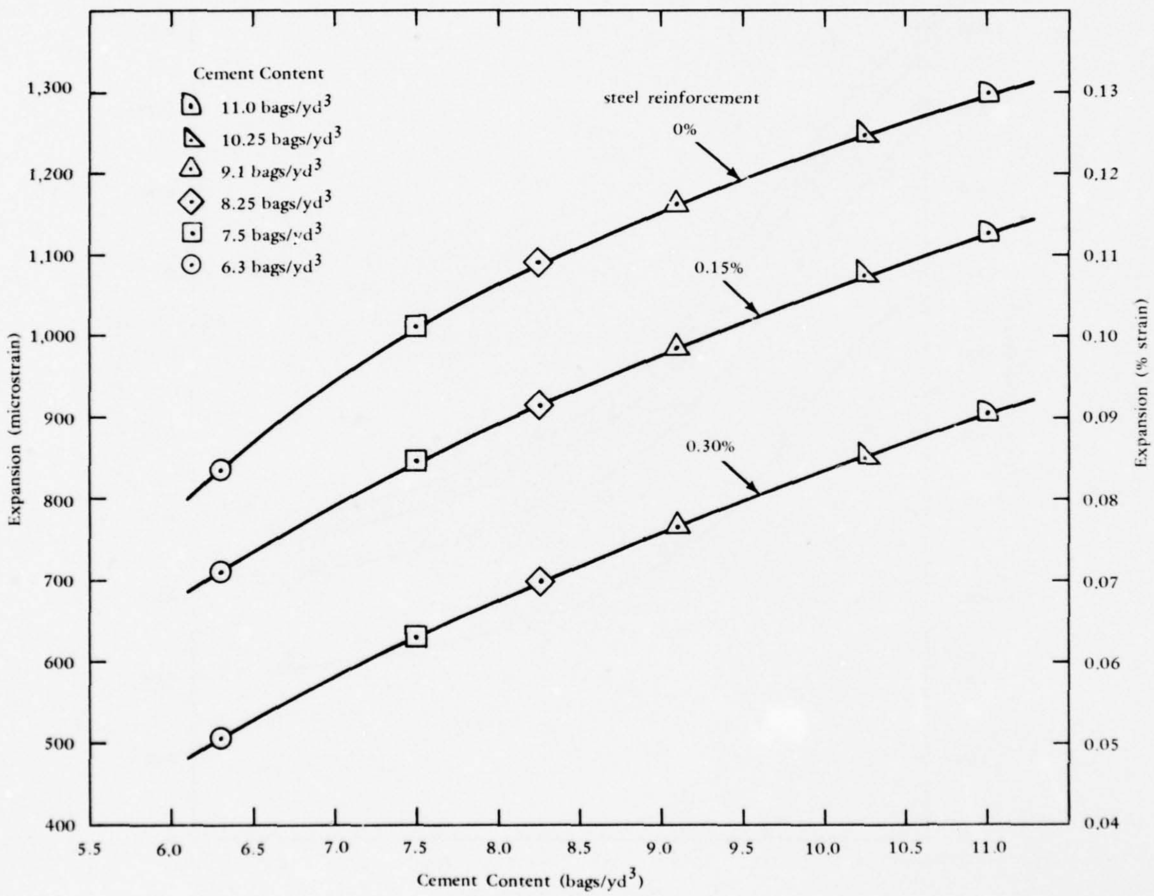


Figure 4. Expansion strains of 1-in.-thick prisms of 7.5 SC concrete after 14 days of fog curing, based on cement content.

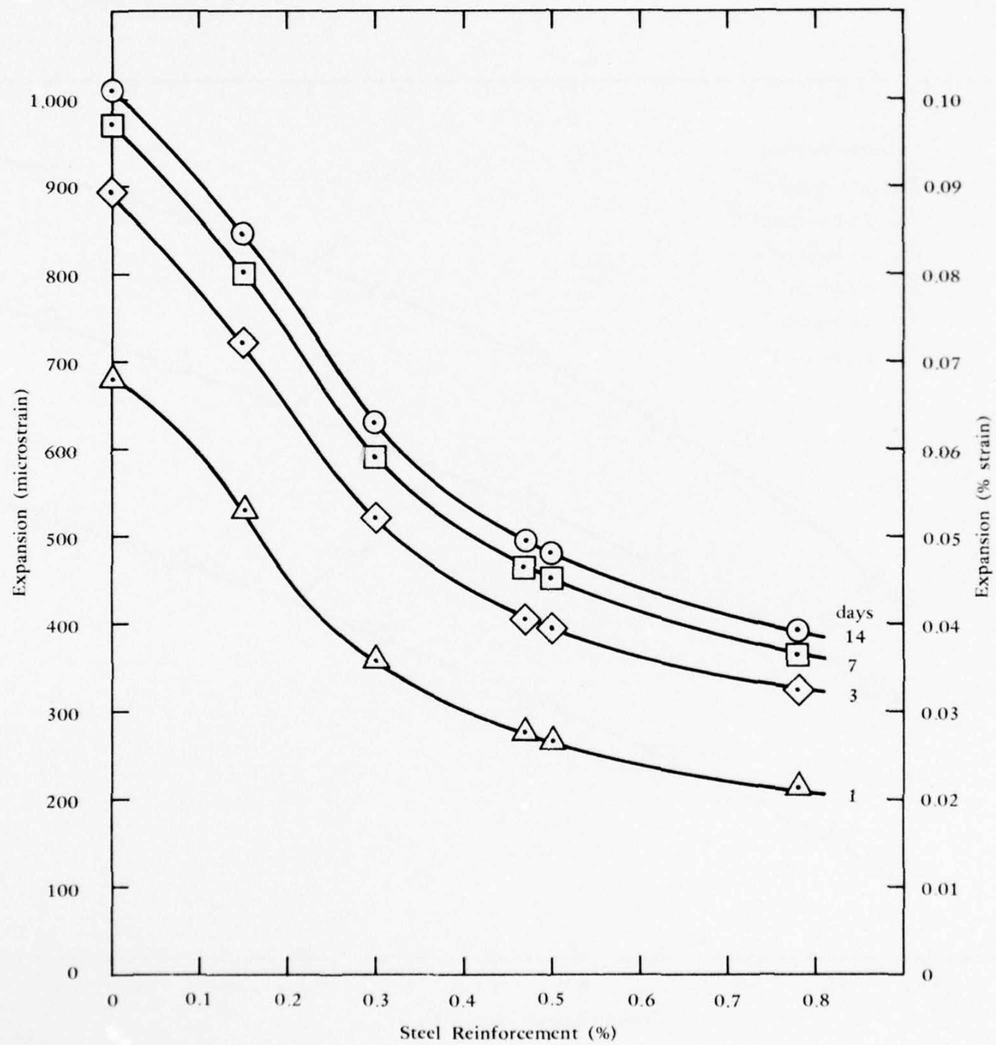


Figure 5. Expansion strains of 1-in.-thick prisms of 7.5 SC concrete during 14 days of fog curing, based on steel reinforcement percentage.

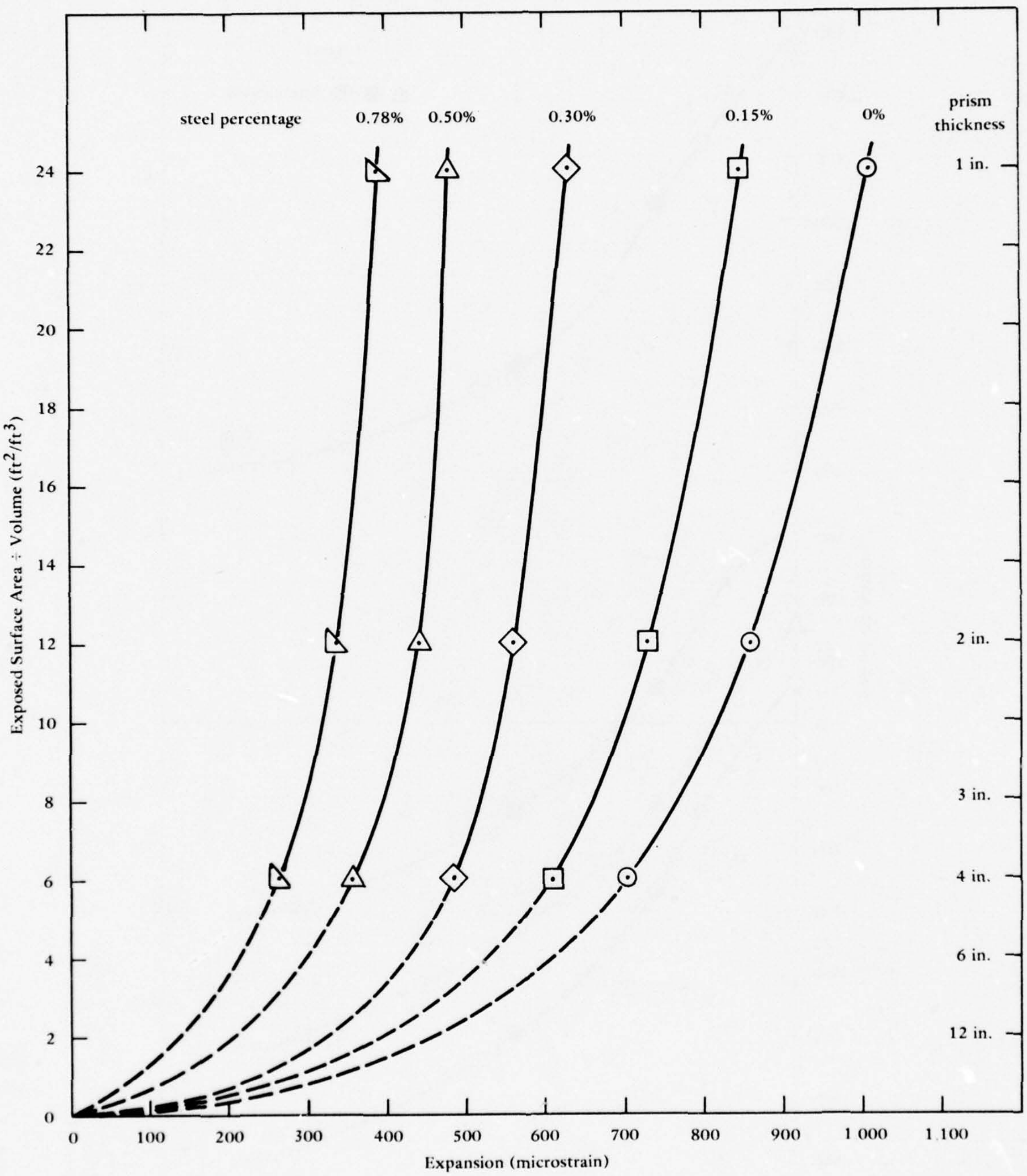


Figure 6. Expansion as a function of surface-to-volume (S/V) ratio, 7.5 SC concrete, after 14 days of fog curing.

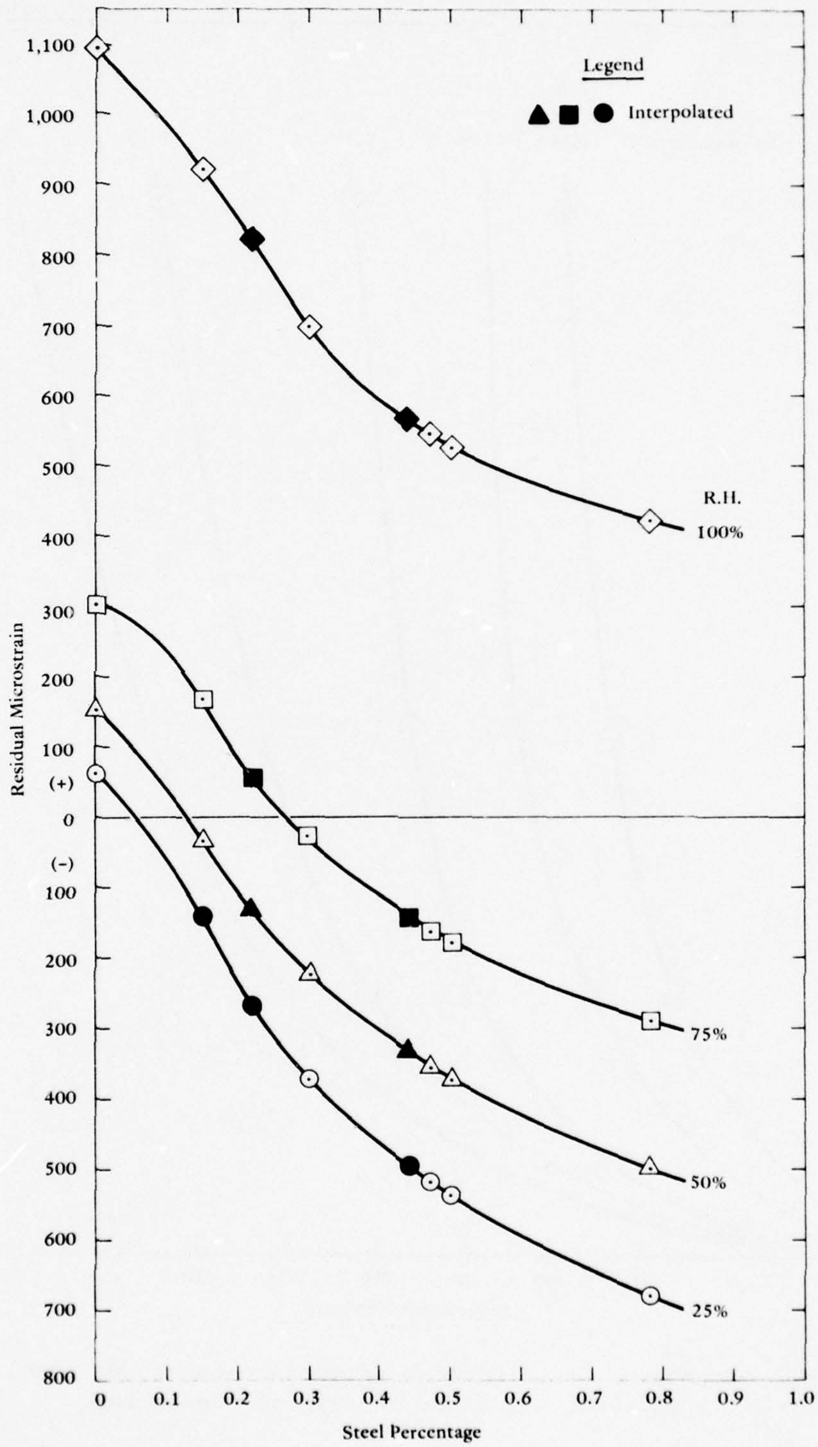
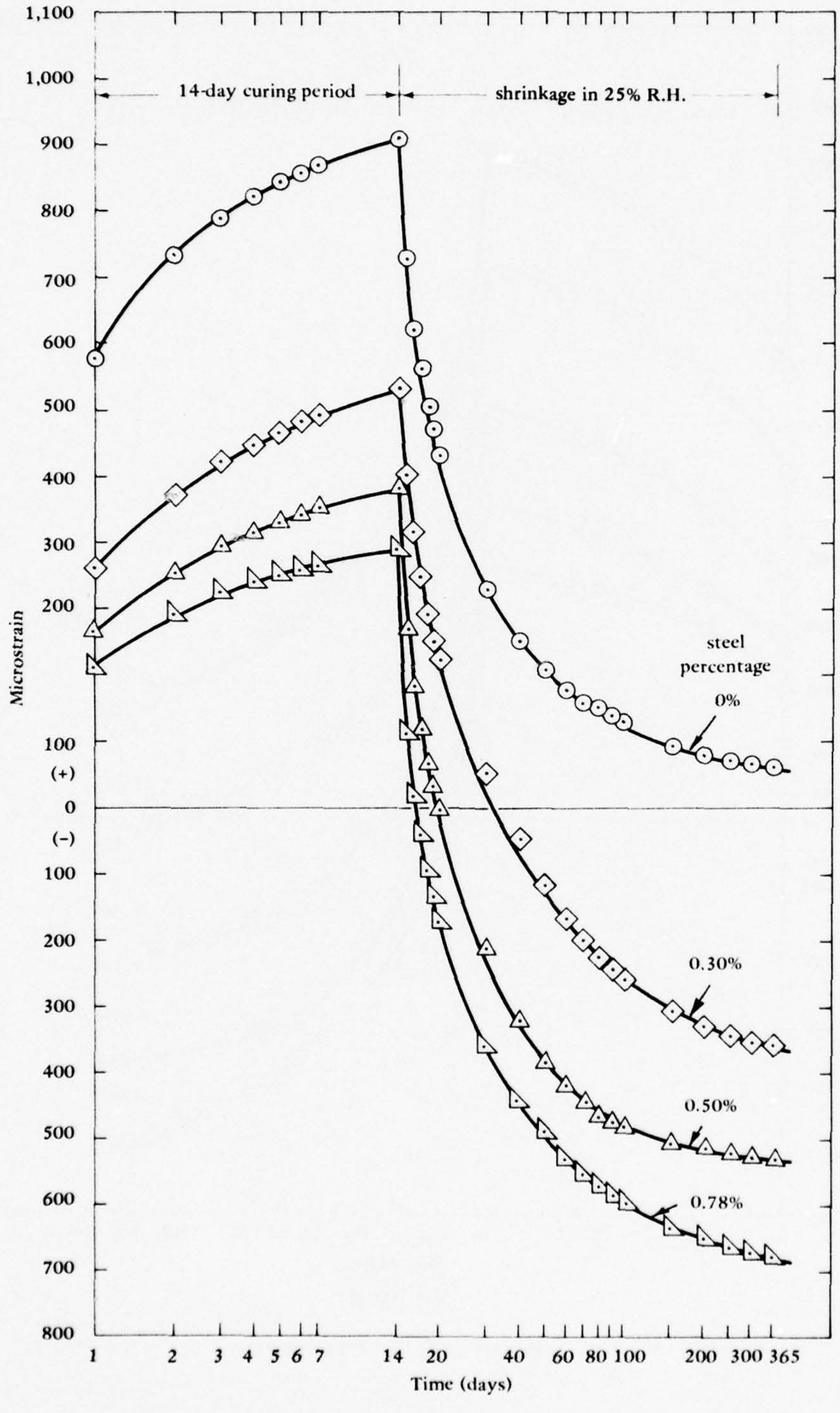
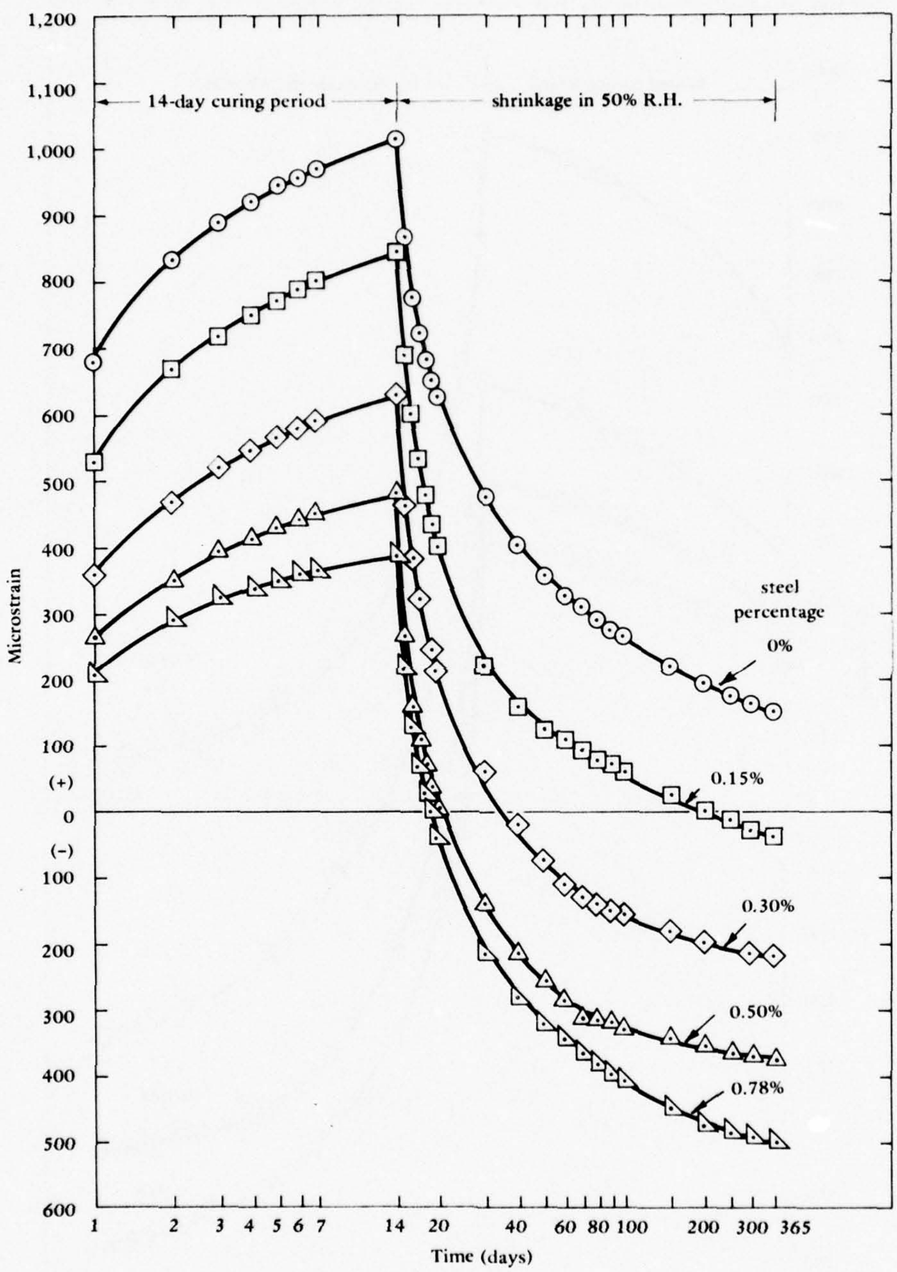


Figure 7. Strain in 1-inch thick prisms of 7.5 SC concrete after 365 days in controlled environments.



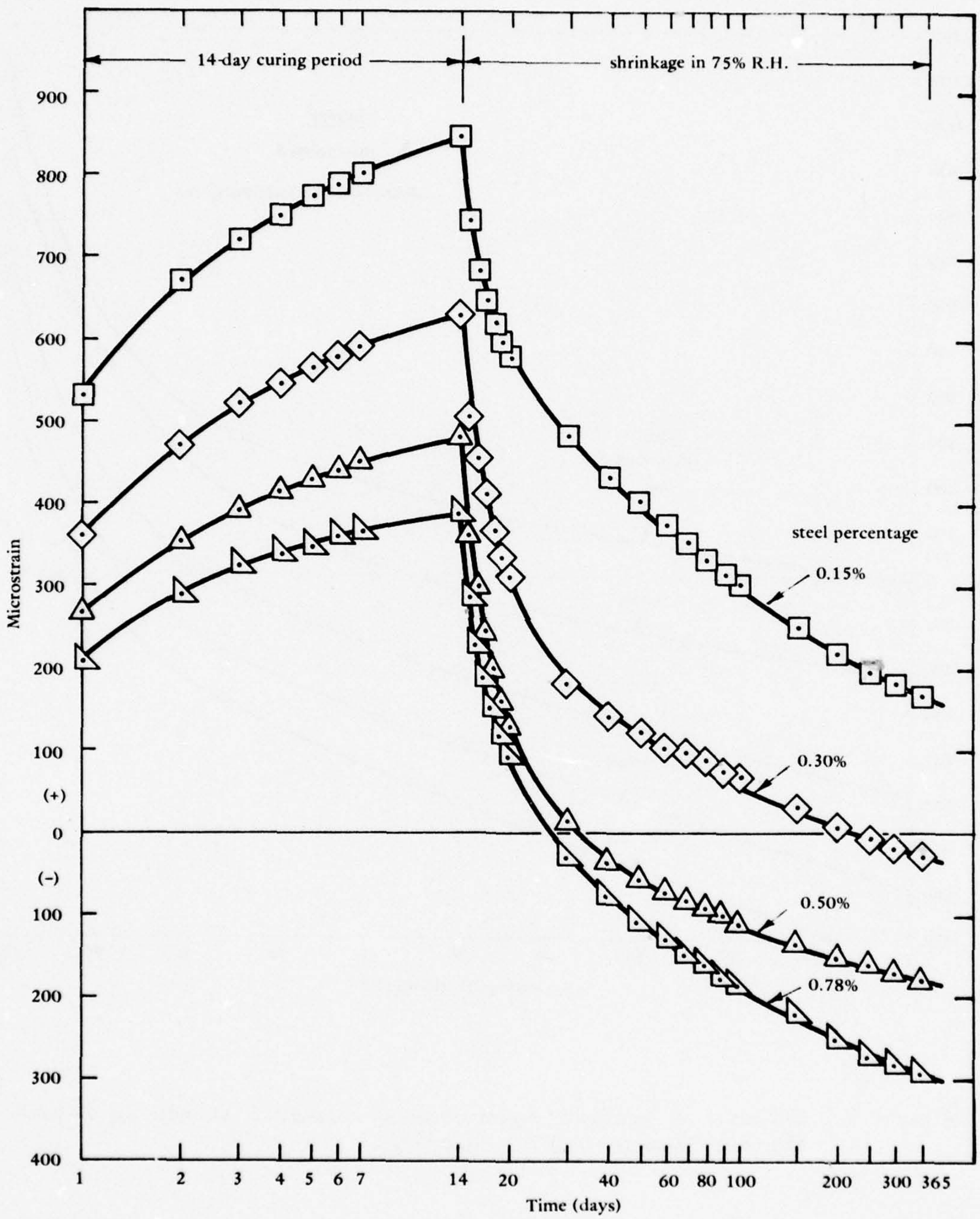
(a) 25% R.H.

Figure 8. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SC concrete.



(b) 50 R.H.

Figure 8. Continued



(c) 75% R.H.

Figure 8. Continued

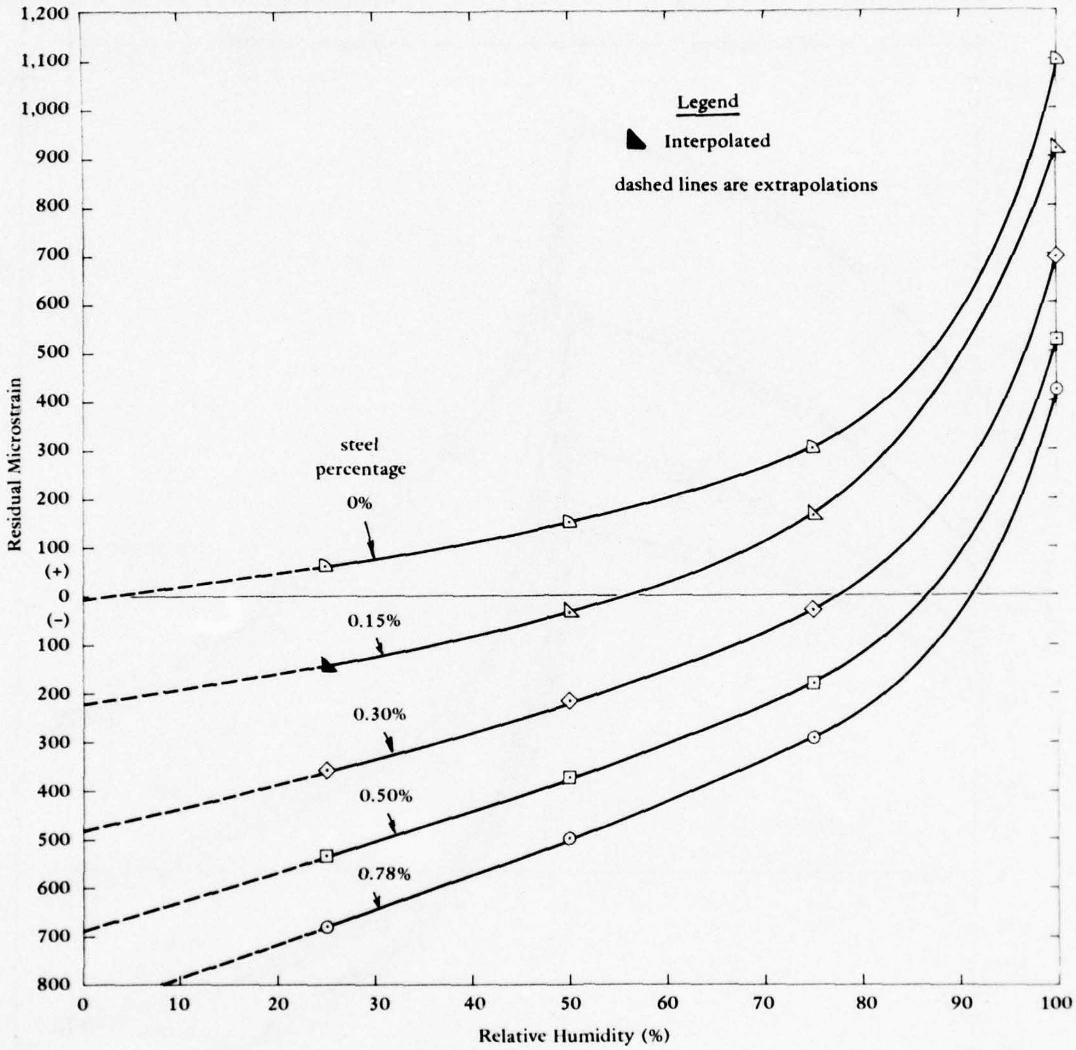


Figure 9. Effects of humidity upon 365-day residual strain in 1-inch-thick prisms of 7.5 SC concrete.

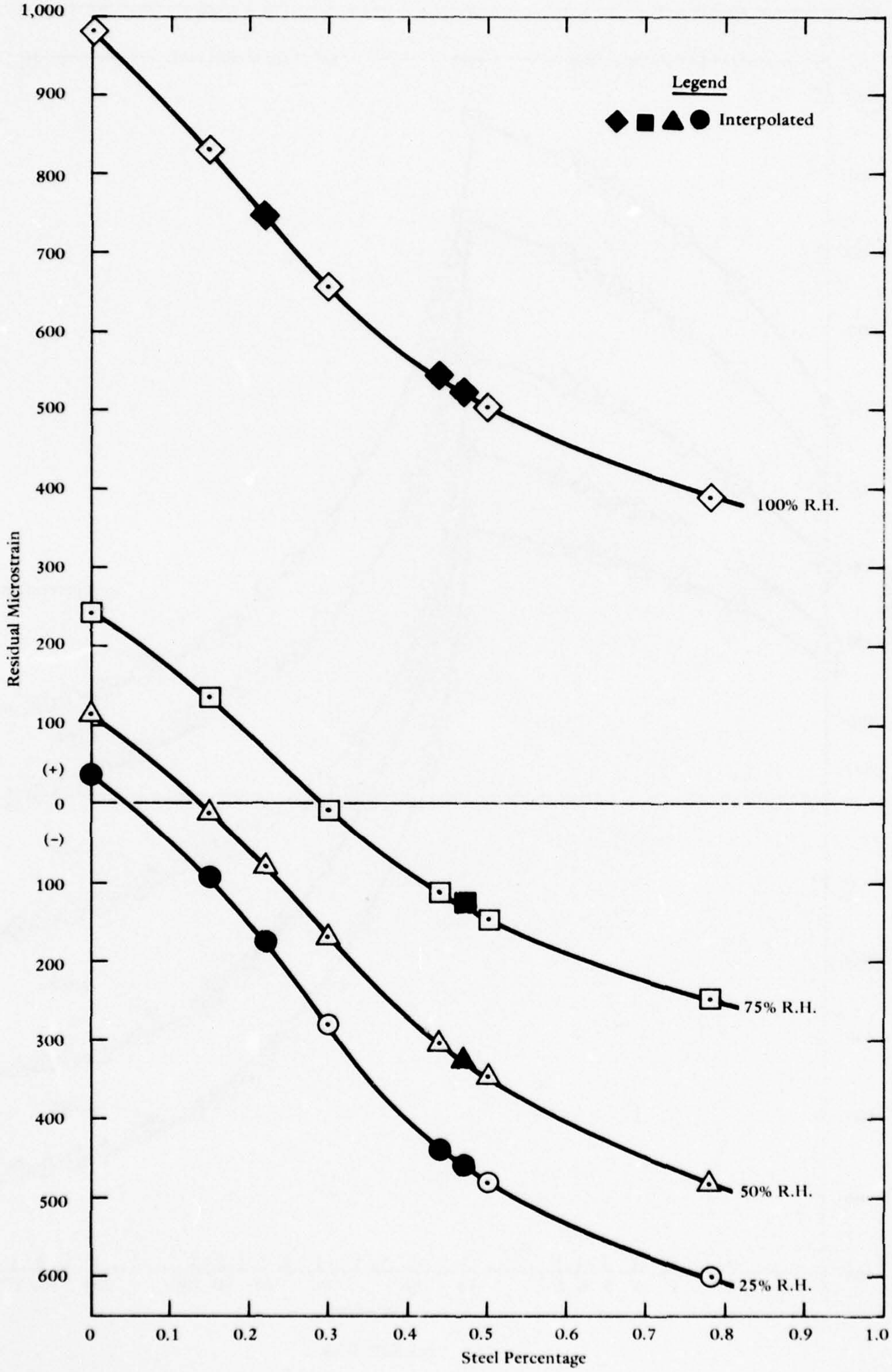
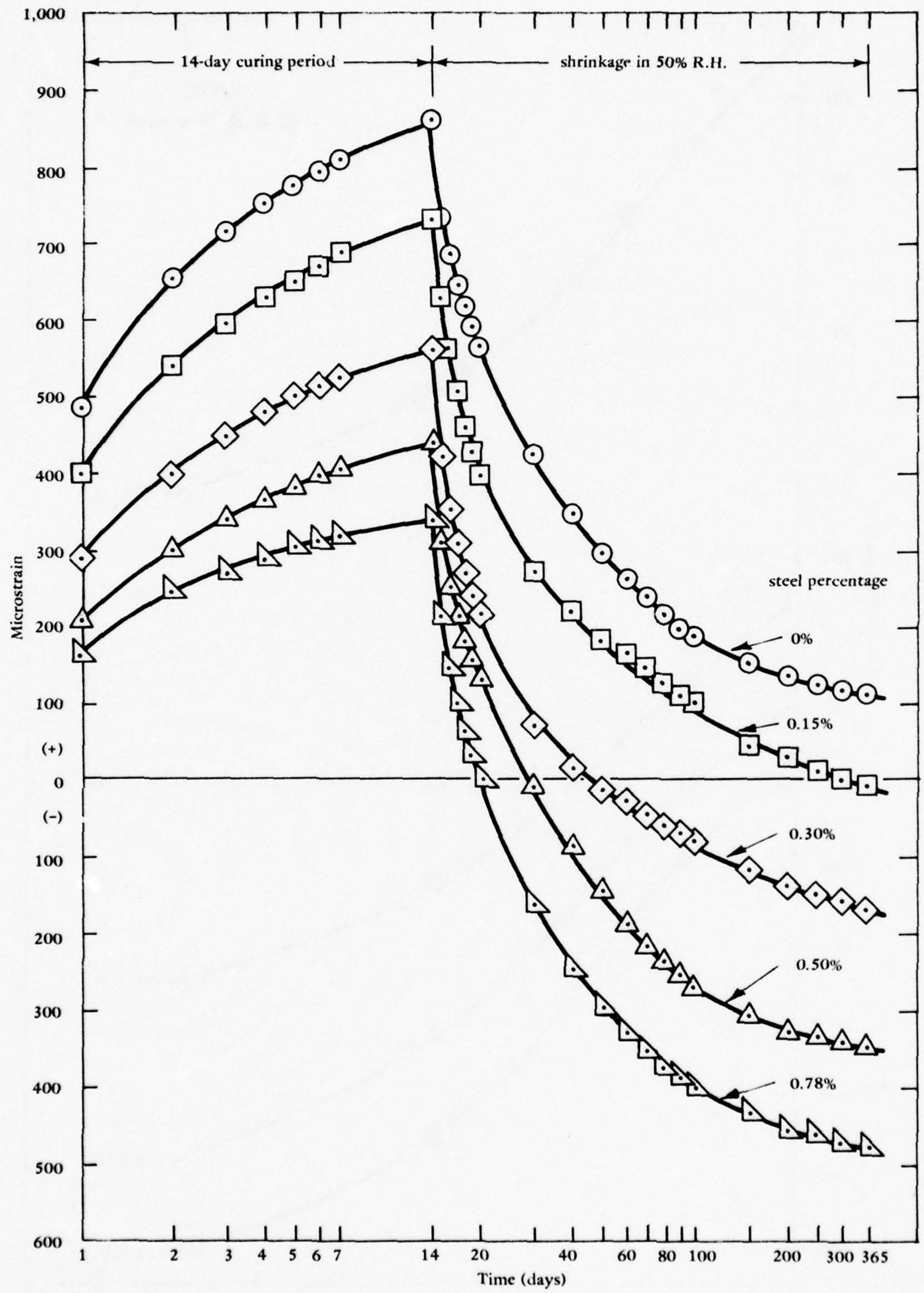
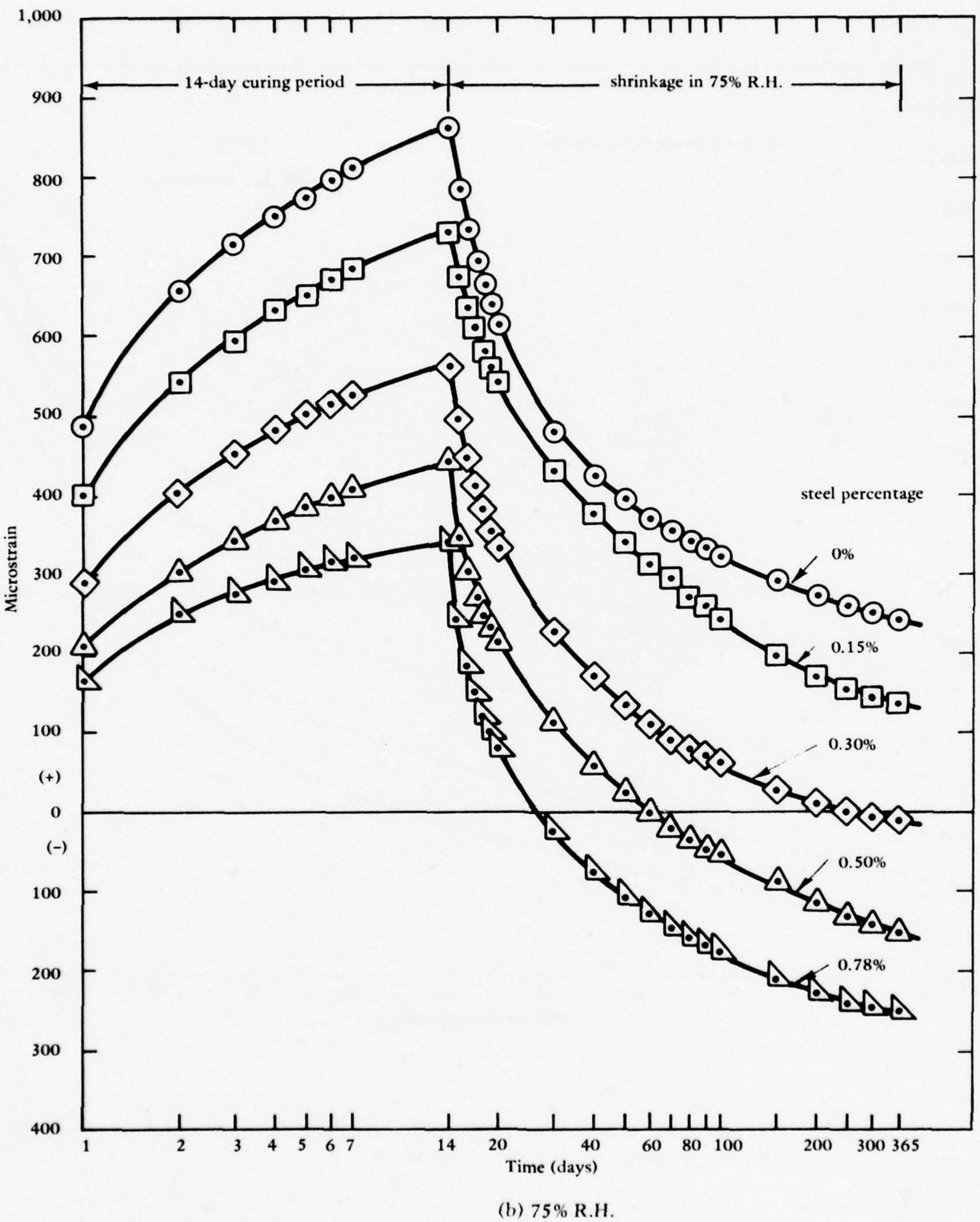


Figure 10. Strain in 2-in.-thick prisms of 7.5 SC concrete after 365 days in controlled environments.



(a) 50% R.H.

Figure 11. Expansion-shrinkage of 2-in.-thick prisms of 7.5 SC concrete.



(b) 75% R.H.

Figure 11. Continued

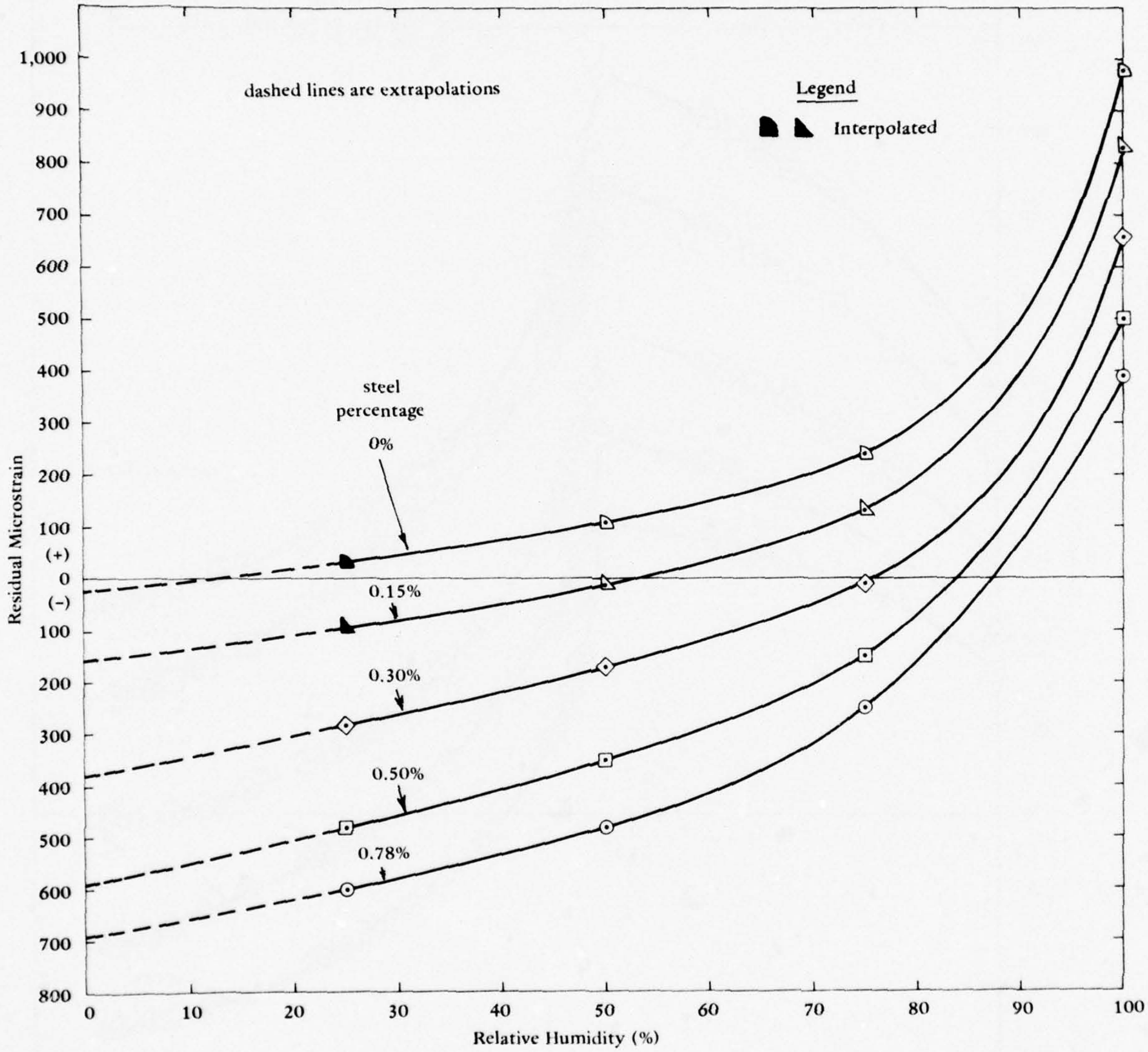


Figure 12. Effects of humidity upon 365-day residual strain in 2-inch-thick prisms of 7.5 SC concrete.

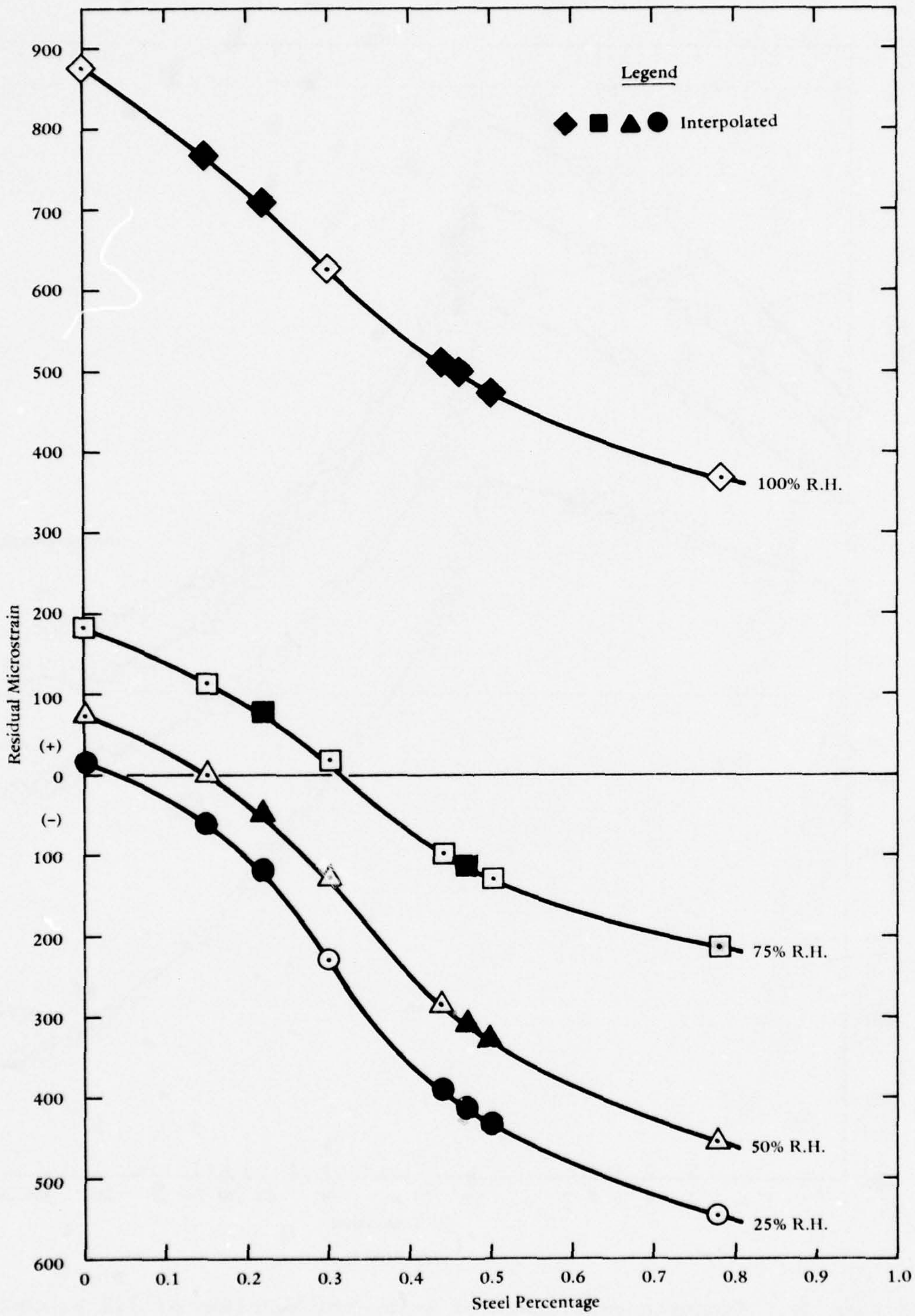
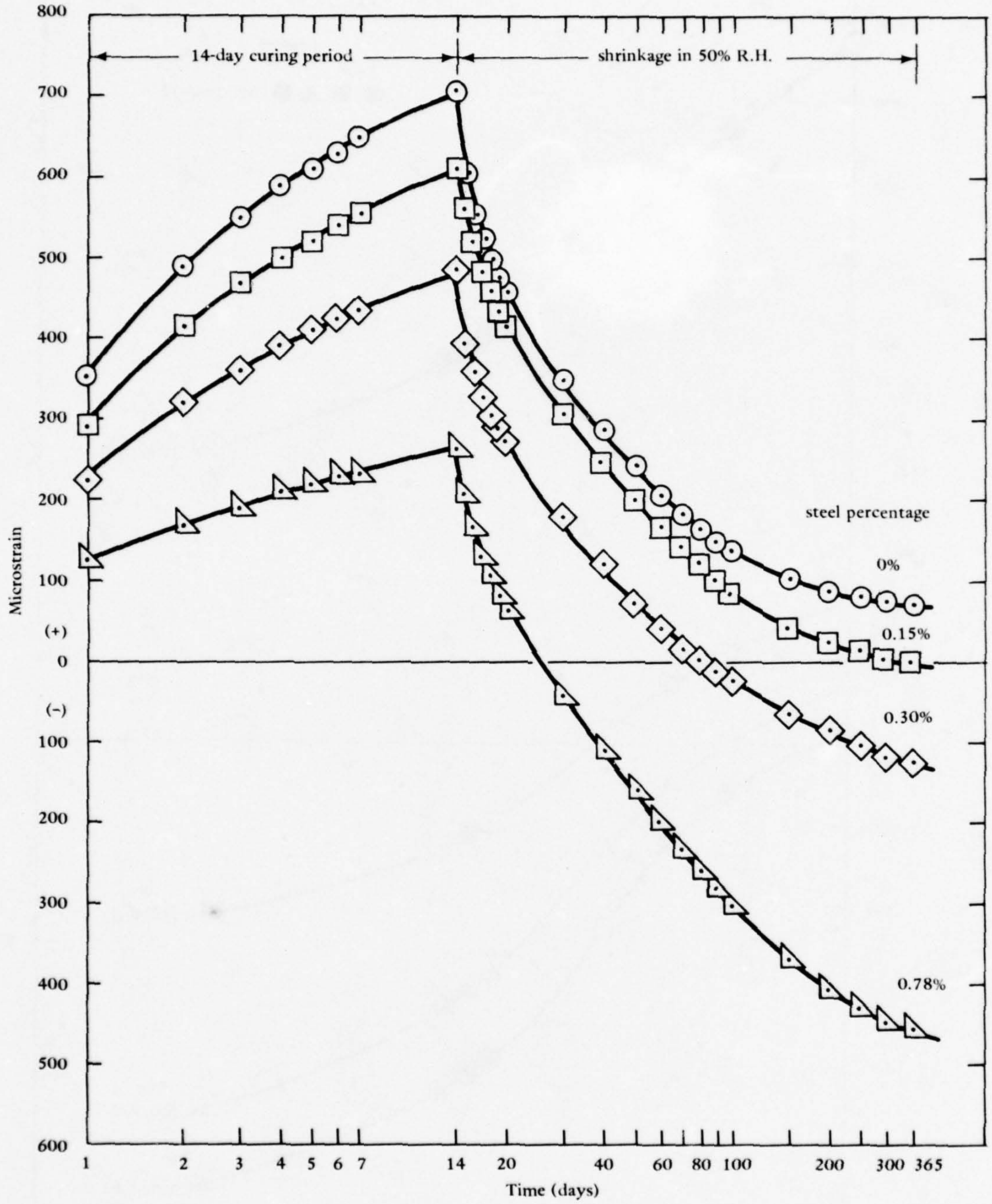
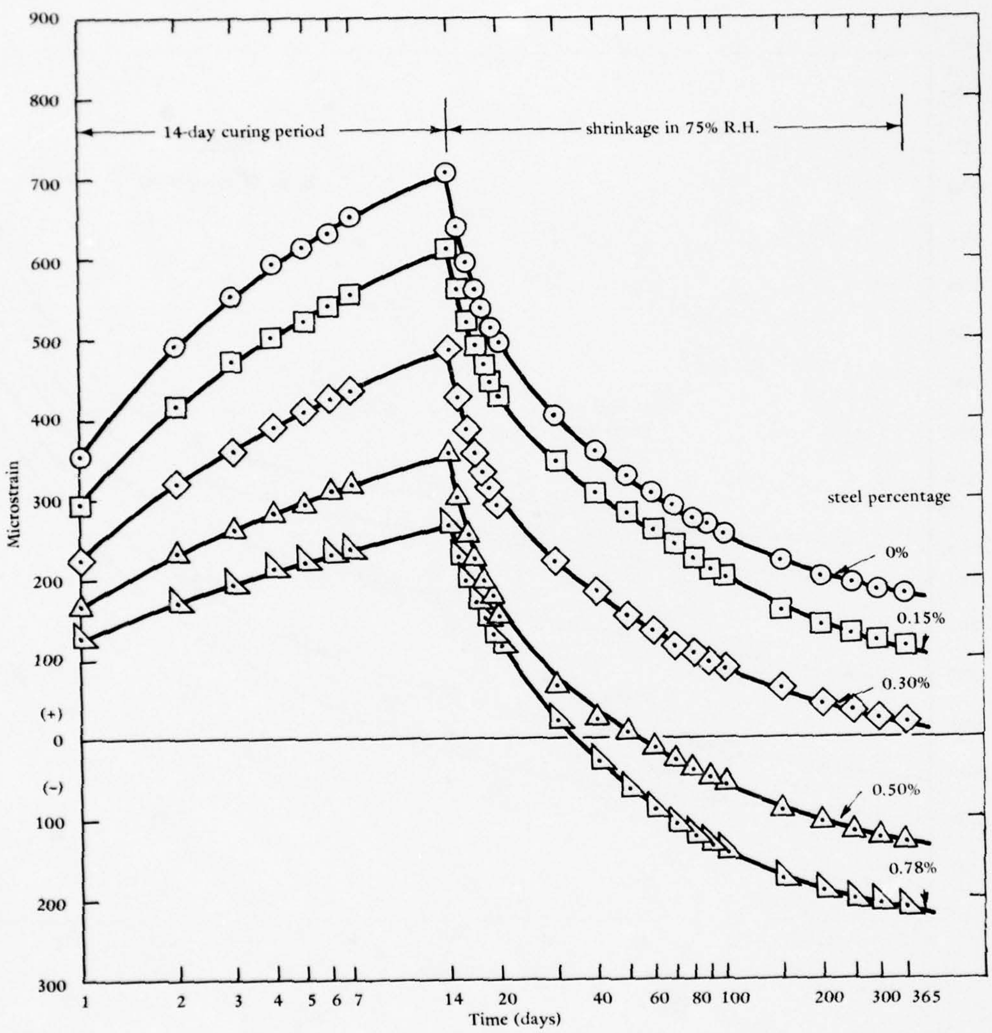


Figure 13. Strain in 4-in.-thick prisms of 7.5 SC concrete after 365 days in controlled environments.



(a) 50% R.H.

Figure 14. Expansion-shrinkage of 4-in.-thick prisms of 7.5 SC concrete.



(b) 75% R.H.

Figure 14. Continued

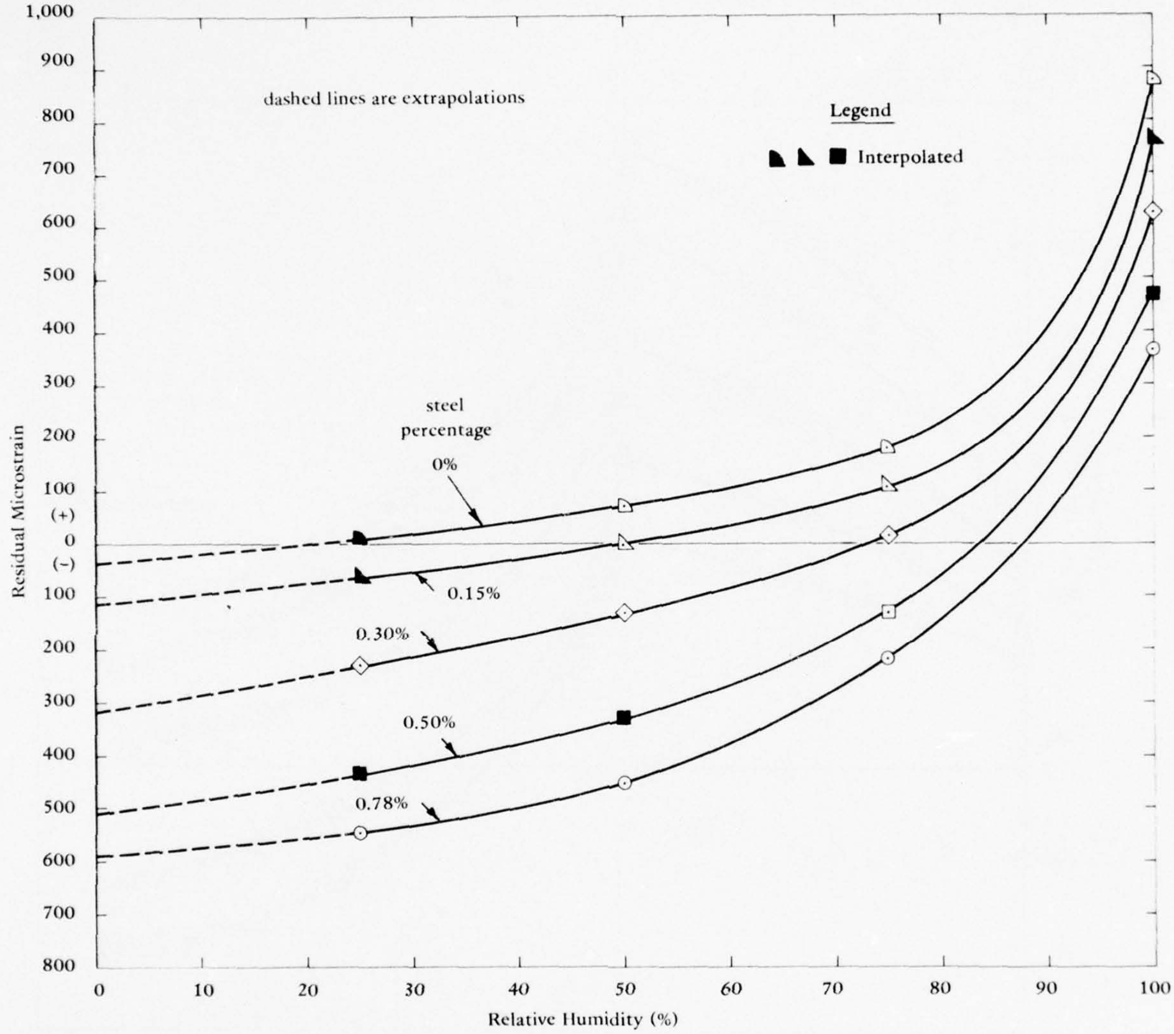
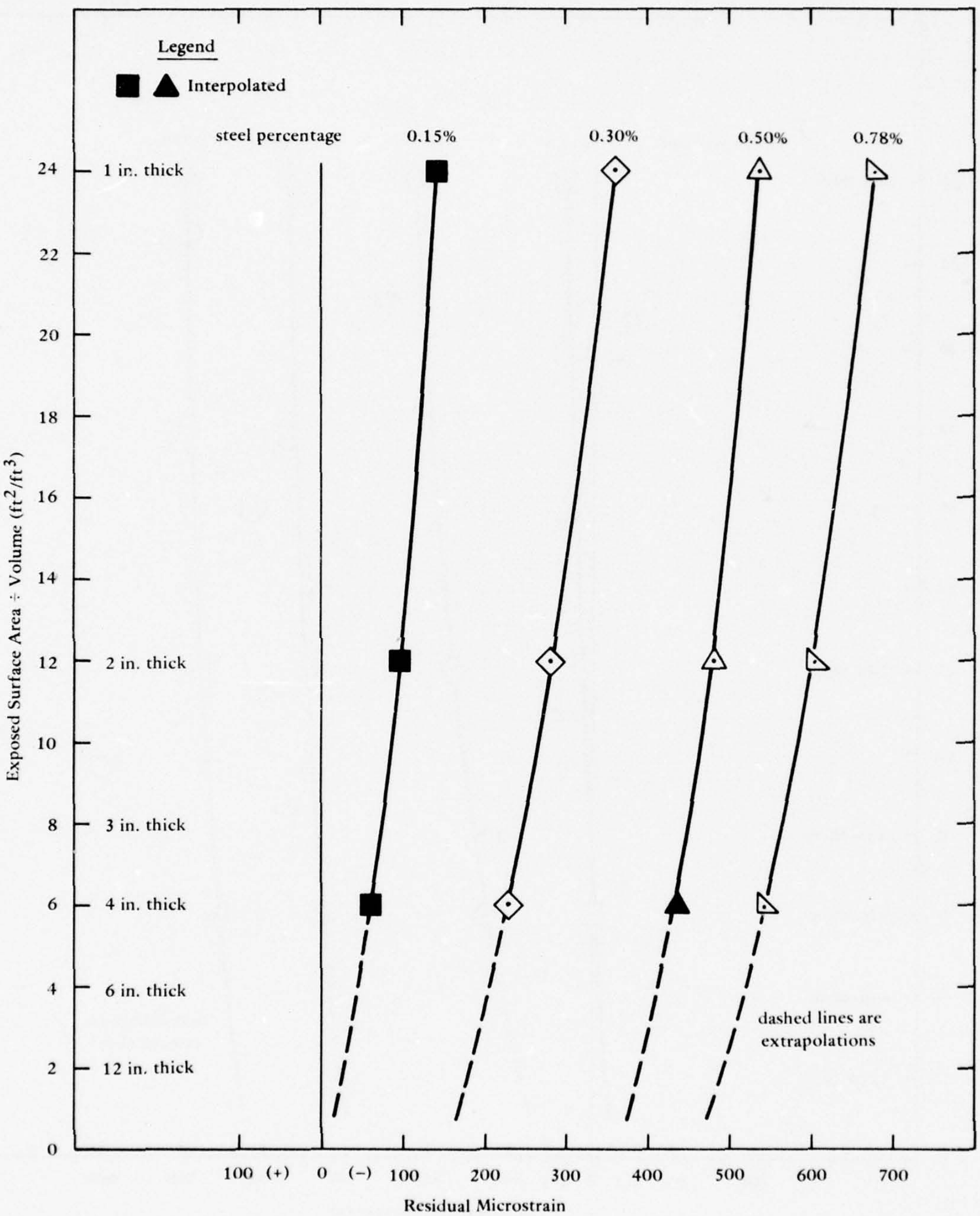
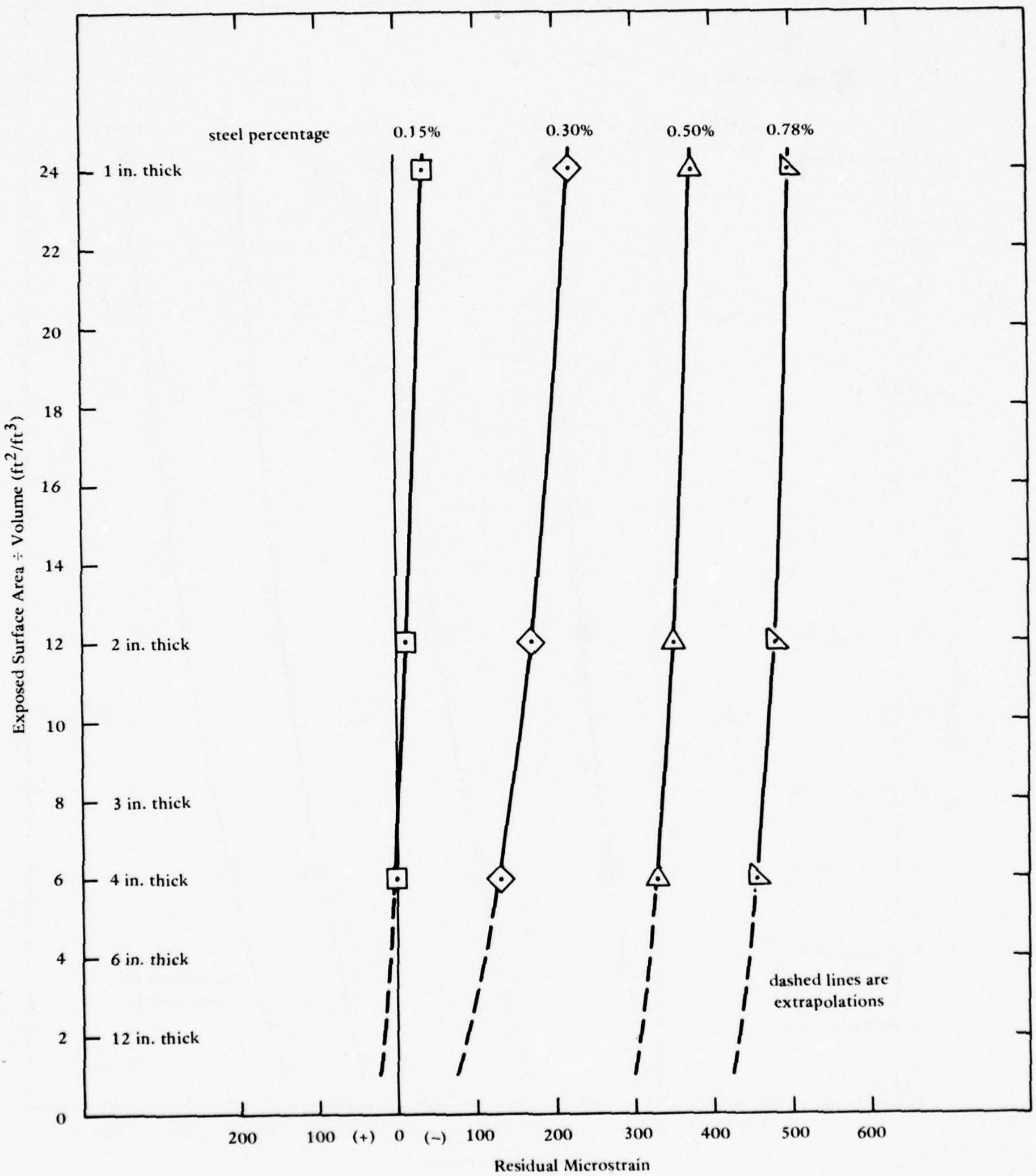


Figure 15. Effects of humidity upon 365-day residual strain in 4-in.-thick prisms of 7.5 SC concrete.



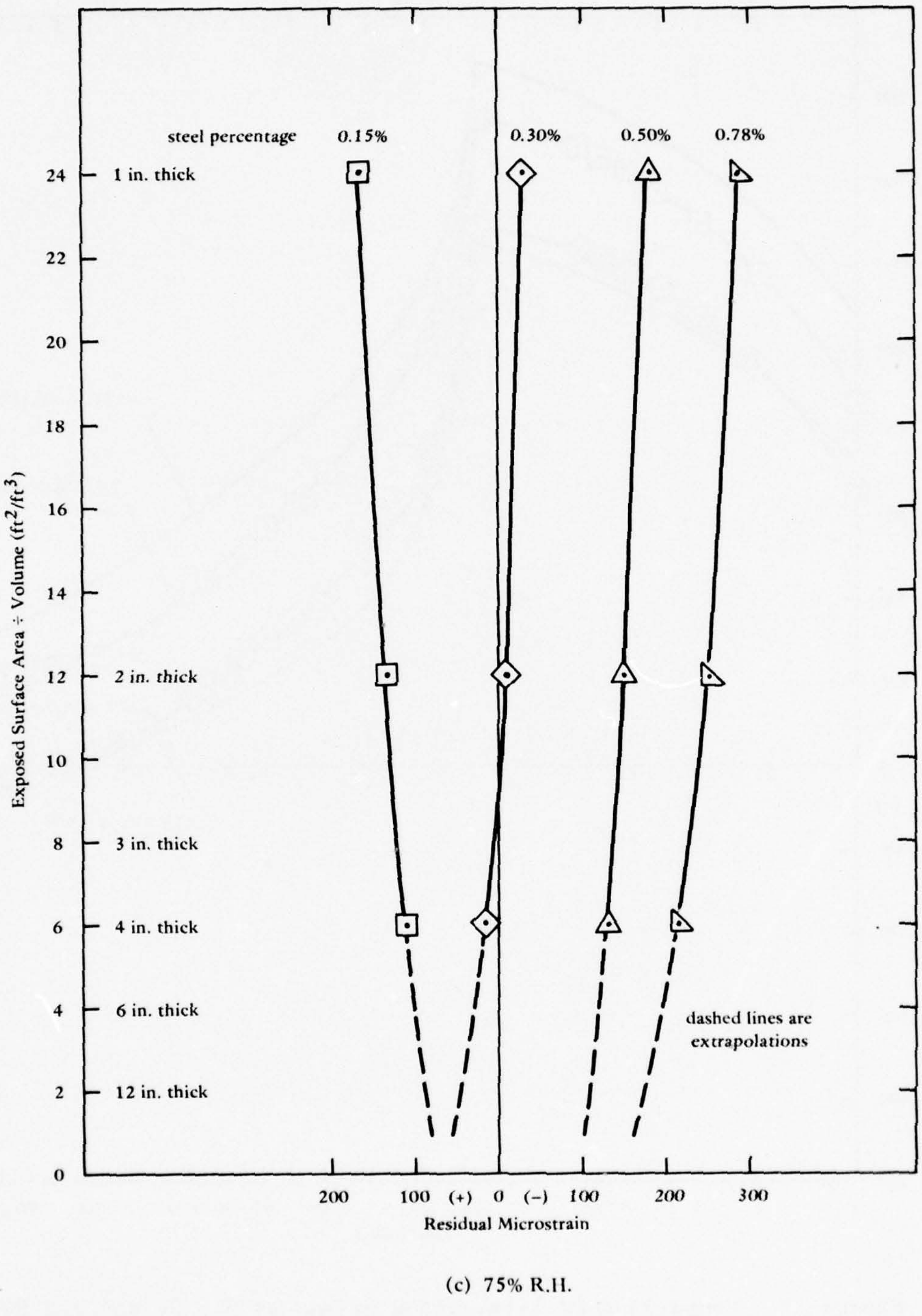
(a) 25% R.H.

Figure 16. Residual strain as a function of S/V for 7.5 SC concrete.



(b) 50% R.H.

Figure 16. Continued



(c) 75% R.H.

Figure 16. Continued

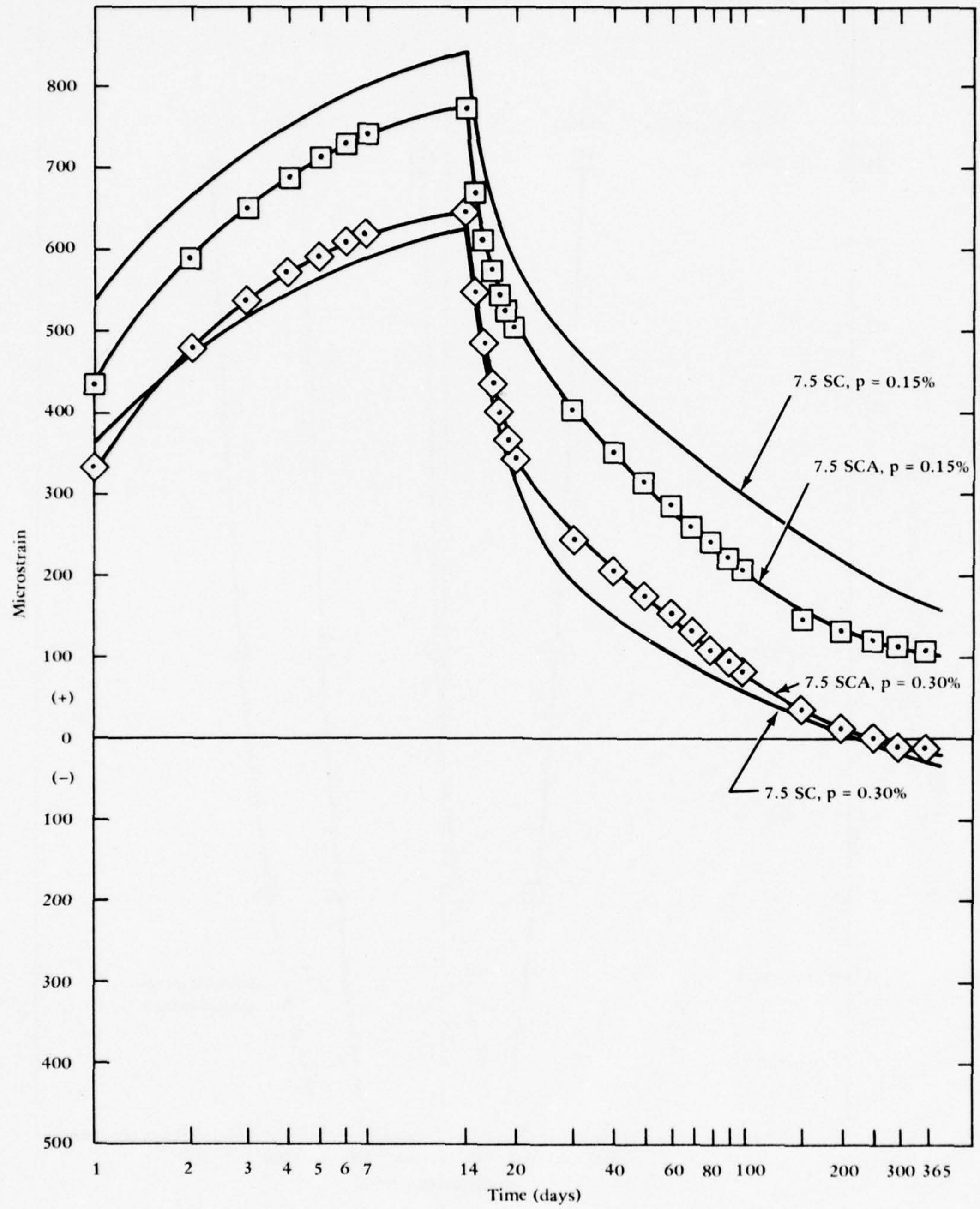
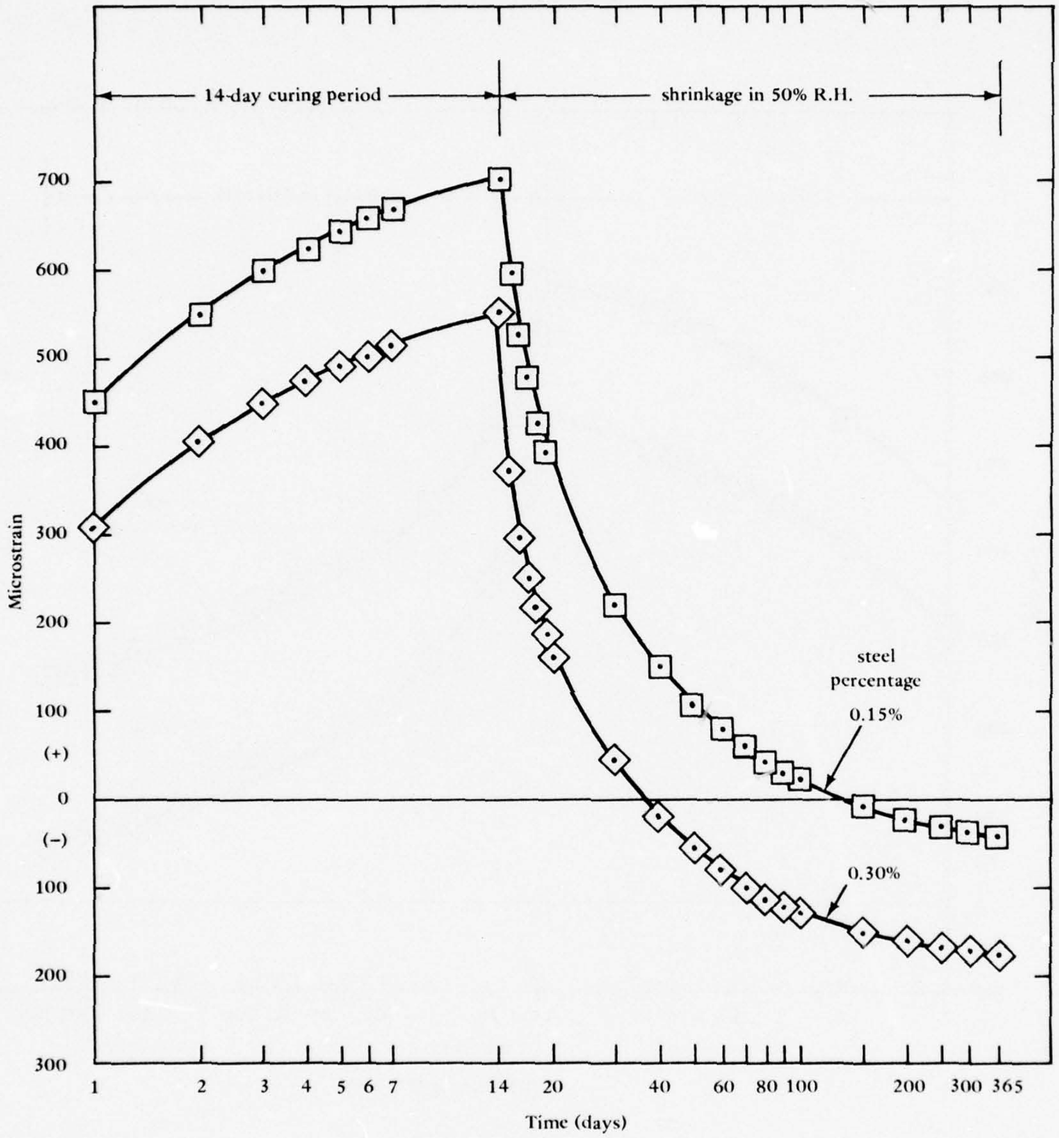
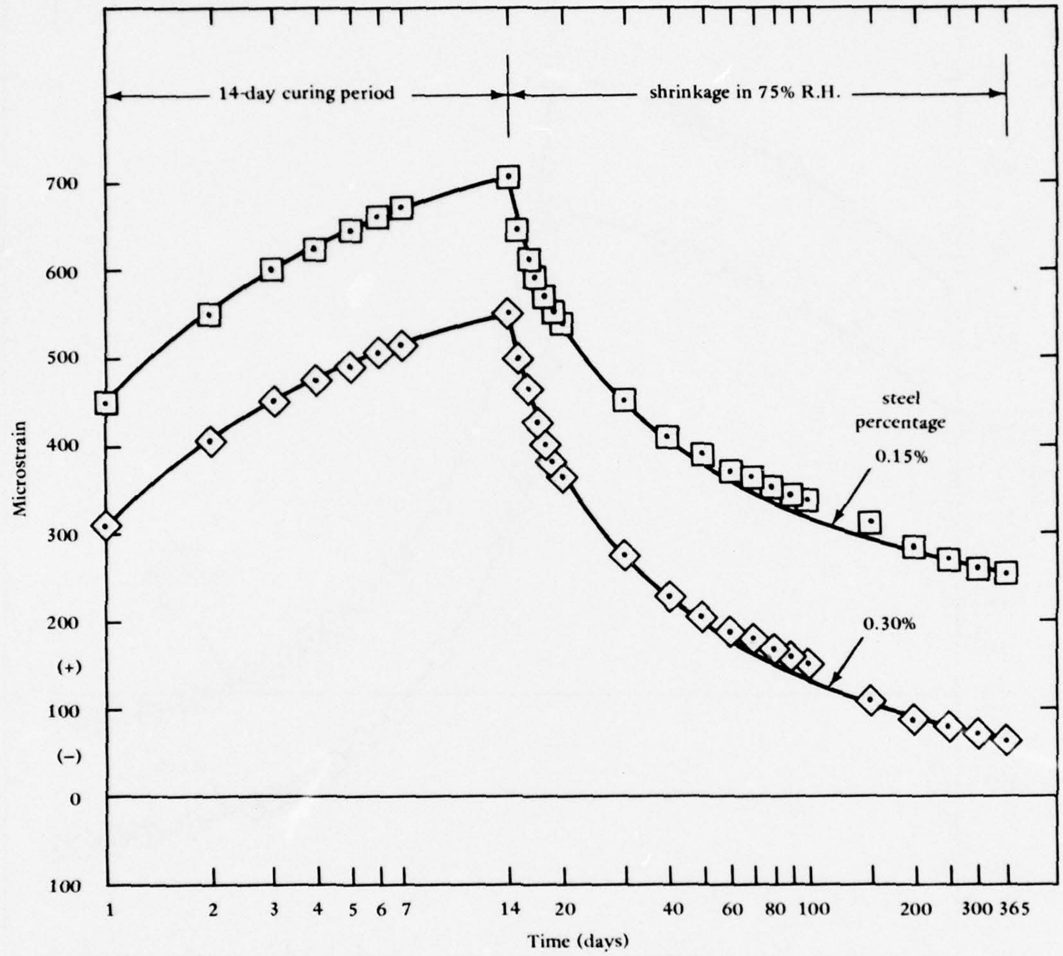


Figure 17. Comparison of 1-in.-thick prisms of 7.5 SC and 7.5 SCA concretes in 75% R.H.



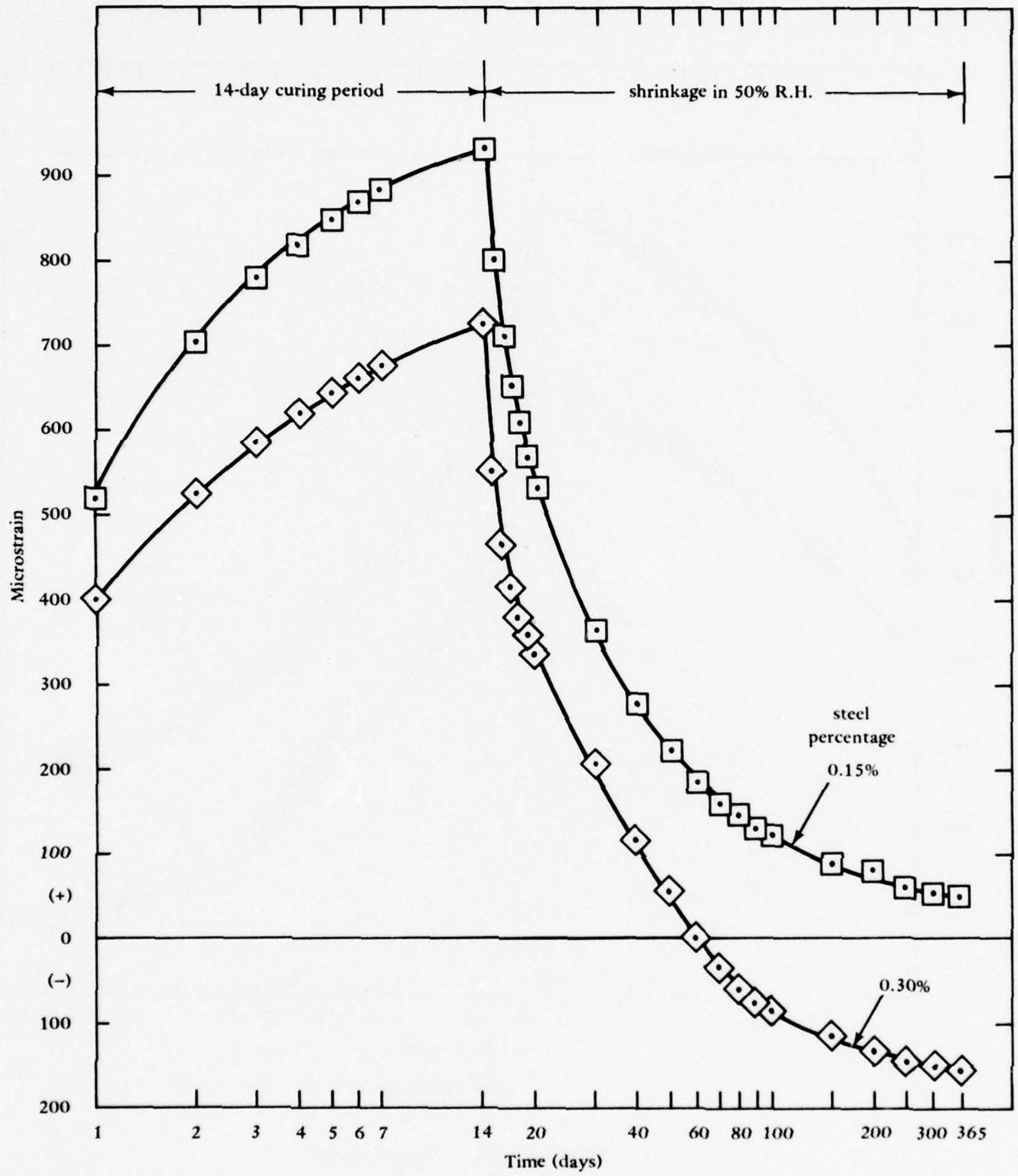
(a) 50% R.H.

Figure 18. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SC-L concrete.



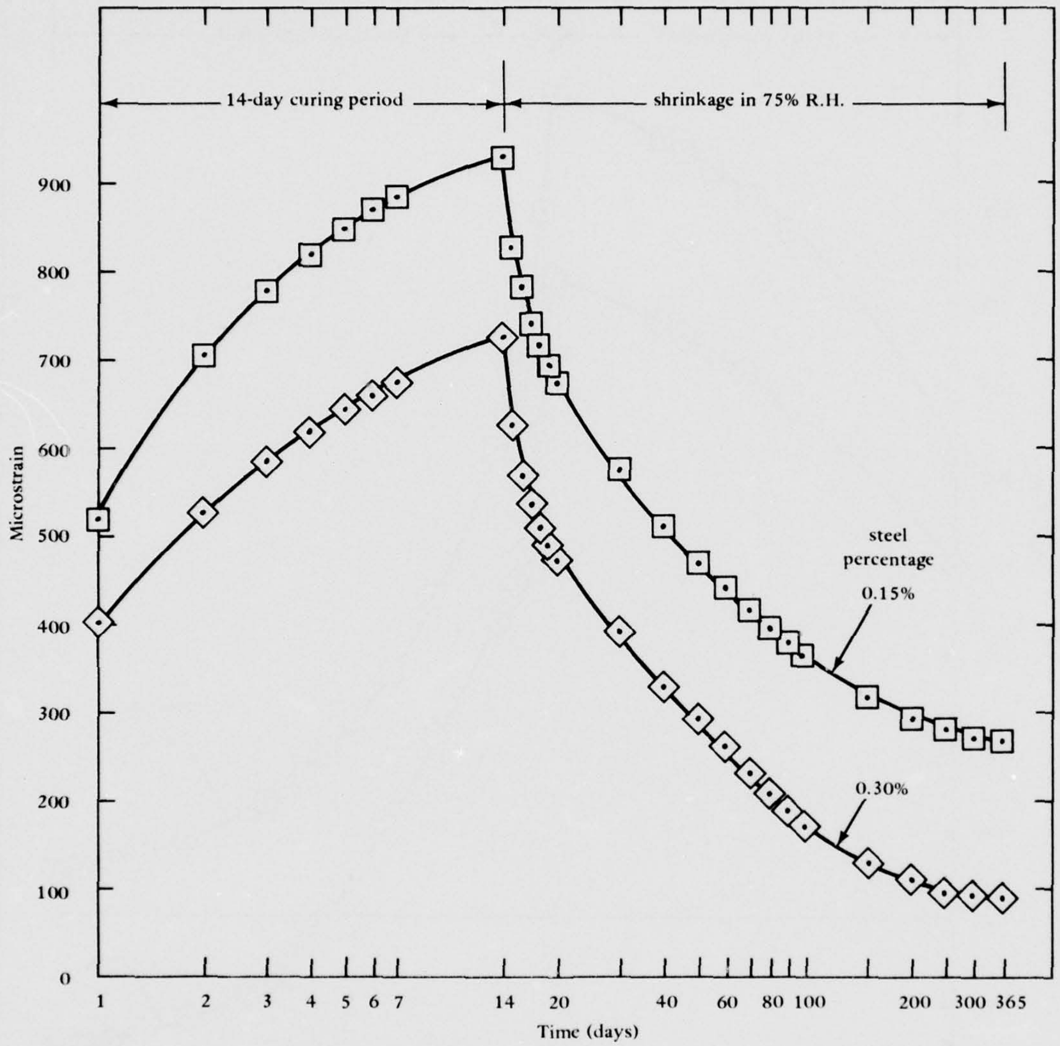
(b) 75% R.H.

Figure 18. Continued



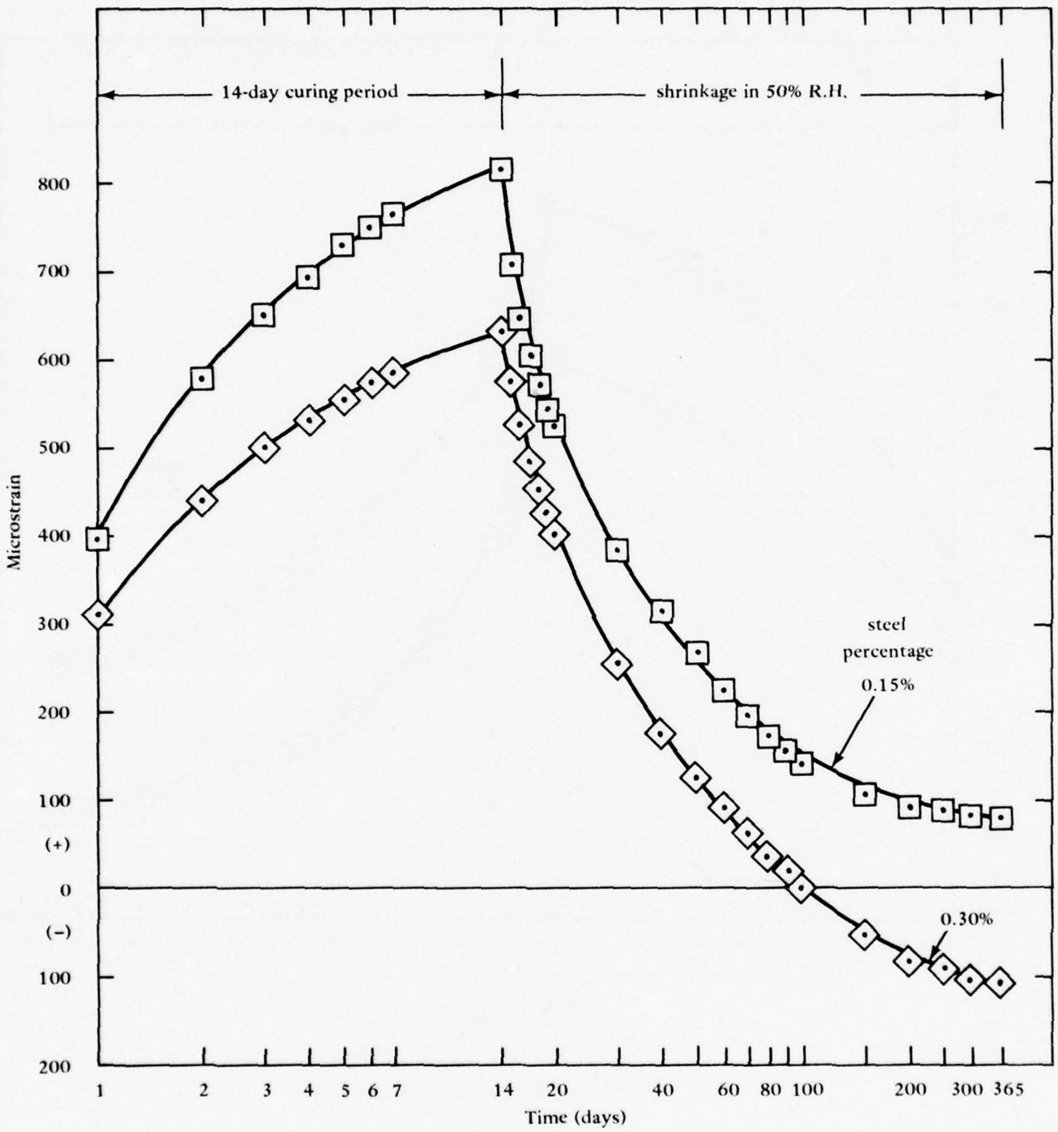
(a) 50% R.H.

Figure 19. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SCA-SLW concrete.



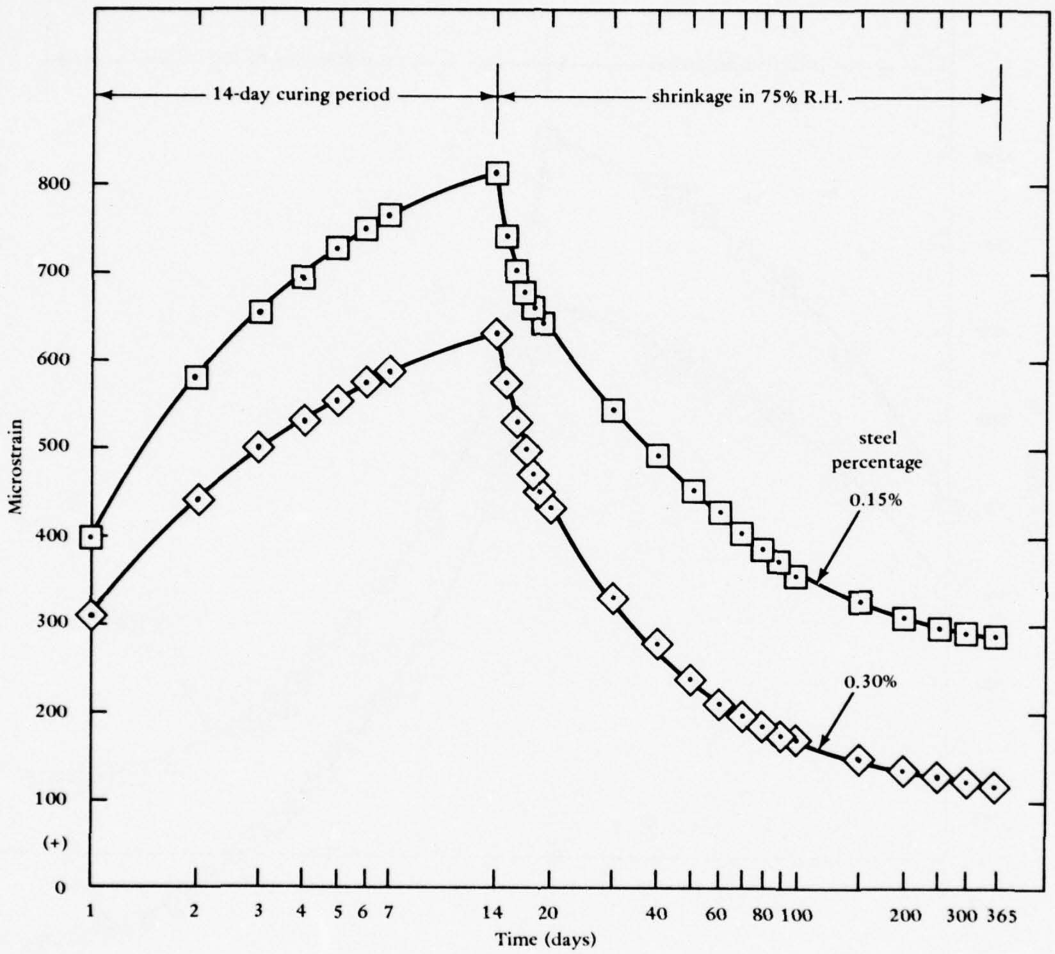
(b) 75% R.H.

Figure 19. Continued



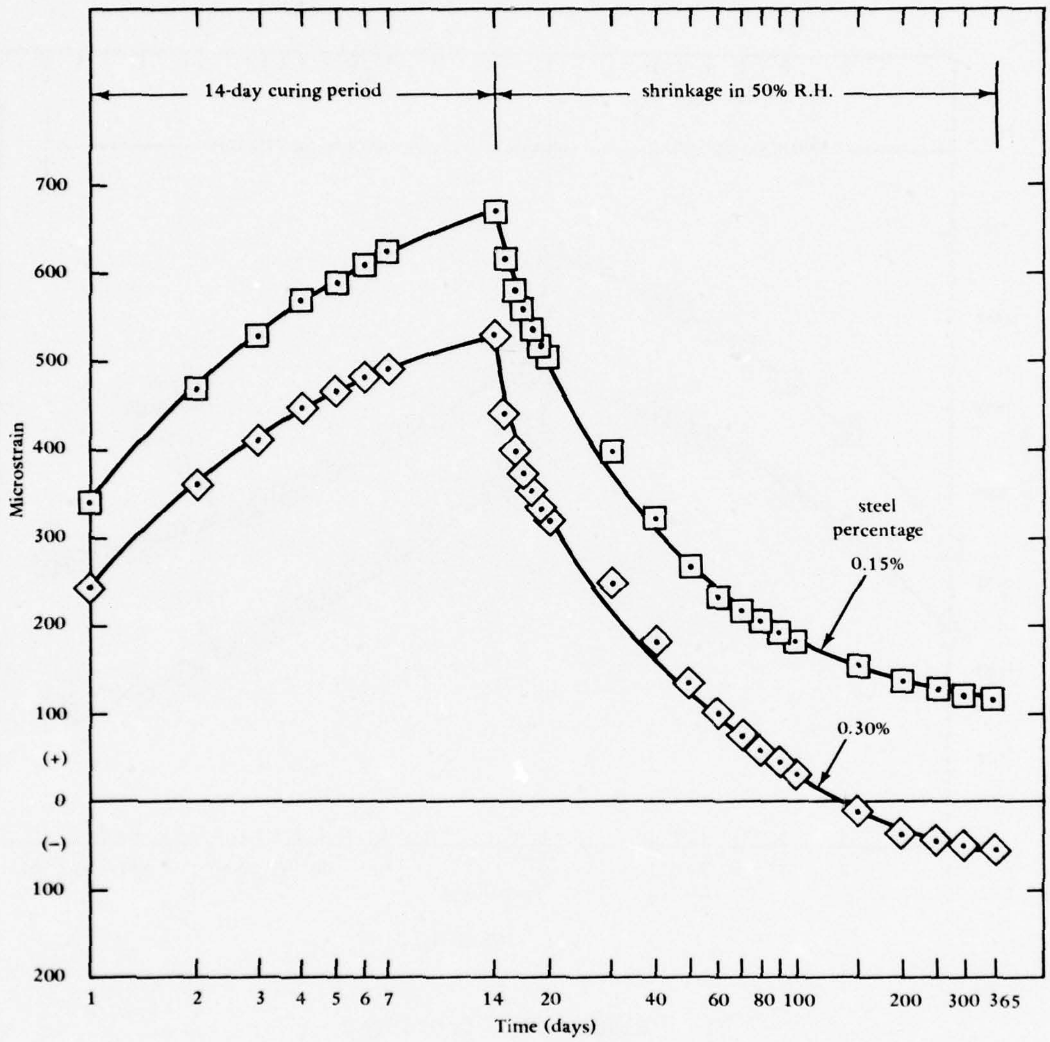
(a) 50% R.H.

Figure 20. Expansion-shrinkage of 2-in.-thick prisms of 7.5 SCA-SLW concrete.



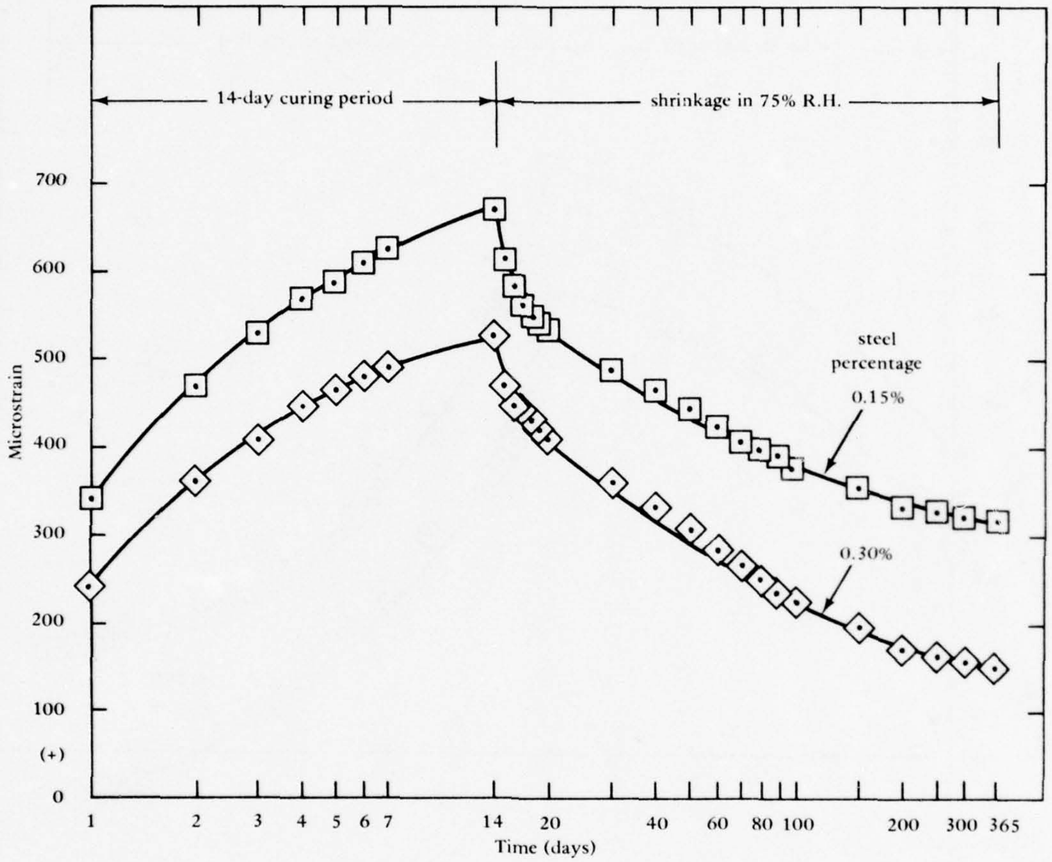
(b) 75% R.H.

Figure 20. Continued



(a) 50% R.H.

Figure 21. Expansion-shrinkage of 4-in.-thick prisms of 7.5 SCA-SLW concrete.



(b) 75% R.H.

Figure 21. Continued

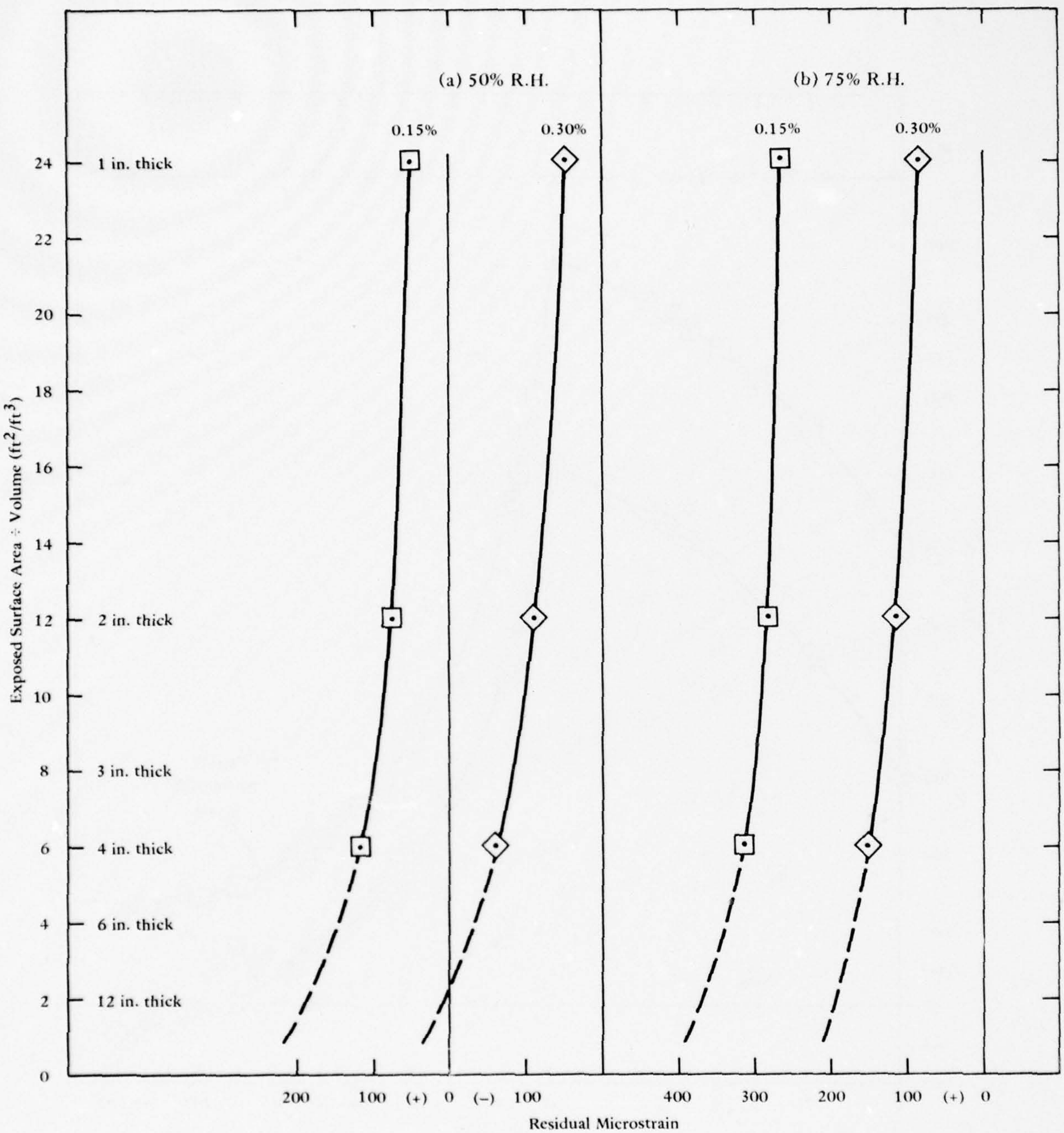
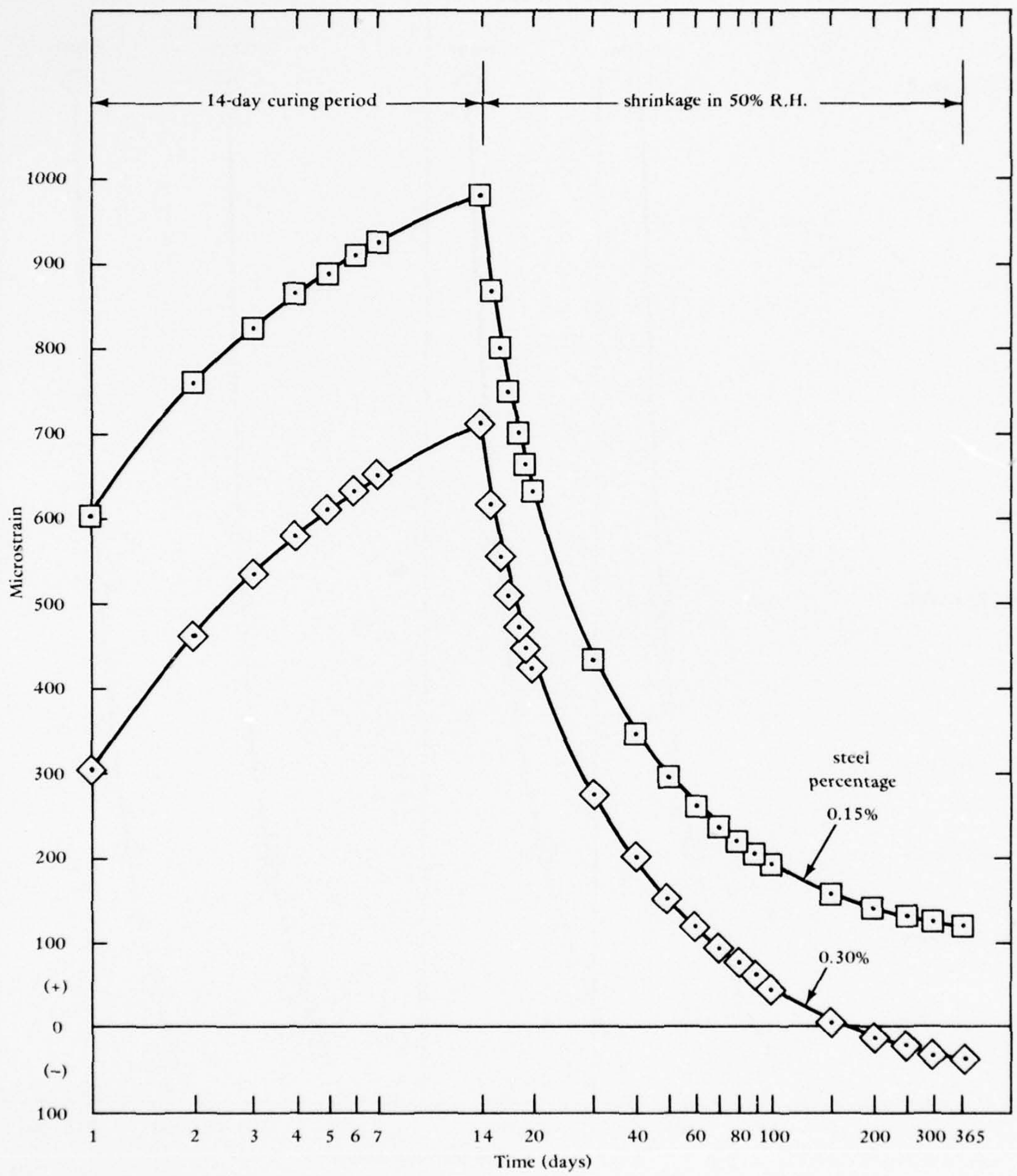
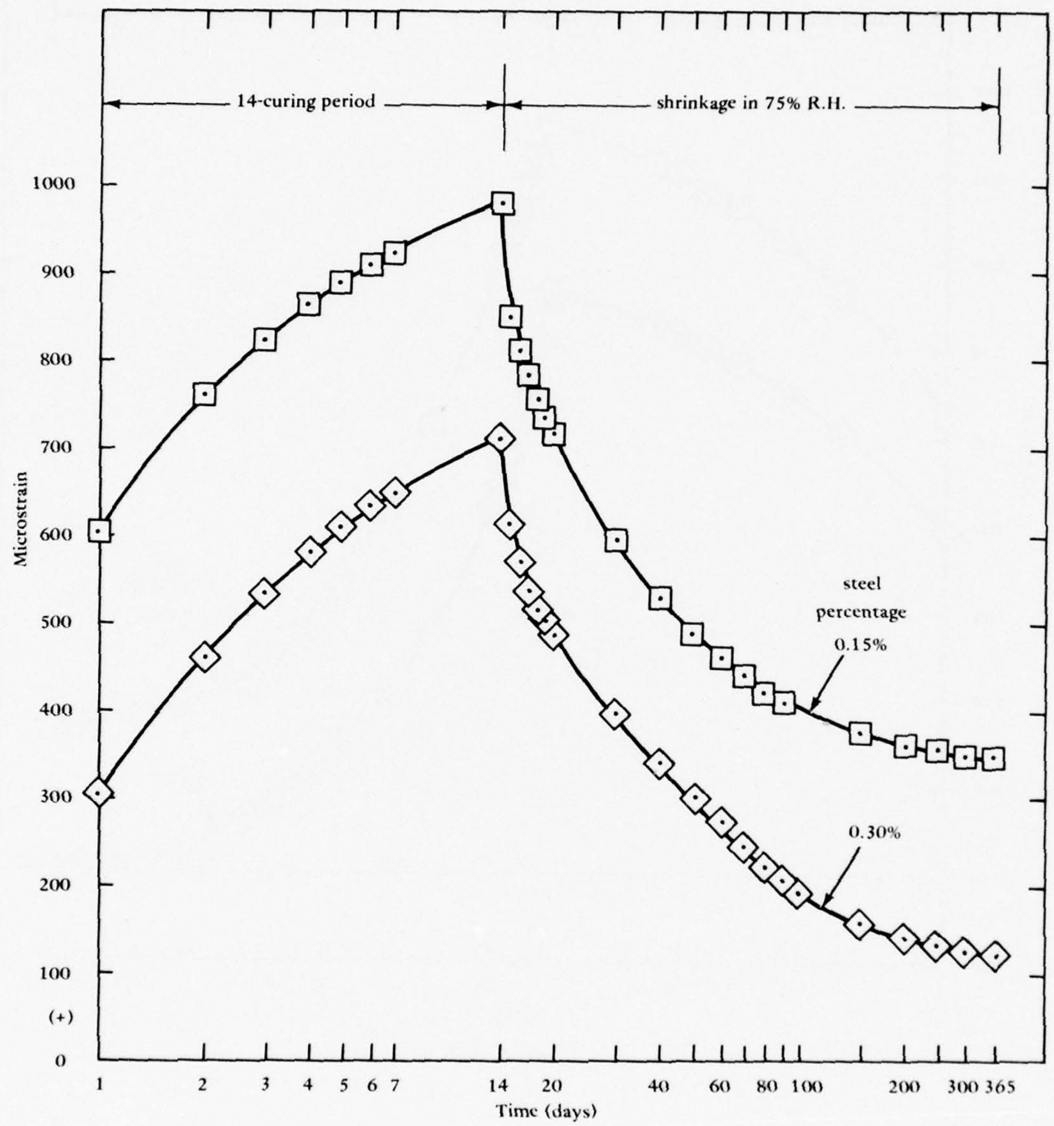


Figure 22. Residual strain after 365 days as a function of S/V for SCA-SLW concrete.



(a) 50% R.H.

Figure 23. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SCA-LW concrete.



(b) 75% R.H.

Figure 23. Continued

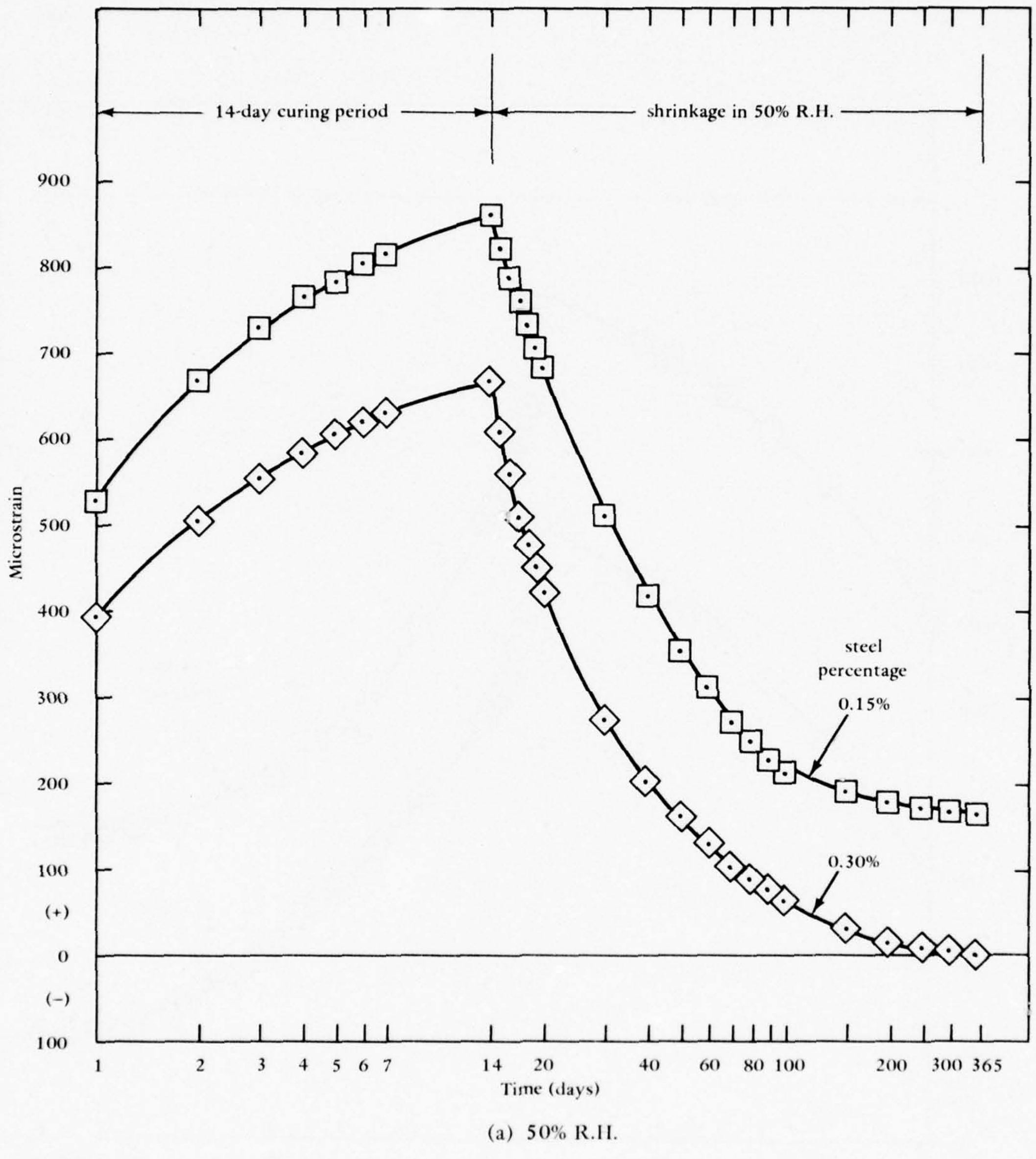
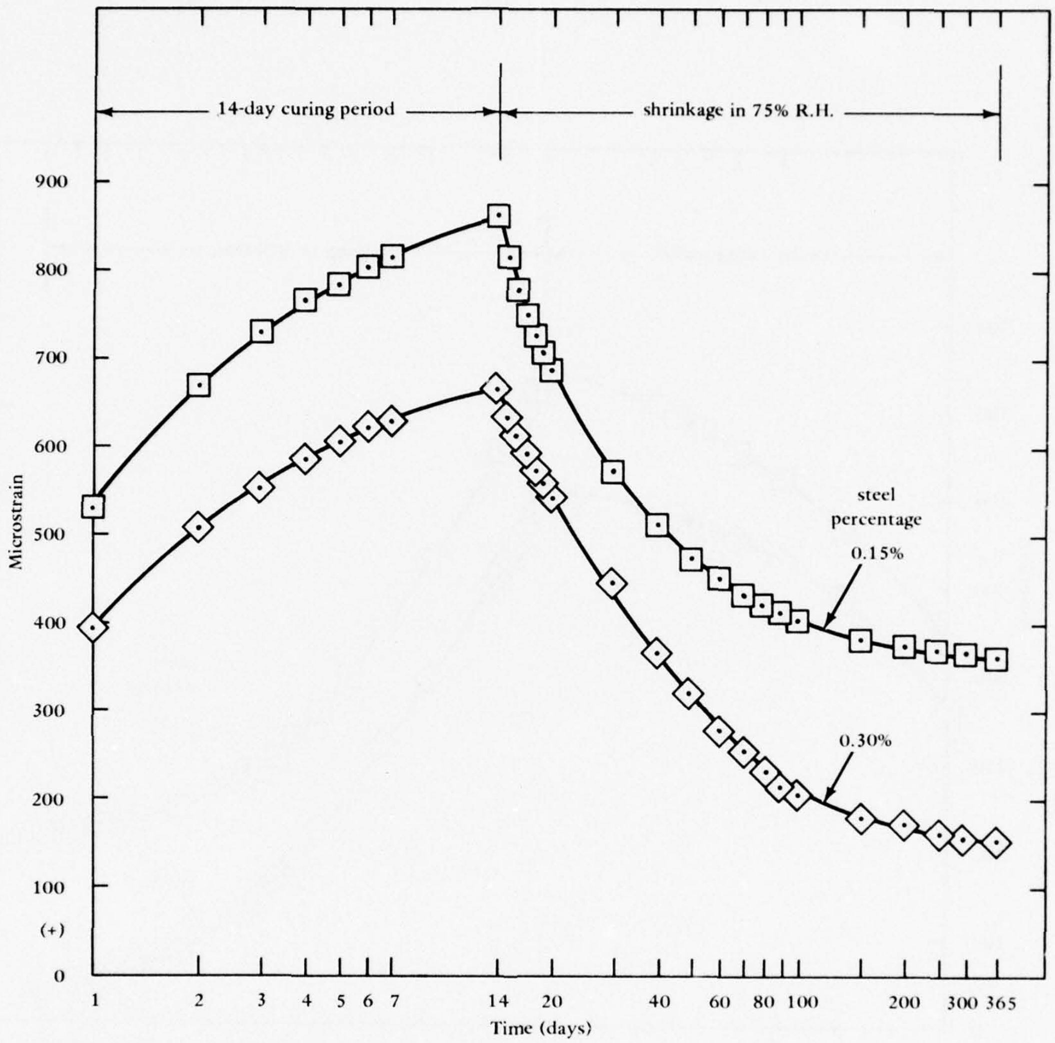
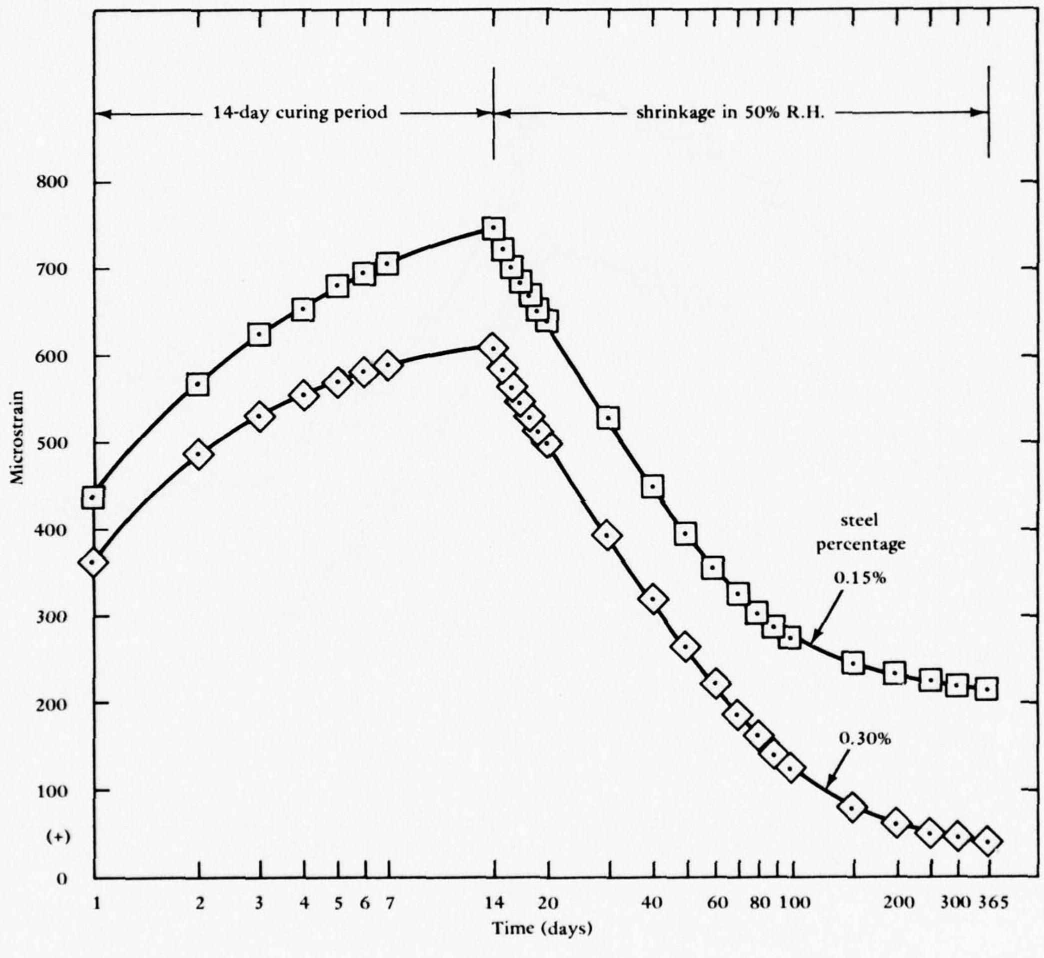


Figure 24. Expansion-shrinkage of 2-in.-thick prisms of 7.5 SCA-LW concrete.



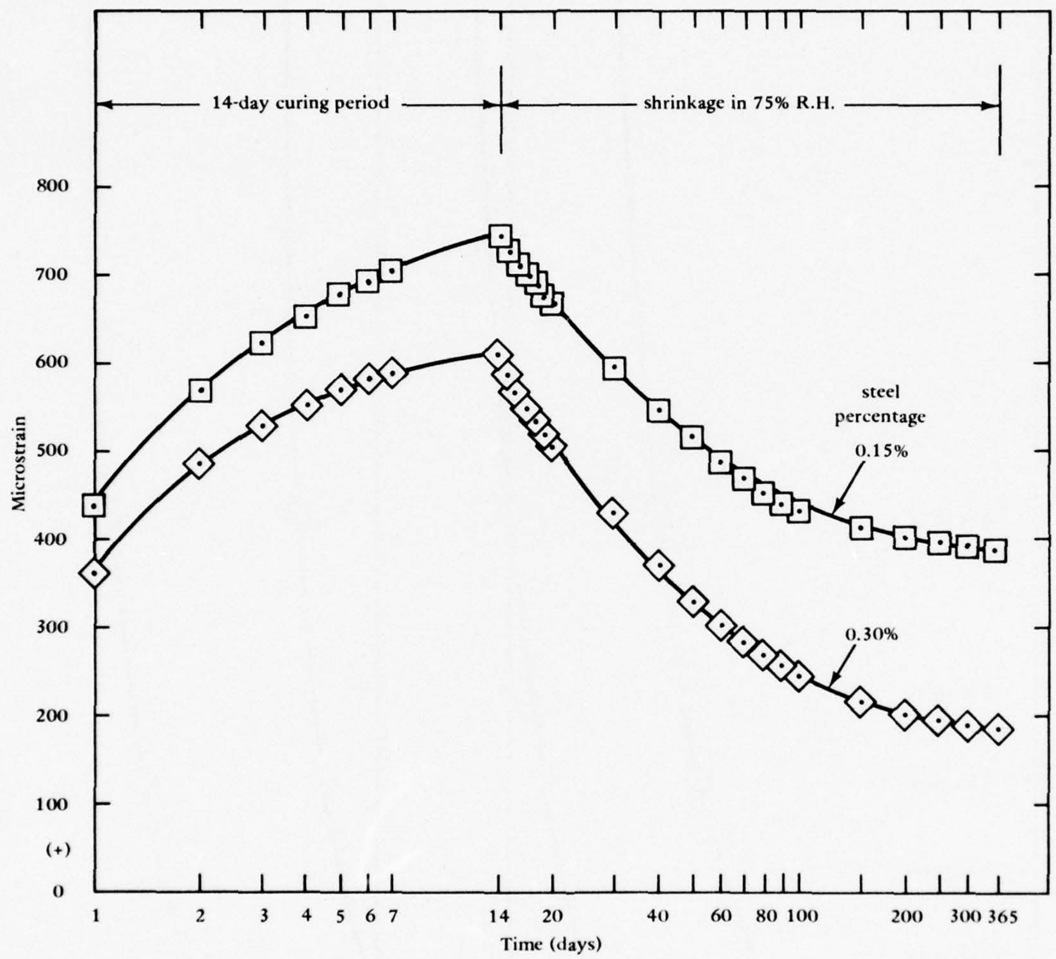
(b) 75% R.H.

Figure 24. Continued



(a) 50% R.H.

Figure 25. Expansion-shrinkage of 4-in.-thick prisms of 7.5 SCA-LW concrete.



(b) 75% R.H.

Figure 25. Continued

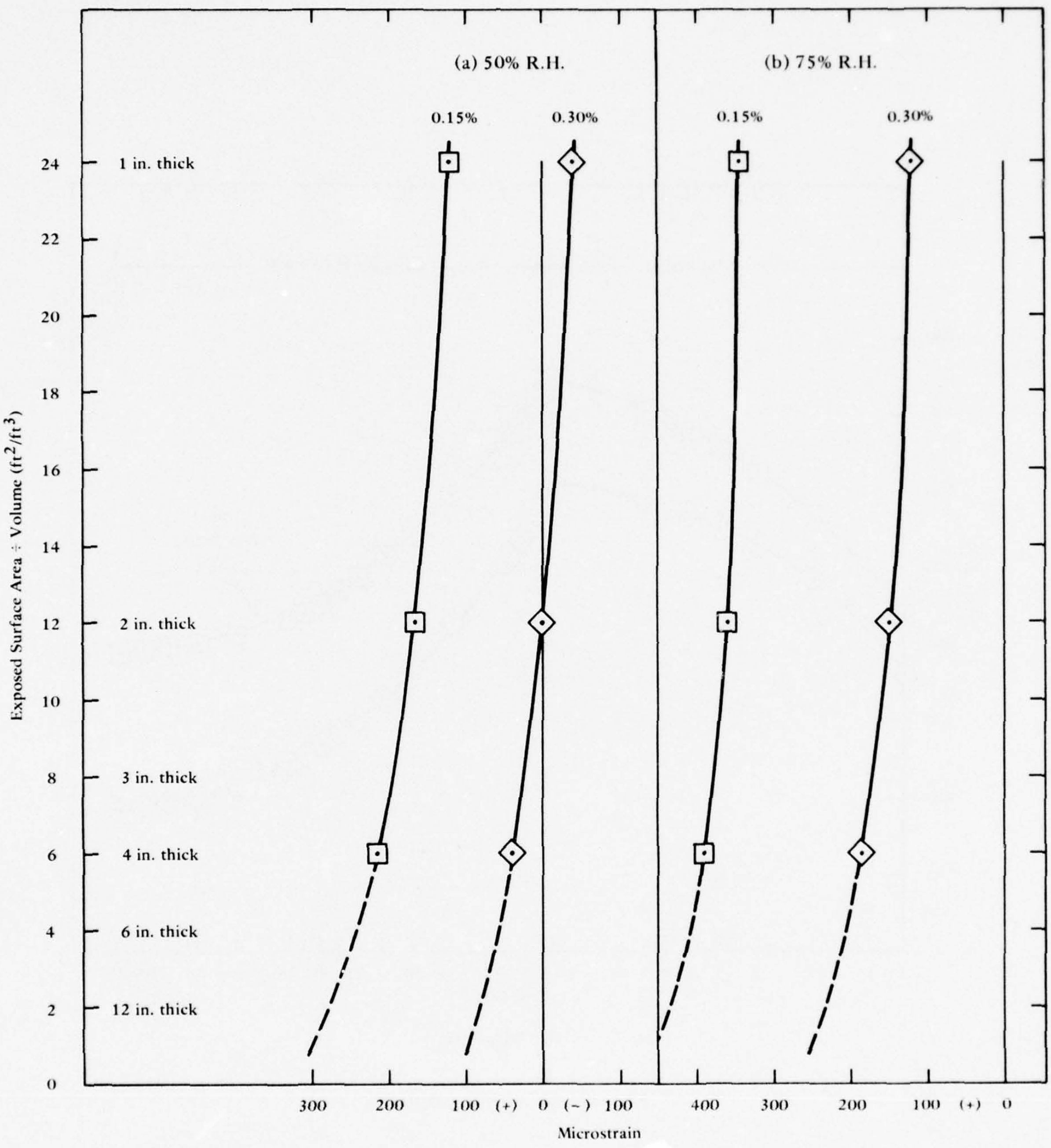
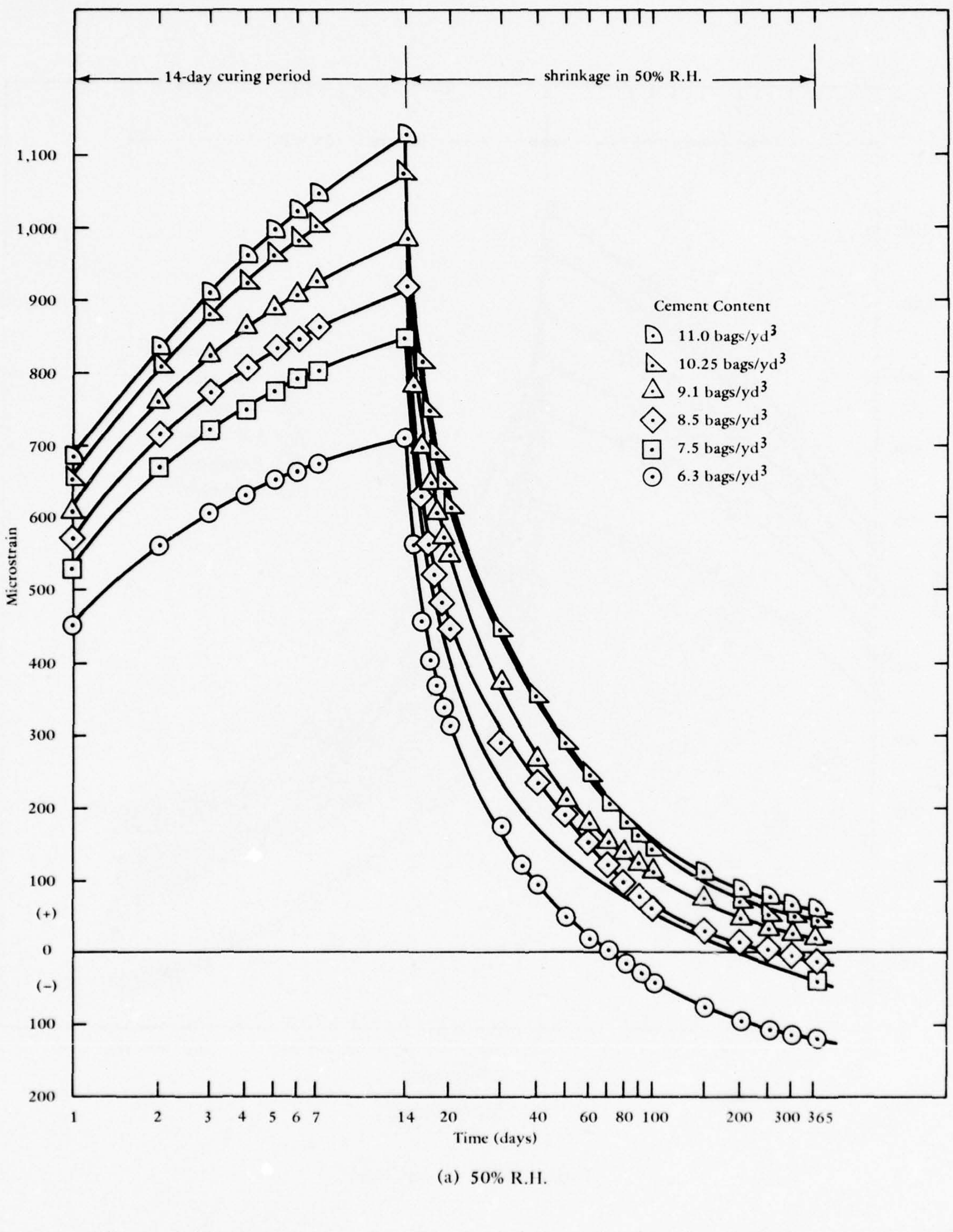
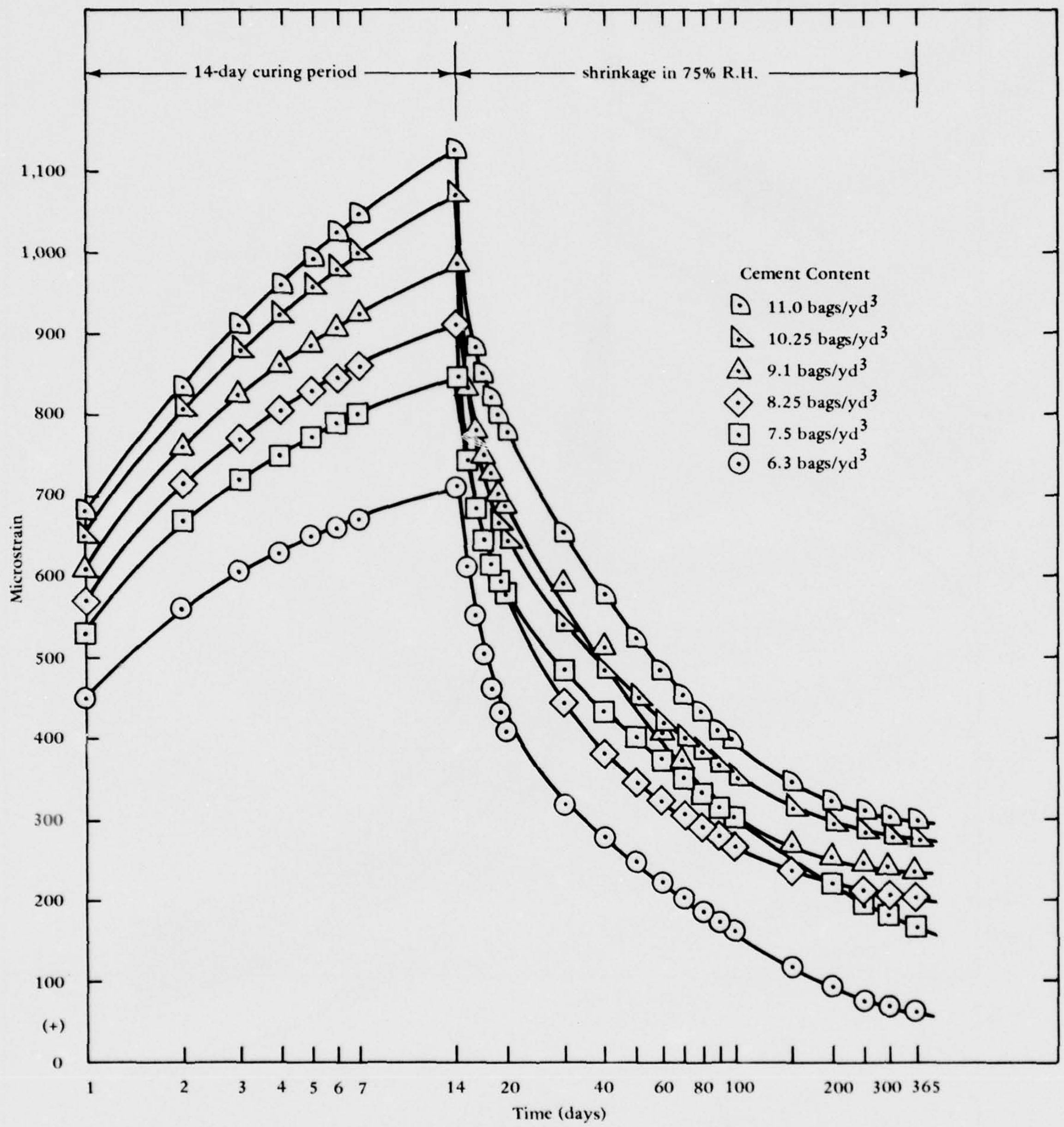


Figure 26. Residual strain after 365 days as a function of S/V for 7.5 SCA-LW concrete.



(a) 50% R.H.

Figure 27. Expansion-shrinkage of 1-in.-thick prisms of SC mixes with different cement contents.



(b) 75% R.H.

Figure 27. Continued

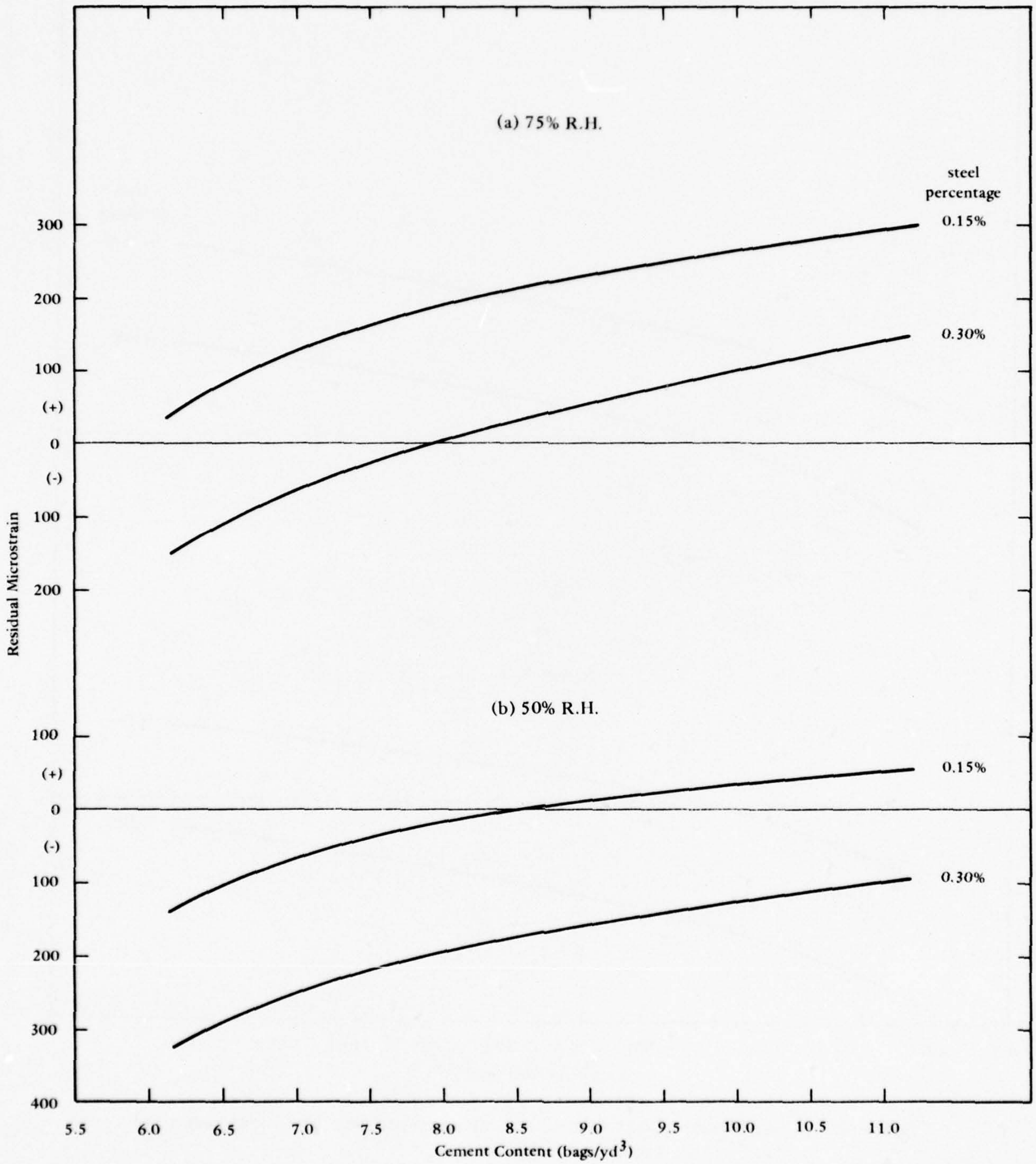


Figure 28. Residual strains after 365 days in 1-in.-thick prisms of SC mixes with different cement contents.

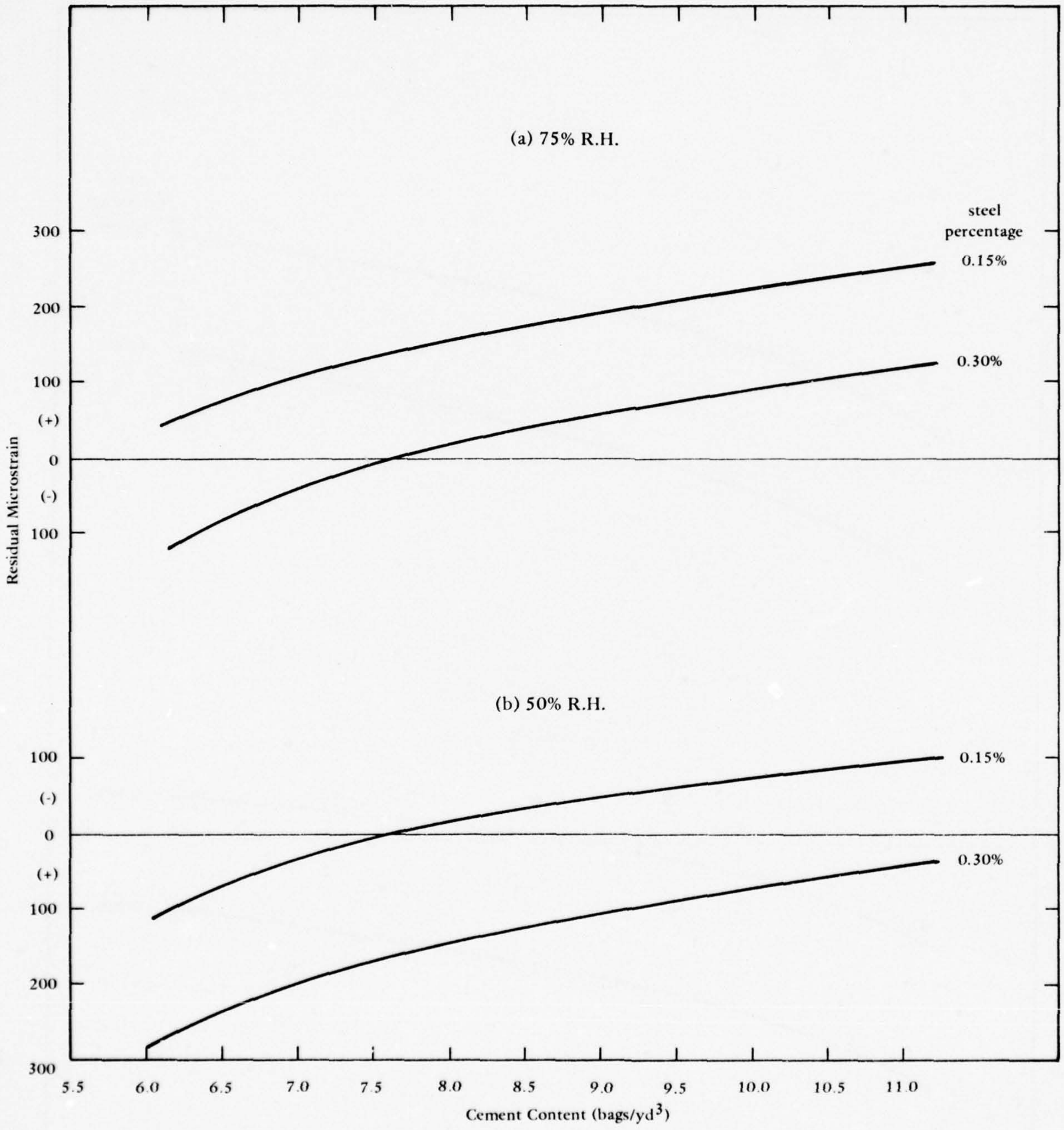
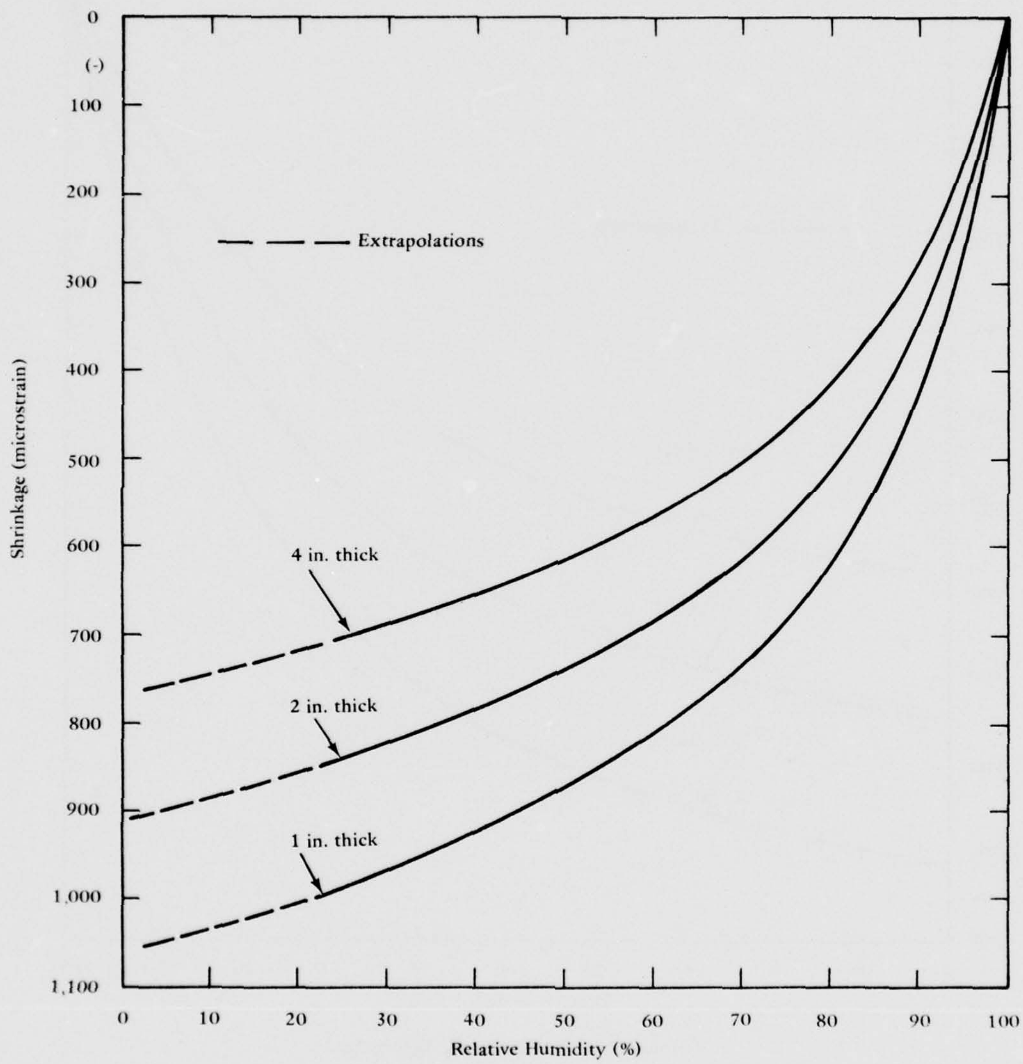
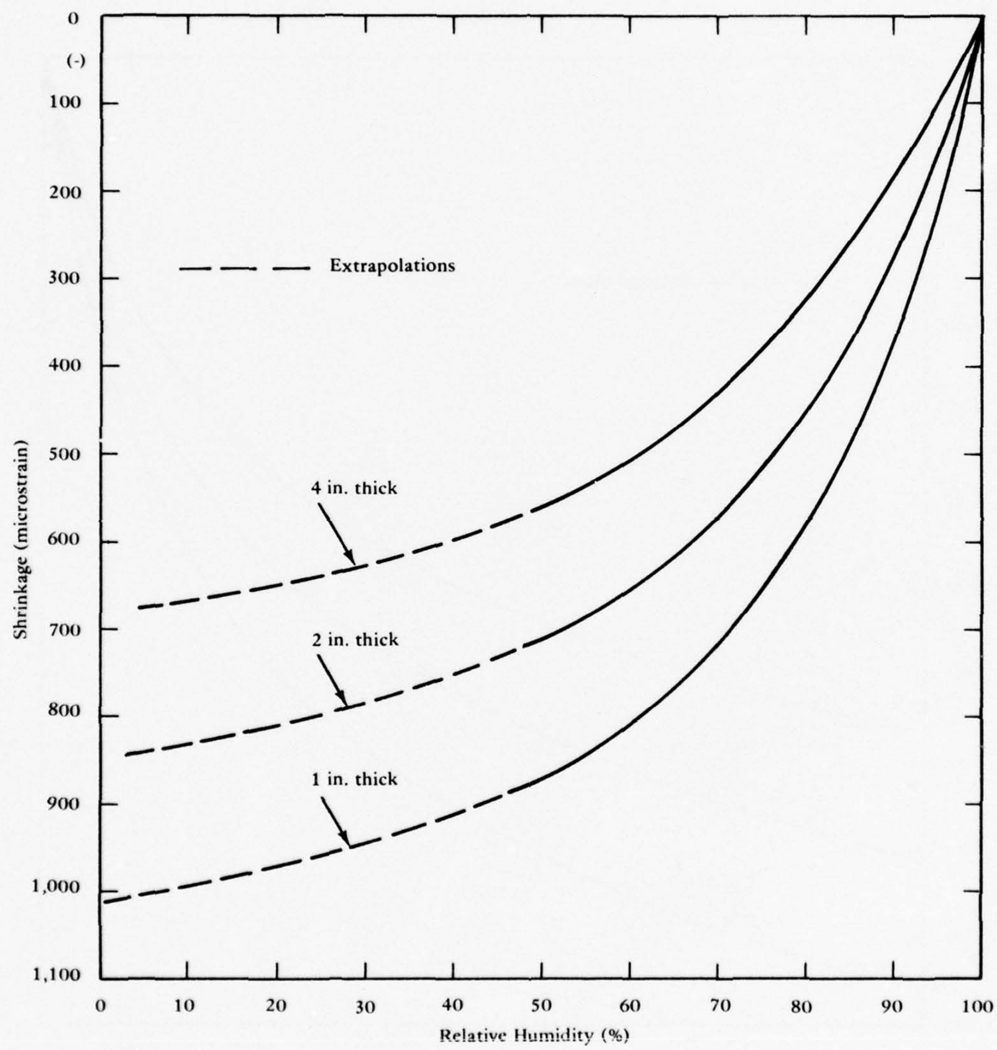


Figure 29. Residual strain in 2-in.-thick prisms of SC mixes with different cement contents.



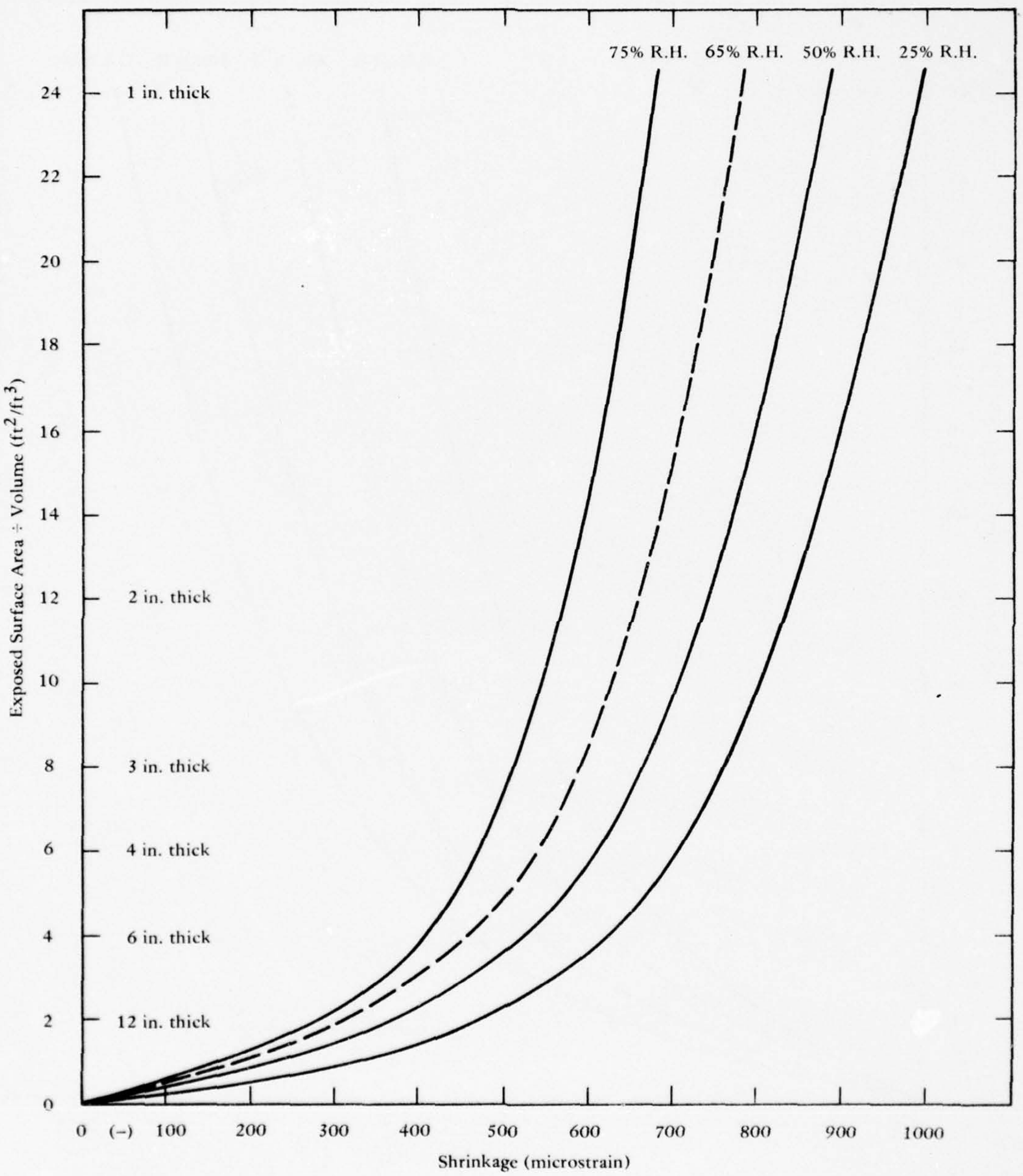
(a) Made with normal weight aggregate.

Figure 30. Shrinkage versus humidity for 7.5 SC concretes.



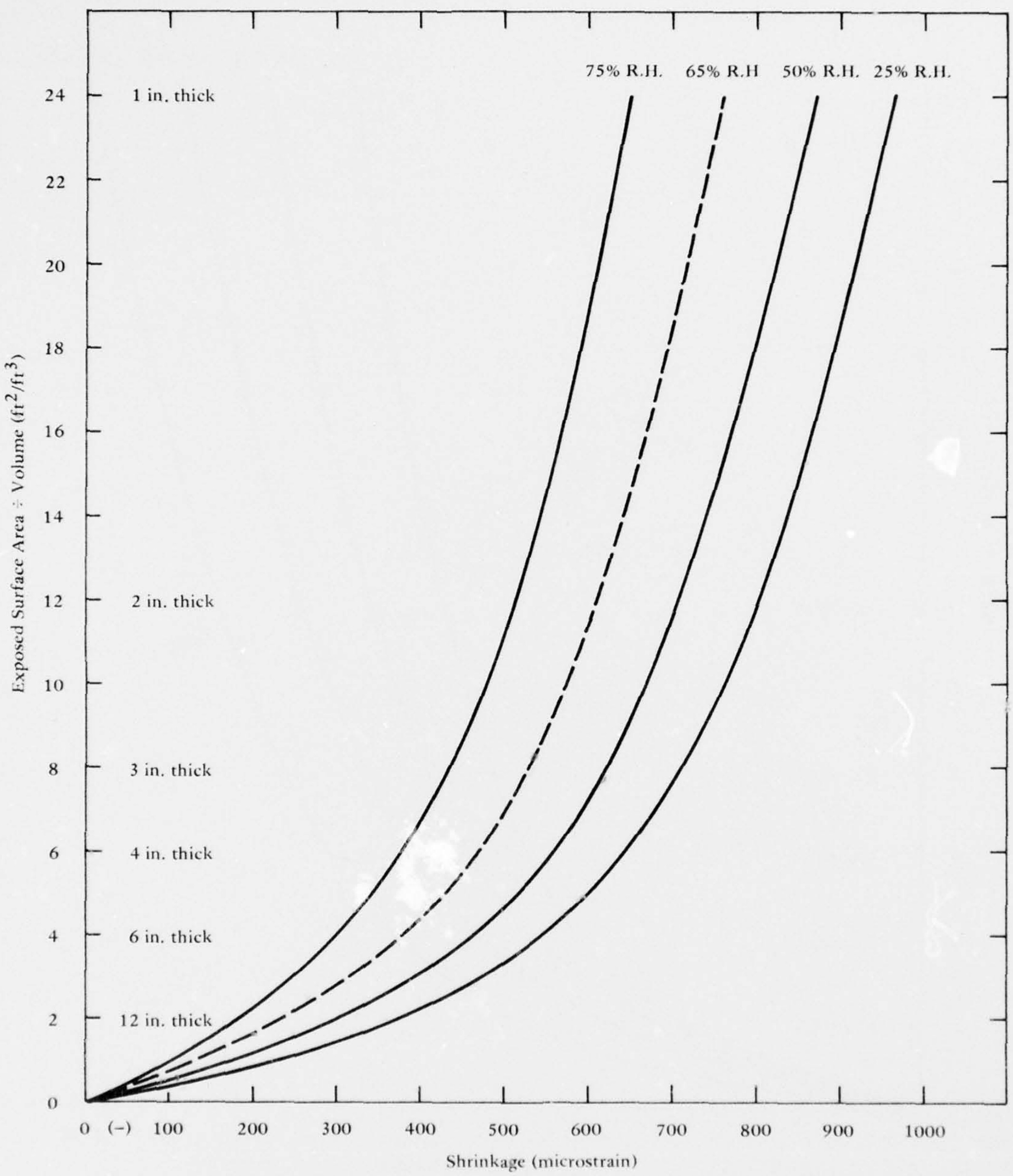
(b) Made with lightweight aggregates.

Figure 30. Continued



(a) Made with normal weight aggregates.

Figure 31. Shrinkage versus S/V for 7.5 SC concretes.



(b) Made with lightweight aggregates.

Figure 31. Continued

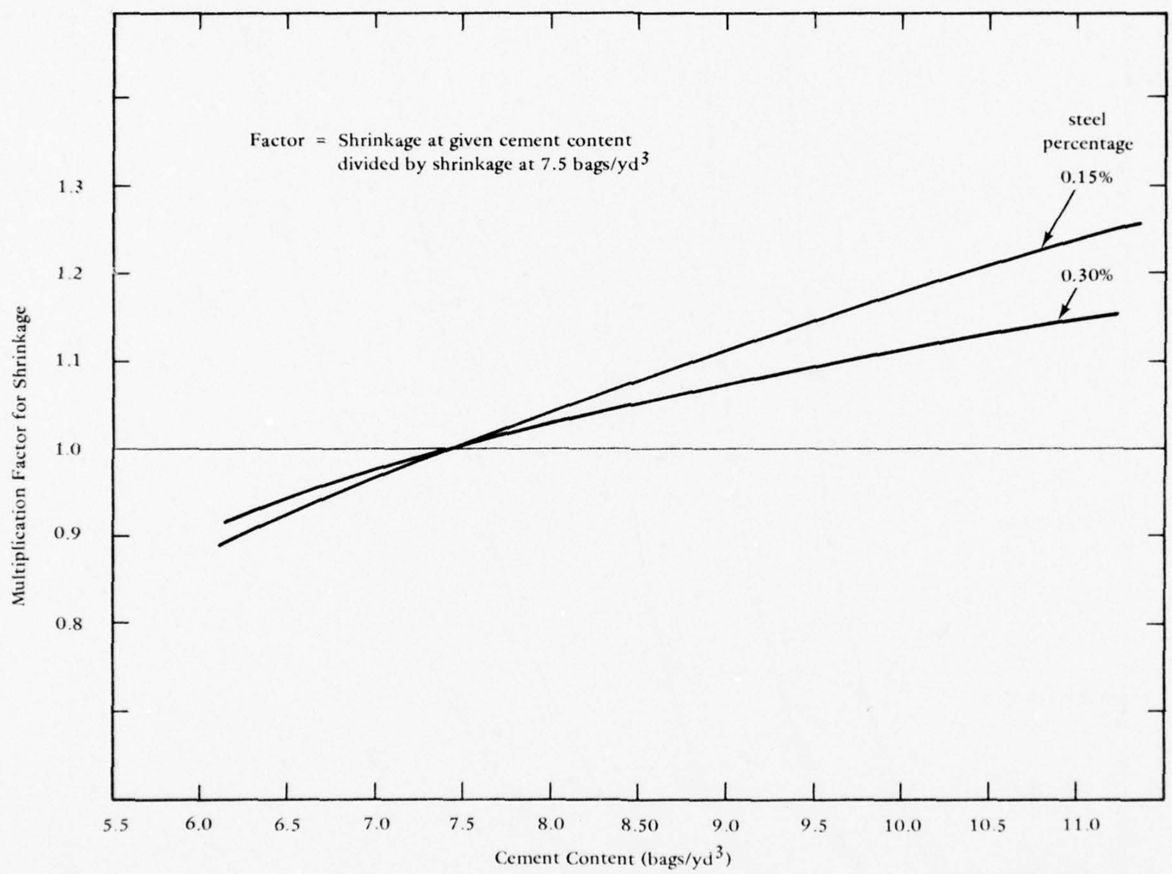
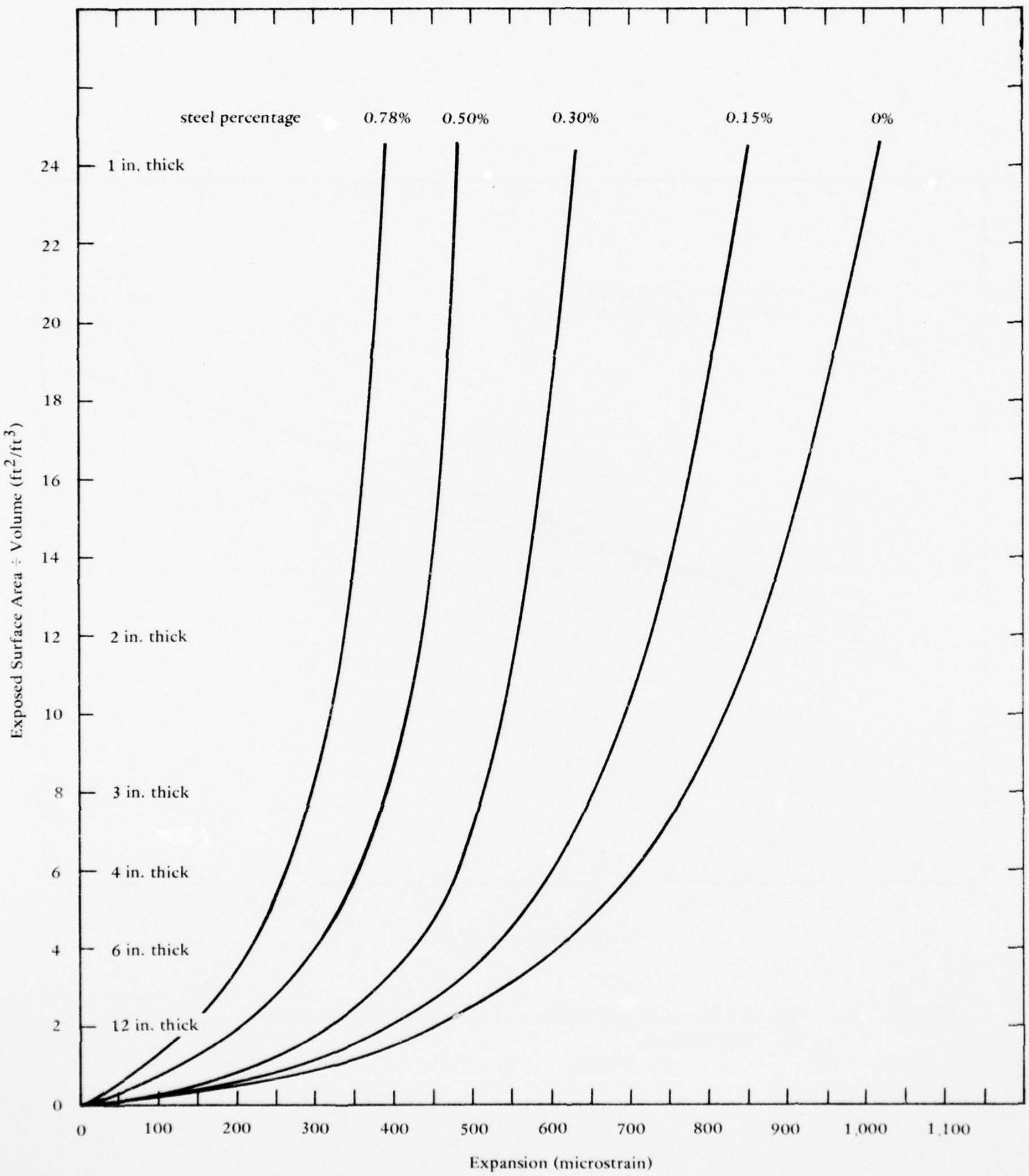
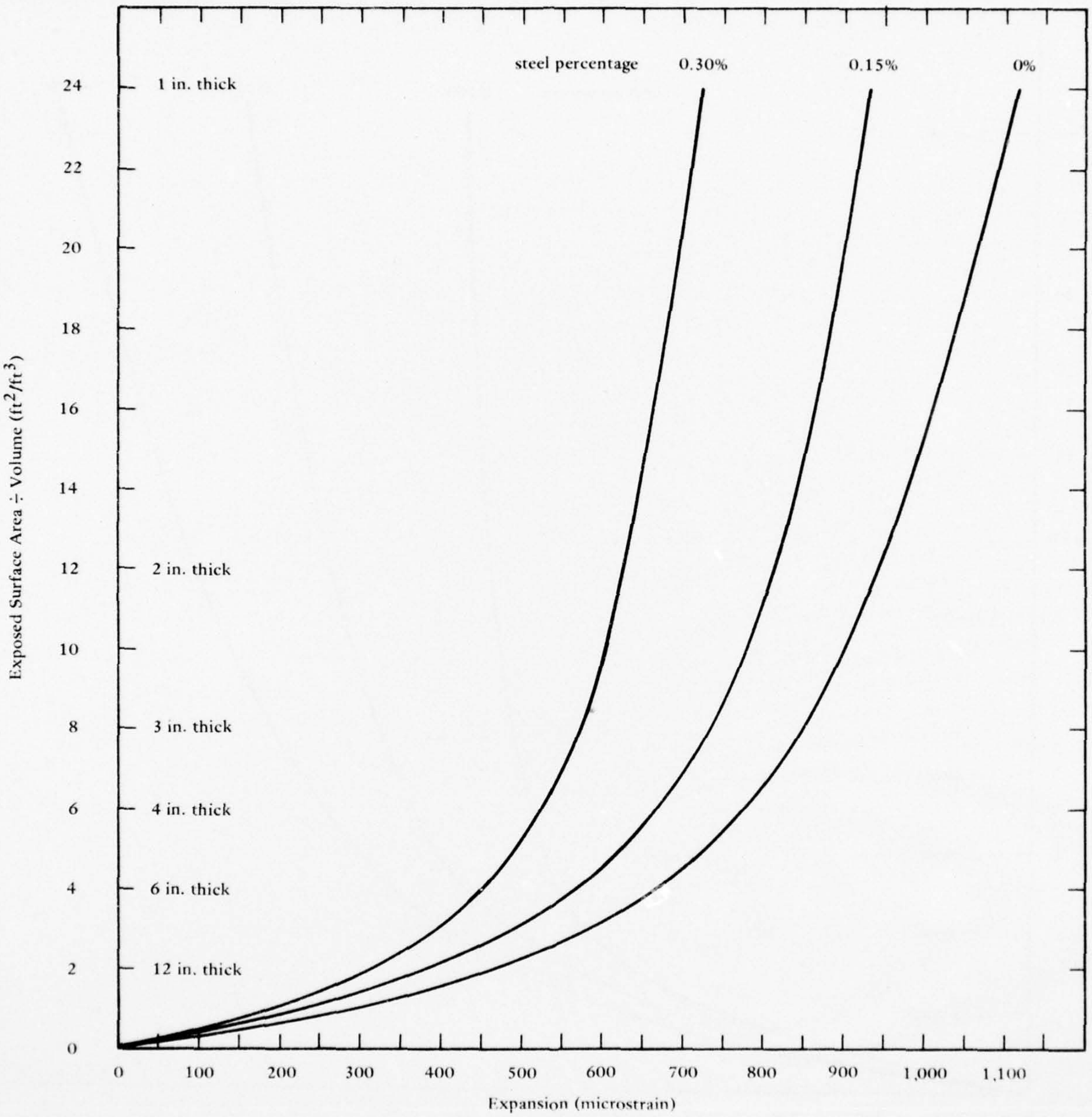


Figure 32. Multiplication factors for effects of cement content on shrinkage.



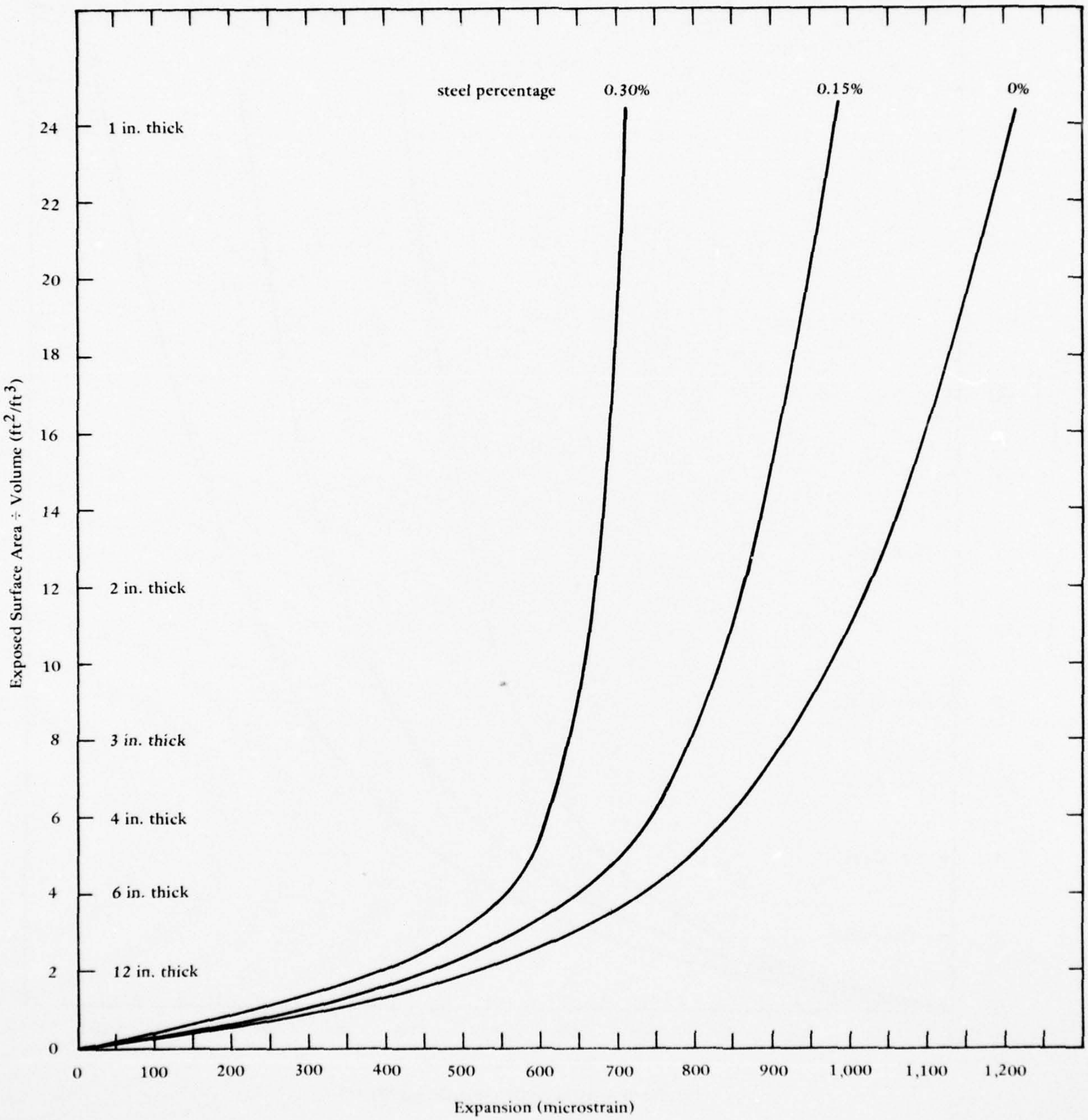
(a) Made with normal weight aggregates.

Figure 33. Expansion after 14 days of curing versus S/V for 7.5 SC concretes.



(b) Made with sand-lightweight aggregates.

Figure 33. Continued



(c) Made with all-lightweight aggregates.

Figure 33. Continued

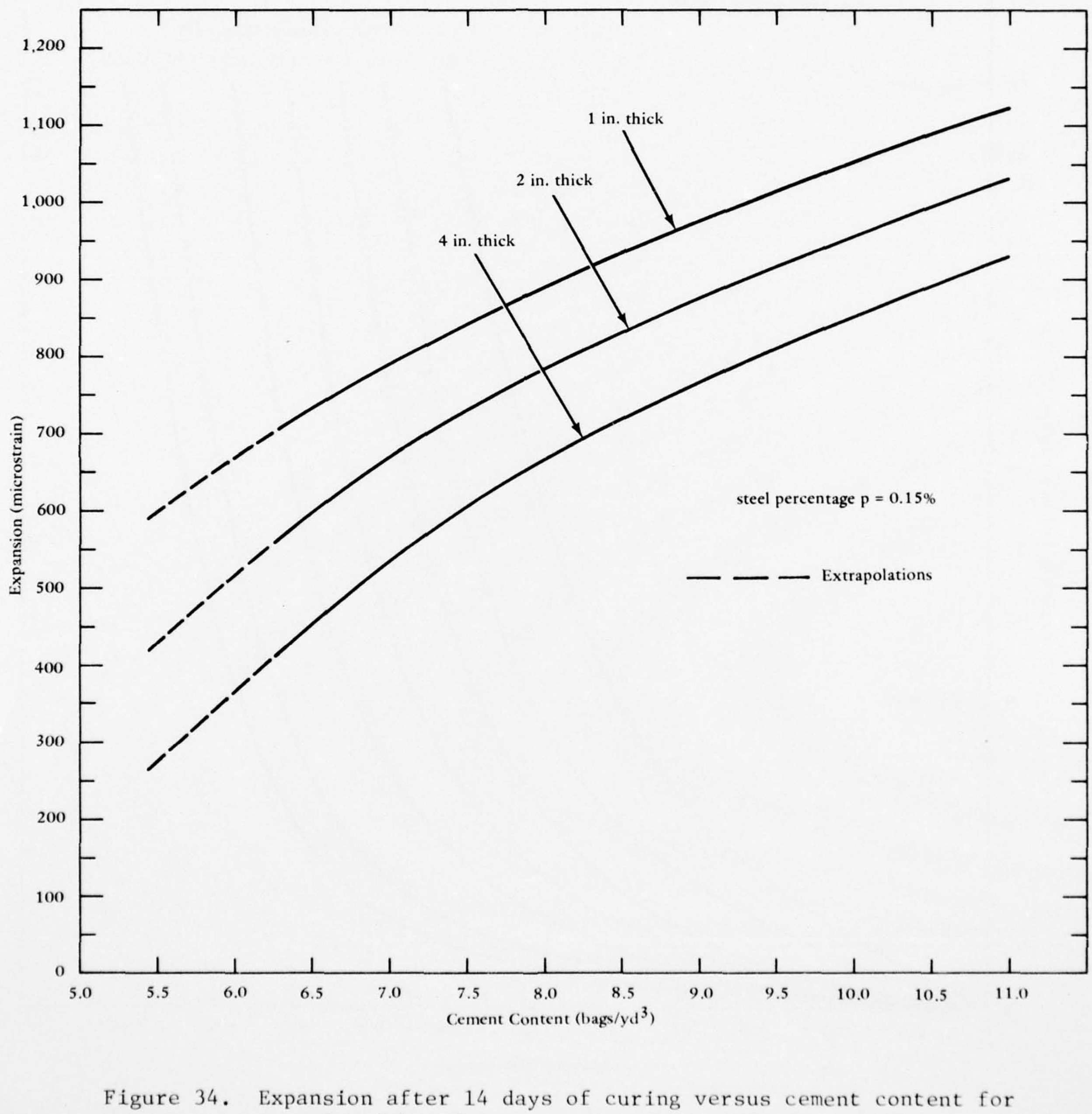


Figure 34. Expansion after 14 days of curing versus cement content for normal weight SC concretes.

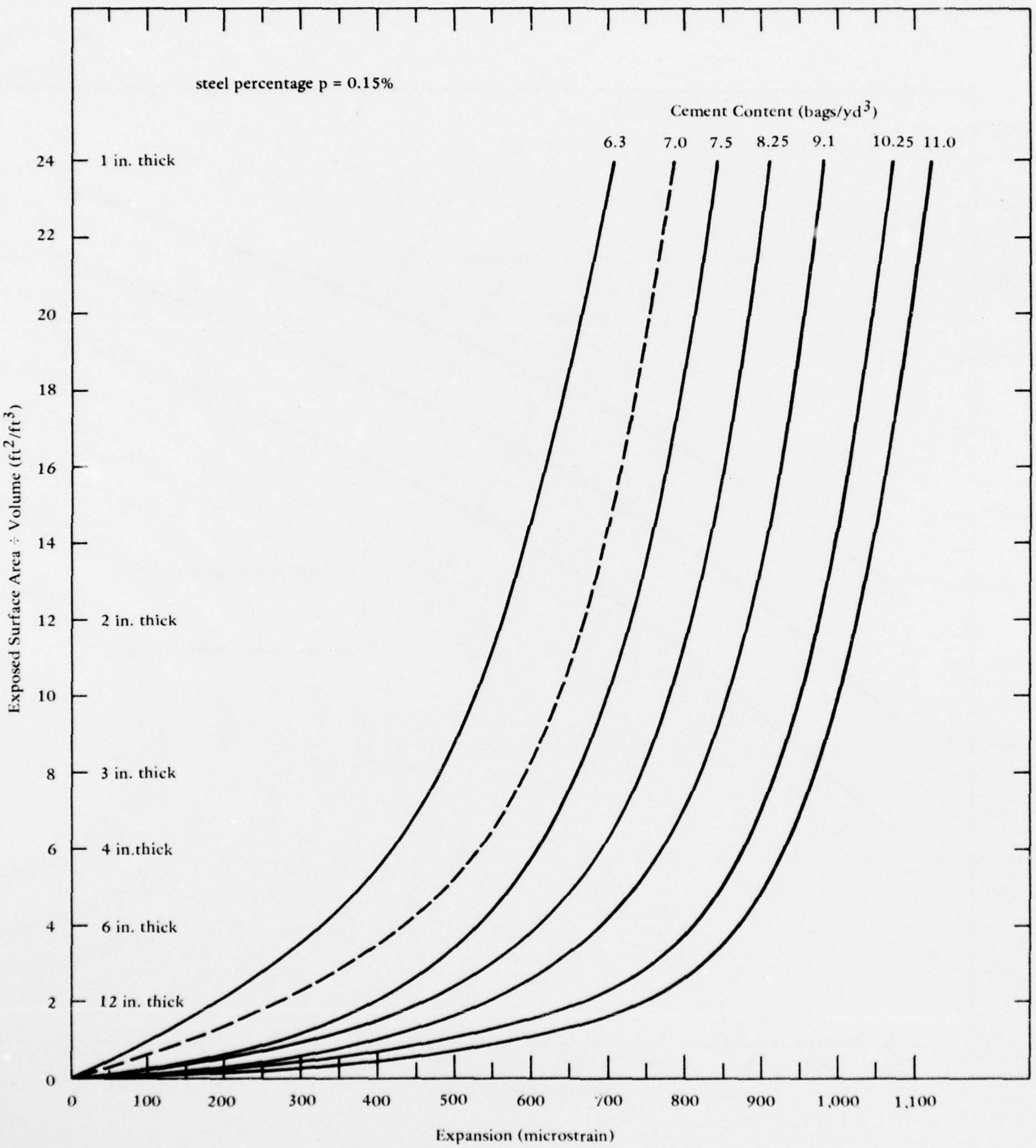


Figure 35. Expansion after 14 days of curing versus S/V for normal weight SC concretes made with different cement contents.

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