THE USE OF LIGHTWEIGHT FINES
FOR THE INTERNAL CURING OF CONCRETE

Prepared for:

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INTRODUCTION

The benefits of using lightweight aggregates in concrete to help reduce cracking in slabs and bridge decks has been intuitively known for decades by the lightweight aggregate industry but the reasons as to why this occurred were not extensively examined and the benefits were not widely promoted. It was believed, and correctly so, that the lower modulus of the LWA and the improved transition zone around the LWA particles due to their generally vesicular surface, helped reduce stress concentrations between the paste and the aggregate and those reductions subsequently reduced the amount of early-age cracking in the concrete. In the 1980's, the production of high-strength concrete (HSC) became more common and, to accomplish it, came the use of higher cement contents, supplementary cementing materials such as silica fume, fly ash and blast furnace slag cement, and lower water-binder ratios as a result of the extensive use of superplastizers. The term "high-performance" concrete (HPC) also emerged with a focus on providing special properties of concrete above what would normally be expected from concrete produced for general use. Most of the HPC was directed at improved durability. The durability improvements came by reducing or eliminating the transport mechanisms of the environment into the concrete and this generally followed the same modifications of the mixture proportions that occurred for HSC.

With the mixture proportion changes for HSC/HPC, came a shrinkage problem. Concrete shrinkage, over time, induces cracking that can severely reduce the life expectancy of concrete. Long-term drying shrinkage has typically been what is addressed in the literature and what is considered in structural design. Lately, much more attention has been paid to early-age shrinkage, as it can be responsible for cracking when the concrete has not gained significant strength to withstand internal stresses. The components of both early-age and long-term shrinkage are drying, autogenous, and thermal shrinkage, with carbonation shrinkage also contributing to the overall long-term shrinkage (1).

The use of HSC/HPC in pavements is further complicated by the "fast track" approach to paving where the concrete gets only minimal moist curing. ACI 308-92 (2) notes that for moist curing pavements and other slabs on the ground at temperatures above 40^{o}F (5^{o}C), "the recommended minimum period of maintenance of moisture and temperature for all procedures is 7 days or the time necessary to attain 70% of the specified compressive or flexural strength, whichever period is less." This curing period may have to be extended when fly ash is included as part of the binder because of its slower initial strength development. Also, when silica fume and other pozzolans are used, the water demand is much greater. For structures and buildings, ACI 308-92 (2) notes that the use of liquid membrane-curing compound not be authorized "when the concrete has a water-cement ratio of 0.4 or less by weight." This implies that even by not allowing the moisture in the concrete to leave using the membrane, initially there is probably insufficient moisture in the concrete for complete hydration to occur and that moist curing procedures should be followed.

AUTOGENOUS SHRINKAGE AND SELF-DESICCATION

Autogenous shrinkage is defined as a concrete volume change occurring without moisture transfer to the environment (1). It is the result of the internal chemical and structural reactions of the concrete components. Autogenous shrinkage has typically been viewed as "insignificant" in typical concrete mixtures due to the dominant role of drying shrinkage. For HSC/HPCs, the role of autogenous shrinkage becomes more prominent due to the reduced amount of water and increased amount of various binders used to produce them.

At early ages (the first few hours), before the concrete has formed a hardened skeleton, autogenous shrinkage is the result of only chemical shrinkage. At later ages (> 1+ days), the autogenous shrinkage can also result from self-desiccation since the hardened skeleton resists the chemical shrinkage. Self-desiccation is the localized drying resulting from a decreasing relative humidity (RH) (3,4). The lower humidity is the result of the cement requiring extra water for hydration.

In a HSC/HPC with a low w/c, the finer porosity causes the water meniscus to have a greater radius of curvature. These menisci cause a large compressive stress on the pore walls, thus having a greater autogenous shrinkage as the paste is pulled inwards. Self-desiccation is only a risk when there is not enough localized water in the paste for the cement to hydrate; thus the water is drawn out of the capillary pore spaces between the solid particles. At later ages, a strong correlation exists between internal relative humidity and free autogenous shrinkage.

USE OF LIGHTWEIGHT AGGREGATE FOR INTERNAL CURING

In 1991, Philleo (5) suggested incorporating saturated lightweight fine aggregate into the concrete mixture to provide an internal source of water to replace that consumed by chemical shrinkage during hydration of the paste. LWAs typically have 24-hour absorptions in the range of 5% to 25% and, if properly preconditioned prior to their introduction into the mixture, can provide additional internal water for curing the concrete. His suggestion finally gained some recognition in the mid-1990's with a considerable amount of work being done on the use of saturated LWA to alleviate autogenous shrinkage. Many of these studies are described in later sections of this report.

A reasonable explanation of how the LWA reduces or eliminates autogenous shrinkage is provided by Weber and Reinhardt (6). During hydration, a system of capillary pores is formed in the cement paste. The radii of these pores are smaller than the pores of the LWA. As soon as the RH decreases (due to hydration and drying), a humidity gradient develops. With the LWA acting as a water reservoir, the pores of the cement paste absorb the water from the LWA by capillary suction. The unhydrated cement particles from the cement paste now have more free-water available for hydration. The new hydration products grow in the pores of the cement paste thus causing them to get smaller. The capillary suction, which is the inverse to the square of the pore radius, increases as the radius becomes smaller and thus enabling the pores to continue to absorb water from the LWA. This continues until all the water from the LWA has been transported to the cement paste.

The use of mineral admixtures, such as fly ash and silica fume, tend to refine the pore structure towards a finer microstructure. If there is a finer microstructure, the water consumption will be increased and the autogenous shrinkage due to self-desiccation will be increased.

At the surface of the concrete, an additional humidity gradient occurs due to evaporation from the concrete surface. This accelerates the appearance of the localized humidity gradient. The water from the LWA near the surface is then used up faster than in the interior of the concrete thus causing the near-surface layer of the concrete to be come more dense in a shorter period of time. This helps reduce the amount of water that would normally evaporate and contributes to improved internal curing of the concrete. It also leads to reduced or no stresses due to drying, and helps eliminate surface cracking.

INTERNAL CURING WATER REQUIREMENTS

As early as 1948 (7), it was shown that autogenous shrinkage due to self-desiccation occurs when the *w/c* is below 0.42 as all the mixing water is consumed at this ratio. Other investigations noted that the *w/c* limit can vary between 0.36 and 0.48 depending on cement type. When the w/c is much lower than 0.42, and can no longer gain curing water, the cement seeks extra water from the internal pores and thus lowers the RH. More currently, Mather and Hime (8) have noted that a lot of modern "high-performance" concrete, made with water/cement ratios (*w/c*) below 0.4 (by weight) will not have all the original mixing water-filled space filled with hydration product. In concluding this, they too observed that the critical feature of the chemical reaction between the constituents of cement and the mixing water is the ratio of the volume of the water to the volume of the cement. In a simplified form, if that ratio is 1.2, then all the water and all the cement can combine, and the hydration product can fill all of the space originally occupied by the mixing water (the original mixing water-filled space) (8). This ratio is approximately equivalent to a water/cement ratio (*w/c*) of 0.4 (by weight). If the *w/c* is lower than 0.4, some of the cement will always remain unhydrated. They further noted that about 0.2 *w/c* goes into chemical combination with the cement and that the other 0.2 *w/c* was the amount needed to fill the gel pores with the hydration product. It was also observed that, in practice, externally available water on low *w/c* concretes does not get very far into larger masses of concrete.

Early external water curing is efficient in reducing autogenous shrinkage in concrete having a low water/binder ratio and in concretes containing silica fume. However, the maximum efficiency of this water curing is typically 1 to 2 days when the capillary pores are still interconnected. Early water curing can lead to higher strain gradients when the skin of the concrete becomes well cured (no shrinkage) whereas, autogenous shrinkage, which is generally difficult to control, begins at the interior of the concrete (9). These problems can be mitigated by use of a pre-soaked LWA that can provide a concrete that is not sensitive to deficient curing.

Bentz and Snyder (10) developed equations to estimate the replacement level of saturated LWA fines that would be needed to provide all of the water needed for the complete curing of a HPC. Their calculations assumed that there was no water exchange between the concrete and external environment (sealed curing). From computer simulations, they addressed the proximity of the cement paste to the surfaces of the LWA fines using the "protected paste volume concept" for air-entrained concrete where the interest is in the volume of paste within a given distance of an air void surface. Using a previously developed three-dimensional continuum microstructural model for concrete, in which they ignored the interfacial transition zone and focused only on a paste shell surrounding the LWA particles, they were able to determine the relative proximity of the cement paste to the additional water source contained in the LWA. From several simulations, using various percentage replacements of the normal weight fine aggregate by its saturated LWA fines counterpart and two aggregate gradations, they concluded that a well dispersed system of small saturated LWA fines would be very beneficial to the curing of field concrete, much in the same manner that a well dispersed system of small entrained air bubbles is beneficial in protecting concrete from damage due to freezing and thawing.

SUPPORTING RESEARCH

GERMAN RESEARCH

Research in Germany (6) used Liapor LWA in the 5/32- to 5/16-in. (4- to 8-mm) range of the aggregate gradation with a rounded sand and gravel (with a maximum size of 5/8-in. (16 mm)), The amount of LWA represented approximately 25% of the total aggregate volume. It had a dry density of 88.6 lb/ft^3 (1420 kg/m^3) and a porosity of approximately 50%. The moisture content after 24-hours submersion was 20.2% by mass. The mixture proportions are shown in Table 1.

The test specimens were 4-in. (100 mm) cubes cured in a moist room the first 24-hours. They were then subjected to four different curing conditions: 6-days submerged in water, then in air at 68^{o}F (20^{o}C) and 65% RH; in air at 68^{o}F (20^{o}C) and 65% RH; in air, temperature varying between 59^{o}F (15^{o}C) and 77^{o}F (25^{o}C) with the RH varying between 40% and 45%; and sealed in aluminum and polyamid foils.

The concretes were evaluated for changes in mass, compressive strength, porosity, pore size distribution, degree of hydration, and chemical composition at ages up to one year. The average compressive strengths at 28-days was 14,215 psi (98 MPa) for the sealed cubes, 14,360 psi (99 MPa) for curing at 65% RH, and 14,650 psi (101 MPa). Regardless of the curing condition, all the concrete continued to gain strength up to 360 days. The researchers concluded (6) that the concrete was insensitive to the type of curing and that the continued strength gain was due to the continual contribution of moisture from the LWA. They also observed a continual decrease of porosity with time with a tendency toward smaller pores. The smaller pores are the result of continuous hydration. The degree of hydration improved approximately 20% from ages 180 days to 360 days.

Table 1 Mixture Proportions for Reference 6

Material	Amount
Portland cement (CEM I 42.5 R), lb/yd^3 (kg/m^3)	758 (450)
Silica Fume, lb/yd^3 (kg/m^3)	76 (45)
Aggregates	
5/16- to 5/8-in. (8- to 16-mm), lb/yd^3 (kg/m^3)	956 (567)
5/32- to 5/16-in. (4- to 8-mm) – LWA, lb/yd^3 (kg/m^3)	394 (234)
5/64- to 5/32-in. (2- to 4-mm), lb/yd^3 (kg/m^3)	438 (260)
0- to 5/64-in. (0- to 2-mm), lb/yd^3 (kg/m^3)	794 (471)
Superplasticizer, oz/yd^3 (L/m^3)	352 (13.6)
Retarder, oz/yd^3 (L/m^3)	45 (1.75)
Water, lb/yd^3 (kg/m^3)*	253 (150)
Water/Binder Ratio	0.30
*Includes added water, silica fume slurry water, surface moisture on the aggregates and the water in both admixtures.	

DUTCH RESEARCH

Work performed by the Dutch (11) found that mixtures with a water/cement ratio of 0.4 were susceptible to cracking due to autogenous shrinkage in the case of full restraint. To alleviate the self-desiccation in the concrete, they examined the use of saturated LWAs as a partial replacement of NWAs. The LWAs used were either Lytag or Liapor F10 at replacement percentages of 10%, 17.5% and 25% by volume. The size fraction of these aggregates was 5/32- to 5/16-in. (4-mm to 8-mm). Both LWAs had been fully immersed in water for 24-hours prior to mixing and thus were fairly well saturated. Water/cement ratios of 0.4 and 0.33 (by weight) were studied. With the addition of silica fume to some mixtures, the water/binder ratio was lower than the water/cement ratio. The cementitious material used was a blend of Portland cement and blast-furnace slag cement with some silica fume added. Superplasticizers were used to insure good workability. The mixture proportions for this study are shown in Table 4.

The experimental program examined both strength development of cubes to 56-days age and the autogenous deformations and stress development in the mixtures. The volume changes were determined on 6- x 6- x 39.4-in. (150- x 150- x 1000-mm) prisms that were cast in a special mold that allowed the application of different temperature curing regimes to the concrete. The measurement of hydration-induced stress was done using a Temperature Stress Testing Machine (TSTM). The specimens had a prismatic shape, except at the ends where the specimen was enlarged (dog-bone shape). They could also have different temperature curing regimes to the concrete in a manner similar to the shrinkage specimens. Two rigid steel claws held the specimen; one claw was fixed to the test frame while the other was on roller bearings and was connected to a hydraulic actuator. The length changes were measured over the center 29.5-in. (750-mm) of the prism. Both the shrinkage specimens and the specimens for the TSTM were covered in plastic after casting to avoid moisture loss to the environment. The specimens were either kept at 68^{o}F (20^{o}C) or a semi-adiabatic temperature curve was imposed prior to testing.

Table 2 Mixture Proportions for Reference 11

	Materials lb/yd^3 (kg/m^3)						
Mixture Composition	Ref. B85	Ref. B65	25%[a] Liapor	10%[a] Liapor	17.5%[a] Liapor	25%[a] Liapor	25%[a] Lytag
Blast furnace slag cement	400 (237)	506 (300)	400 (237)	400 (237)	400 (237)	400 (237)	400 (237)
Portland cement	401 (238)	169 (100)	401 (238)	401 (238)	401 (238)	401 (238)	401 (238)
Silica fume	84 (50)	----	84 (50)	84 (50)	84 (50)	84 (50)	84 (50)
Crushed aggregate, 5/32- to 5/8-in. (4- to 16-mm)	1642 (974)	1642 (974)	1165 (691)	1475 (875)	1352 (802)	1229 (729)	1230 (730)
Sand, 0- to 5/32-in. (0- to 4-mm)	1343 (797)	1399 (830)	1271 (754)	1343 (797)	1343 (797)	1343 (797)	1343 (797)
Liapor F10	----	----	243 (144)	106 (63)	184 (109)	265 (157)	----
Lytag	----	----	----	----	----	----	256 (152)
Water	270 (160)	270 (160)	322 (191)	270 (160)	270 (160)	270 (160)	270 (160)
Admixture 1	1.6 (0.95)	2.7 (1.6)	1.6 (0.95)	1.6 (0.95)	1.6 (0.95)	1.6 (0.95)	1.6 (0.95)
Admixture 2	16.0 (9.5)	8.1 (4.8)	9.6 (5.7)	16.0 (9.5)	16.0 (9.5)	16.0 (9.5)	16.0 (9.5)
Water/cement ratio	0.33	0.40	0.40	0.33	0.33	0.33	0.33
Water/binder ratio	0.305	0.40	0.36	0.305	0.305	0.305	0.305
a. Replacement percentage of NWA by LWA (by volume).							

The 28-day compressive strength of the w/(bfsc+pc) = 0.40 NWC (Ref. B65) was approximately 10,745 psi (74 MPa) while the comparison mixture with 25% Liapor had a strength of approximately 10,150 psi (70 MPa). The w/(bfsc+c+sf) = 0.305 NWC (Ref. B85) had a 28-day strength of approximately 14,360 psi (99 MPa). Mixtures containing 10%, 17.5% and 25% Liapor had strengths equal to or slightly greater than the NWC while the 25% Lytag mixture had a strength slightly less than the NWC. Similar relationships held at 56-days age.

Fig. 1 shows the autogenous shrinkage of the w/c=0.4 NWC and 25% Liapor LWAC. After about 300 hours, a shrinkage strain up to $-200x10^{-6}$ was observed. This is approximately two times the tensile strain capacity of the concrete and cracking of the concrete can be expected to occur. This was confirmed in the TSTM tests where the concrete cracked at 280 hours at a tensile stress of 480 psi (3.3 MPa). A substantial reduction of the autogenous deformations was achieved with the 25% Liapor LWAC where the strain after 144 hours was $-20x10^{-6}$ rather than the $-140x10^{-6}$ for the NWC. This reduction would have been sufficient to prevent cracking due to autogenous shrinkage.

Fig. 2 shows the non-thermal volume changes for all the mixtures with a w/c=0.33. Mixture shrinkage could not be measured until about 6-hours after casting the specimens. At 12-hours, slight expansions were noted with shrinkage beginning at about 15-hours. When no LWA was present, a shrinkage of approximately $-180x10^{-6}$ after 144-hours whereas with a 25% replacement of saturated Liapor, this value was reduced to approximately $-55x10^{-6}$. The 25% Lytag replacement concrete (not shown) showed a continuous swelling for about 30-hours before it began to shrink. At 144-hours, the Lytag mixture was still on the positive side at $+50x10^{-6}$.

The investigators concluded (11) that:

1. Partial replacement of NWA, up to 25%, by saturated LWA had no negative effect on the compressive strength. At a low w/c=0.33, replacements of 10% and 17.5% of saturated LWA resulted in an improvement in compressive strength over concrete with no LWA replacements.
2. With replacement percentages up to 25%, a significant reduction of the autogenous shrinkages is obtained under isothermal conditions. For one of the LWA types, expansion was still present for at least 144 hours after casting.

Most national design codes have prediction models for the deformations caused by shrinkage. van Breugel, et al, (12) have noted that higher strength concretes (e.g., >9400 psi (65 MPa)) made at a w/c of about 0.4 or less may exhibit substantial autogenous shrinkage and that the codes, which deal with "drying shrinkage", do not take into account the magnitude of that autogenous shrinkage which can be quite significant. In their study of the interaction of autogenous shrinkage and drying shrinkage, they included a mixture that contained 25% of Liapor F10 (0.16- 0.31 in. (4- to 8-mm)). The lightweight aggregate was water saturated. The mixture contained a blend of Portland cement (168 lb/yd^3 (100 kg/m^3)) and blast furnace slag cement (506 lb/yd^3 (300 kg/m^3) for a total cement content of 674 lb/yd^3 (400 kg/m^3) and had a w/c of 0.39. At 28-days, the compressive strength of the mixture containing the lightweight aggregate was 93% of the strength of the control mixture. The autogenous shrinkage measurements were made on 4- x 4- x 15.7-in (100- x 100- x 400-mm) prisms that were sealed at 1-days age. Measurements started at 1-days age and were continued until 90-days age. There was virtually no measurable autogenous shrinkage over the 90-day period. The investigators (12) observed that, in mixtures without the water saturated lightweight aggregate, the total shrinkage (autogenous + drying) was more than predicted by the Dutch Concrete

Code VBC ’95 and the CEB-FIP Model Code ’90. The mixture with the lightweight aggregate showed no shrinkage until the sealing on the prisms was removed. Then, drying shrinkage began, beginning at the surface of the concrete and proceeding into the concrete. There is a strong dependency on the size and shape of the concrete member undergoing this shrinkage. For those mixtures that did not contain the saturated lightweight aggregate, the investigators noted that between 39% and 53% of the observed total shrinkage was due to autogenous shrinkage. They also noted that any effects that the paste composition had on autogenous shrinkage was completely over-ruled by the presence of the moisture in the LWA.

The influence of the moisture flow from LWA particles to the paste on the early-age deformations of the concrete has also been studied (13). LWAC mixtures with an effective water/binder ratio of 0.35 were studied. The binder consisted of a blend of portland cement (401 lb/yd^3 (238 kg/m^3)), blast furnace slag cement (399 lb/yd^3 (237 kg/m^3)), and silica fume (42 lb/yd^3 (25 kg/m^3)) for a total binder content of (843 lb/yd^3 (500 kg/m^3)). The lightweight aggregate was Liapor in different grades and size fractions: F8 and F10, 5/32- to 5/16-in. (4- to 8- mm); F8, 5/16- to 5/8-in. (8- to 16-mm); and sand, pan to 5/32-in. (0- to 4-mm). The mixture proportions are shown in Tables 3 and 4.

Table 3 Mixture Proportions with Liapor F10 and Different Degrees of Saturation for Reference 13

Constituent	Type of Lightweight Aggregate		
	Liapor F10 100% sat.	Liapor F10 70% sat.	Liapor F10 30% sat.
Portland Cement, lb/yd^3 (kg/m^3)	401 (238)	401 (238)	401 (238)
Blast Furnace Slag Cement, lb/yd^3 (kg/m^3)	399 (237)	399 (237)	399 (237)
Silica Fume, (slurry, 50% solids lb/yd^3 (kg/m^3)	42 (25)	42 (25)	42 (25)
Lightweight Aggregate, lb/yd^3 (kg/m^3)	1035 (614)	984 (584)	933 (553)
Normal Weight Sand, lb/yd^3 (kg/m^3)	1302 (772)	1302 (772)	1302 (772)
Water (incl. water in admixtures), lb/yd^3 (kg/m^3)	296 (176)	296 (176)	296 (176)
Lignosulphonate, lb/yd^3 (kg/m^3)	1.68 (1.0)	1.68 (1.0)	1.68 (1.0)
Naphthalene Sulphonate, lb/yd^3 (kg/m^3)	12.0 (7.1)	16.0 (9.5)	20.0 (11.9)
w/(pc+bfs+sf)	0.35	0.35	0.35

The autogenous deformations of the mixtures of Table 3 are shown in Fig. 3. For 100% saturation, the concrete reached its maximum expansion at 24-hours and remained at that level until 6-days when the measuring was stopped. One hundred percent saturation was defined as the 24-hour absorption based on immersion. The mixture at 70% saturation showed minor shrinkage in the very early stages of hydration and began to expand after 10-hours. The maximum expansion occurred at 72-hours and remained fairly constant after that. The mixture with a degree of saturation of 30% had intensive shrinkage until an age of 13 hours was reached. This was followed by rapid expansion between 13 and 18 hours and moderate expansion over the next 5-days. For the period of observation, there was only resulting shrinkage at this level of saturation.

Fig. 4 shows the autogenous deformation of the mixtures of different LWA particle sizes (Table 4). The expansion of the mixture containing the Liapor sand was fairly continuous and was larger than the expansions observed when larger size particles were used.

Table 4 Mixture Proportions with Different Particle Sizes of Liapor (Ref. 13)

Constituent	Type of Lightweight Aggregate		
	Liapor F8 5/32- to 5/16-in. (4- to 8- mm)	Liapor F8 5/16- to 5/8-in. (8- to 16-mm);	Liapor Sand Pan to 5/32-in. (0- to 4-mm).
Portland Cement, lb/yd^3 (kg/m^3)	401 (238)	401 (238)	401 (238)
Blast Furnace Slag Cement, lb/yd^3 (kg/m^3)	399 (237)	399 (237)	399 (237)
Silica Fume, (slurry, 50% solids, lb/yd^3 (kg/m^3)	42 (25)	42 (25)	42 (25)
Lightweight Aggregate, lb/yd^3 (kg/m^3)	1035 (614)	984 (584)	933 (553)
Normal Weight Sand, lb/yd^3 (kg/m^3)	1302 (772)	1302 (772)	1302 (772)
Water (incl. water in admixtures), lb/yd^3 (kg/m^3)	296 (176)	296 (176)	296 (176)
Lignosulphonate, lb/yd^3 (kg/m^3)	1.68 (1.0)	1.68 (1.0)	1.68 (1.0)
Naphthalene Sulphonate, lb/yd^3 (kg/m^3)	12.0 (7.1)	16.0 (9.5)	20.0 (11.9)
W/(pc+bfs+sf)	0.35	0.35	0.35

Based on extended periods of submersion of the LWAs, the investigators noted with prolonged submersion, the finer particles tend to absorb more water (by weight) and could provide more water for the internal curing. For 1-day submersion, the amount of water absorbed by various size fractions was similar. The practicality of prolonged submersion periods was not addressed. They also looked at the transport mechanism of the water in the aggregate into the paste using a black ink solution with white cement as a binder. The preliminary findings indicated that the ink solution progressed at least 1-mm from the aggregate within two weeks of casting. This is indicative that liquid transport does occur, but because the ink molecules may not diffuse with the same speed and to the same depth as water, it does not provide quantitative values for the water migration. If it is assumed that the distance of water transport is on the millimeter scale, that is an argument for using smaller, more closely spaced particles to achieve the internal curing.

The investigators also observed that not all the water contained in the LWA is available for internal curing. They concluded that only about 2/3 of the water absorbed in the LWA is readily available for transport to self-desiccating paste. Some water remains in the LWA in the high RH range and only comes into play when the overall RH humidity in concrete is significantly reduced.

Concrete made with a low water/binder ratio will experience self-desiccation. This self-desiccation will be accompanied by a drop in relative humidity (RH) within the concrete and by autogenous shrinkage. In order to reduce the autogenous shrinkage, the normal weight aggregate can be replaced wholly or partially by water containing lightweight aggregates. When the RH in the hardening paste begins to drop, a moisture flow begins from the LWA to the drying paste thus increasing the RH and reducing the autogenous shrinkage.. The efficiency of the LWA for this behavior depends on the initial moisture content of the LWA, the size of the aggregate and its distribution. The Dutch (14) examined all of these aspects using two different LWAs; Lytag and Liapor. Most of the testing was done with Liapor.

The percentage of the water present in the LWA relative to the amount at full saturation was varied between 30% and almost 100%. Three different particle sizes of Liapor were used: 5/16-5/8 in. (8-16 mm), 5/32-5/16 in. (4-8 mm), and 0-5/32 in. (0-4 mm). The mixture proportions for the variable moisture contents and different aggregate dimensions are shown in Tables 5 and 6, respectively.

Table 5 Mixture Proportions for LWAC
With Variable Aggregate Moisture Contents for Reference 14

Material Composition	Target saturation level of Liapor		
	100%	60%	20%
Blast furnace slag cement, lb/yd^3 (kg/m^3)	401(238)	401(238)	401(238)
Portland cement, lb/yd^3 (kg/m^3)	400 (237)	400 (237)	400 (237)
Silica fume, lb/yd^3 (kg/m^3)	84 (50)	84 (50)	84 (50)
Liapor F10, 5/32- to 5/16-in. (4- to 8-mm), lb/yd^3 (kg/m^3). (absorption capacity=13%)	1035 (614)	984 (584)	1554 (922)
Sand, 0- to 5/32-in., (0- to 4-mm), lb/yd^3 (kg/m^3)	1302 (772)	1302 (772)	1302 (772)
Water, lb/yd^3 (kg/m^3) (including water in the admixtures and the silica fume slurry)	296 (176)	296 (176)	296 (176)
Admixture 1, lb/yd^3 (kg/m^3)	1.7 (1.0)	1.7 (1.0)	1.7 (1.0)
Admixture 2, lb/yd^3 (kg/m^3)	12.0 (7.1)	16.0 (9.5)	20.0 (11.9)
Water/cement ratio	0.37	0.37	0.37
Water/binder ratio	0.335	0.335	0.335

The 100% absorption capacity was determined as the 24-hour absorption by aggregate immersion. The required degrees of target saturation were obtained by spraying the aggregate. Siliceous sand was used as the fine aggregate and two superplastizers (lignosulphonate and napthalene sulphonate) were used to improve workability. The Lytag mixture(100% saturation) differs only for the type of LWA.

The mixture proportions for the LWAC with different dimensions of the aggregates are shown in Table 6. The water absorbed by the aggregates was fixed as the quantity required to saturate the type of aggregate with the lowest absorption capacity (Liapor F8, 5/16-5/8 in. (8-16 mm)). This quantity amounts to 0.152 lb of water per 1.0 lb (0.152 kg per 1.0 kg) of dry aggregates. The weight of the LWAs was different for the three mixtures, so the quantity of absorbed water also differed. The difference was quite relevant in the case of the Liapor sand, while the other two mixtures were almost equivalent.

Table 6 Mixture Proportions for LWAC
With Variable Aggregate Dimensions for Reference 14

Material Composition	Type of lightweight aggregate		
	Liapor F8 5/32-5/16 in. (4-8 mm)	Liapor F8 5/16-5/8 in. (8-16 mm)	Liapor Sand 0-5/32 in. (0-4 mm)
Blast furnace slag cement, lb/yd^3 (kg/m^3)	401(238)	401(238)	401(238)
Portland cement, lb/yd^3 (kg/m^3)	400 (237)	400 (237)	400 (237)
Silica fume, lb/yd^3 (kg/m^3)	84 (50)	84 (50)	84 (50)
Lightweight aggregate*, lb/yd^3 (kg/m^3)	920 (546)	989 (586)	649 (385)
Sand, 0- to 5/32-in., (0- to 4-mm), lb/yd^3 (kg/m^3)	1302 (772)	1302 (772)	1302 (772)
Water, lb/yd^3 (kg/m^3) (including water in the admixtures and the silica fume slurry)	296 (176)	296 (176)	296 (176)
Admixture 1, lb/yd^3 (kg/m^3)	1.7 (1.0)	1.7 (1.0)	1.7 (1.0)
Admixture 2, lb/yd^3 (kg/m^3)	12.0 (7.1)	12.0 (7.1)	12.0 (7.1)
Water/cement ratio	0.37	0.37	0.37
Water/binder ratio	0.335	0.335	0.335
***** The lightweight aggregates differ in specific weight of the particles (Liapor F8 and Liapor Sand			

The volume changes of the concretes described in Tables 5 and 6 were determined using 39.4 x 5.9 x 5.9 in.(1000 x 150 x 150 mm) concrete prisms. They were cast in a special mold that allowed heating or cooling of the specimen so that temperatures differences within the cross section of the specimen were kept at from 1.8 to 2.7^{o}F (1.0 to 1.5^{o}C). The specimens were cured isothermally at 68^{o}F (20^{o}C). The exposed surface of the specimen was sealed with a plastic foil to prevent moisture loss during the testing. The length changes of the hardening concrete were measured with LVDT's over a length of 29.5 in. (750 mm). These were positioned outside the mold and registered the relative movement of two steel bars cast in both ends of the prism. Using this method, early volume changes before the concrete hardened and adhered to the bars could not be measured.

The non-thermal length changes of concrete for mixtures with different degrees of saturation and those with different particle size are shown in Figs. 5 and 6. From Fig. 5, those aggregates with higher degrees of saturation showed swelling almost from the onset of measurements. The Liapor with a saturation of 31.2% (which is actually a moisture content of the aggregate of 4% (approx.)) showed some initial shrinkage before some swelling began.

The LWAs in the mixtures in Fig. 6 were indicated (14) as all having the same initial moisture content but that value is not given in the paper. It is assumed that it is a higher saturation value because of the observed swelling of the concrete. All three mixtures showed expansion from the beginning of the measurements (approx. 16 hours after casting). The mixture made with the Liapor sand showed the most expansion.

Fig. 7 shows the cube compressive strength development for the various mixtures with different degrees of saturation of the aggregates (See Table 5). The mixture with a saturation of 69.3% (approx. 9% moisture content of the aggregate) provided the best strengths. The Lytag aggregate, which is inherently weaker than the Liapor, produced lower strength concrete although the its strength development trend is similar to the Liapor. In all these cases, the only curing the concrete received was from the internal moisture provided by the LWA thus demonstrating the beneficial effect of this additional moisture.

The investigators (14) concluded using smaller saturated aggregate particles resulted in a more homogeneous distribution of the water-containing particles and shorter transport distances of the moisture from the aggregate to the drying paste. They recommended that a partial substitution of normal weight aggregates with LWAs be used to reduce autogenous shrinkage in HPC with low w/c ratio and that this LWA be of small size and fully saturated to be most effective.

An investigation of the effects of LWA fractions used to replace portions of the normal weight aggregate in HSC (15) included some observations on reducing autogenous shrinkage. The research found that the compressive strength, the compressive strain at maximum stress, and flexural strength all increased as the mean particle size of fraction replaced by LWA decreased. The investigators also noted that the replacement of fine fractions of HSC by lightweight fines provides better workability in the fresh state and may reduce autogenous shrinkage in HSCs.

SAUDI ARABIAN RESEARCH

In the arid areas of the Middle East, continuous wet curing is typically required for at least 7 days. When it is done, it usually is by spraying and is a very costly process. The high temperature and low relative ambient humidity evaporate most of this water. Arafah (16) examined the effect of moist curing versus dry curing on compressive strength of concrete made with a lightweight coarse aggregate that was volcanic in nature and was categorized as pozzolanic scoria and tuff. The mixture proportions are shown in Table 7. The LWA was submerged in water for 24-hours to allow most of the pores in the aggregate to become water-filled. Just prior to batching, the LWA was spread on burlap outside the laboratory (Saudi Arabia) for 30-minutes to get a dry surface condition. The test specimens were 6-in. (150-mm) cubes. All cubes were cured in the molds for 24-

hours at 73°F (23°C). One half of the total number of specimens were then cured in water at the same temperature while the other half were stored in air at that temperature but at 43% relative humidity. All cubes were tested for compressive strength at 28-days age. The results are shown in Table 8. The conclusions reached (16) were that dry curing performs as well as moist curing when pre-wetted lightweight coarse aggregate is used in LWC. The comparable performance of the LWC that received no moist curing was attributed to the presence of humidity in the LWA that maintained the required hydration process.

Table 7 Mixture Proportions for Reference 16

Material	Mixture Proportions lb/yd^3 (kg/m^3)
Cement	590 (350)
Silica Sand	1380 (820)
Lightweight Aggregate	1165 (690)
Free Water	206.5 (122.5)
Superplasticizer	38 oz/100 lb of cement (2.5 L/100 kg of cement)

Table 8 Compressive Strength Results for Ref. 16

Type of Curing	Number of Specimens	Mean Compressive Strength, psi (MPa)	Standard Deviation psi (MPa)
Moist	30	4950 (34.13)	400 (2.76)
Dry	30	5100 (35.15)	260 (1.78)

ISRAELI RESEARCH

In Israel, the use of wet lightweight aggregate as an internal source of water to counteract self-desiccation and the development of stresses in restrained conditions was studied (17). A commercial LWA (Leca) of a single size fraction (3/16- to 3/8-in. (4.5- to 9-mm)) was used. Because of the small size specimens that were evaluated, this size fraction was sieved to a maximum aggregate size of 1/4-in. (7-mm) with a fineness modulus (FM) of 1.52. The NWA was a mixture of crushed dolomite and fine silica sand with a FM of 3.95. The LWA had a specific gravity at SSD condition after 24-hr absorption of 1.38. Water absorption at 24-hr was 8.9% and increased to 11.0% at 72-hr.

Five concretes were studied: a normal density (no LWA) concrete which was the control; two LWACs where one used air-dry (AD) LWA and the other used a SSD LWA; and two concretes where 25% of the total volume of aggregates was either the AD or SSD LWAs with the rest being normal density aggregates. The mixture proportions are shown in Table 9. Both restrained and free shrinkage tests were conducted on 1-9/16x1-9/16x39-3/8-in. (40x40x1000-mm) concrete prisms sealed with a plastic sheet immediately after casting and placed and tested in a controlled environment of 86°F (30°C). Compressive strength cubes (2-in. (50-mm)) were also cured at that temperature. The shrinkage test apparatus allowed the concrete to be cast directly into molds on the apparatus. Testing was done in pairs with one of the specimens being restrained on both ends and the other only restrained on one end.

Table 9 Mixture Proportions for Reference 17

Mixture Variable	w/b	Materials lb/yd^3 (kg/m^3)					
		Water	Cement	Silica Fume	NWA	LWA	Superplasticizer % wt. of binder
NWA	0.33	275 (163)	748 (444)	83 (49)	2894[a] (1717)[a]	----	1.5
AD-LWA	0.33	275 (163)	748 (444)	83 (49)	964[b] (572)[b]	981[c] (582)[c]	2.2
SSD-LWA	0.33	275 (163)	748 (444)	83 (49)	964[b] (572)[b]	944[d] (560)[d]	1.8
25% SSD	0.33	275 (163)	748 (444)	83 (49)	2166[a] (1285)[a]	371[c] (220)[c]	2.0
25% AD	0.33	275 (163)	748 (444)	83 (49)	2166[a] (1285)[a]	357[d] (212)[d]	2.0

a. Mixture of normal-weight coarse aggregate and sand.
b. Sand.
c. Based on SSD condition.
d. Based on the specific gravity to allow absorption for 30 minutes.

The results of the free autogenous shrinkage can be seen in Fig.8 for the LWAC and the NWC. NWC began to shrink after an initial small expansion. Thereafter, autogenous shrinkage of the concrete increased monotonically with time. The autogenous shrinkage behavior of the LWAC was quite different than that of the NWC as its time-dependent tendency depended on the initial moisture states of the LWA. Autogenous shrinkage was completely eliminated when the LWA was in a SSD condition when cast into the concrete. Fig. 9 shows the development of the restraining stresses with time. The restrained autogenous shrinkage for the NWC continued to increase with time until a tensile failure occurred at 6-days when the stress was approximately 435 psi (3 MPa). The LWAC with the SSD aggregate developed very little restrained stress due to the continued hydration, and subsequent expansion, of the binder. The lower modulus of the LWAC caused by the LWA also contributed to this reduction.

Similar results were observed for the concretes with the 25% partial replacement of the coarse aggregate by LWA (Figs. 10 and 11). The results of the compressive strength tests can be seen in Fig. 12 that indicates that having the additional moisture in the concrete has little adverse effect on strength at least up to 7-days age. The differences in strength are the result of the weaker lightweight aggregate and the amount of it in the concrete.

The investigators concluded (17) that:

1. Autogenous shrinkage did not occur in the LWAC with SSD lightweight aggregate. However, expansion was observed in the concrete due to an additional hydration reaction of the cement due to the supply of internal water from the LWA.
2. A partial replacement of normal-weight aggregate by SSD lightweight aggregate was effective in eliminating all the autogenous shrinkage in high-strength concrete.
3. The water retained in air-dry LWA was not sufficient to prevent autogenous shrinkage, although it did reduce its magnitude significantly.
4. The development of stress induced by restrained autogenous shrinkage was consistent with magnitude of free autogenous shrinkage. The stress was reduced by the use of SSD lightweight aggregate, or by partial replacement with SSD lightweight aggregate.

JAPANESE RESEARCH

The Japanese (18) also investigated the use of saturated, coarse size LWA to reduce autogenous shrinkage. Three different LWAs were studied. The first, designated LA, is a crushed and coated type made from expanded shale. The next two, designated HLA1 and HLA2, are pelletized and coated, made from finely ground perlite powder, a binder, and a gas-forming agent. These two aggregates have a coated surface with an interior of closed micro cells that tend to keep the absorption fairly low. A reference mixture using crushed stone was also evaluated. All the mixtures used crushed sand as the fine aggregate. The coarse aggregates were treated in three ways: oven-dried, 24-hour immersion and 2-hours of boiling. Table 10 shows the physical properties of these aggregates. Table 11 shows the mixture proportions for this study.

The concrete specimens were evaluated were prisms nominally 4- by 4- by 16-in. (10- by 10- by 40-cm). Autogenous shrinkage was measured by a 4-in. (10-cm) imbedded strain gage at the center of each prism. An embedded thermocouple allowed the observed strains to be corrected for any thermal contribution from the hydration of the cement. From initial set to 24-hours, the concrete was kept sealed in casting molds that had been fitted with a Teflon sheet to allow free movement of the concrete as it changed volume. After 24-hours, the molds were removed and the specimens sealed with adhesive aluminum tape. The specimens were stored at 68^{o}F (20^{o}C) and 60 percent relative humidity (RH) for the test program.

Table 10 Physical Properties of Coarse Aggregate for Reference 18

Aggregate Type	LA	HLA1	HLA2	CS
Specific gravity in oven-dry condition	1.27	1.17	0.94	2.62
Water absorption (vol. %)				
By immersion for 24-hours	22.3	4.42	4.79	1.94
By boiling for 2-hours	35.4	9.67	8.70	----
Maximum size, in. (mm)	5/8-in. (15)	5/8-in. (15)	5/8-in. (15)	5/8-in. (15)
Fineness modulus	6.47	6.48	6.40	6.51

Figs. 13 and 14 show the measured shrinkage for the HLA1 and LA mixtures, respectively. For the HLA1 concrete (Fig. 13) where the aggregate is pelletized and has a sealed surface, it appears that the simple 24-hour immersion does not provide sufficient moisture in the aggregate to significantly reduce the autogenous shrinkage. For the LA concrete (Fig. 14), the crushed expanded shale aggregate has a more vesicular structure with interconnected pores and thus is capable of absorbing and retaining more water during the pre-wetting of the aggregate and batching of the concrete. That moisture contributes to a swelling of the concrete due to improved hydration that, in turn, eliminates the autogenous shrinkage in this case. Table 12 shows the effects of the quantity of HLA1 used. The aggregate was immersed for 24-hours and had a moisture content 0f 4.42% when batched. Even at low absorptions of the HLA1 aggregate, the more of it that is used, the more additional moisture that is put into the concrete, thus helping reduce the autogenous shrinkage.

Table 11 Mixture Proportions for Reference 18

Aggregate Type	Moisture Content, vol. %	Cement lb/yd^3 (kg/m^3)	Coarse Aggregate ft^3/yd^3 (L/m^3)	Sand/ Aggregate %	Water lb/yd^3 (kg/m^3)	w/c
LA	22.3 (immersed) 0.0 (oven-dried) 35.4 (boiled)	873 (518)	9.45 (350)	43.3	280 (166)	0.32
HLA1	4.42 (immersed) 0.0 (oven-dried) 9.67 (boiled)	873 (518)	8.64 (320) 10.26 (380) 9.45 (350)	48.2 38.5 43.3	280 (166)	0.32
HLA2	4.79 (immersed)	873 (518)	9.45 (350)	43.3	280 (166)	0.32
CS	1.94 (immersed)	873 (518)	9.45 (350)	43.3	280 (166)	0.32

Table 12 Effect of Quantities of LWA
on Autogenous Shrinkage

Time, days	Autogenous Shrinkage (x10^{-6})		
	10.26 ft^3/yd^3 (380 L/m^3)	9.45 ft^3/yd^3 (350 L/m^3)	8.64 ft^3/yd^3 (320 L/m^3)
0.08	0	0	0
0.28	-20	-20	0
0.40	-30	-30	30
0.50	-30	35	60
1	5	60	115
10	142	215	265
100	255	305	350

The Japanese investigators concluded that autogenous shrinkage of lightweight concrete:

1. Is smaller than that of normal weight concrete.
2. Is related directly to the permeability and absorption capacity of the aggregate.
3. Decreases with increasing moisture content and unit quantity of lightweight aggregate.

USA RESEARCH

Work done in the United States by the Northeast Solite Corporation (19,20,21) used a crushed expanded shale aggregate to promote the internal curing of paving concretes having a water-cement ratio of 0.4 to 0.45. In a series of tests performed in 1999-2000, a standard paving mixture had partial normal weight aggregate replacements made by both lightweight fines and lightweight coarse aggregate (3/8-in. to #8 (9.5- to 2.4-mm)). In separate mixtures, both the natural sand and the normal weight coarse aggregate had LWA replacements of 100-, 200- and 300-lb/yd^3 (59-, 119- and 178-kg/m^3). LWAs from two different sources were used in comparable mixtures. From these mixtures, Table 12 is a summary of the mixture proportions used for the 100-lb/yd^3 (59-kg/m^3) replacement of LWA fines. The LWA fines were saturated when used and had an absorption of 15%.

Table 12 Summary of Mixture Proportions from Reference 19

Constituent	Normal Paving Mixture	New York Solite® Sand Replacement	Kentucky Kenlite® Sand Replacement
Cement, lb/yd^3 (kg/m^3)	588 (349)	588 (349)	588 (349)
Coarse Aggregate, lb/yd^3 (kg/m^3)	1900 (1127)	1900 (1127)	1900 (1127)
NW Fine Aggregate, lb/yd^3 (kg/m^3)	1257 (746)	1123 (666)	1107 (657)
LW Fine Aggregate, lb/yd^3 (kg/m^3)	-----	100 (59)	100 (59)
Water, lb/yd^3 (kg/m^3)	255 (151)	255 (151)	255 (151)
Pozzolith 322N, oz./yd^3 (L/m^3)	29.4 (1.14)	29.4 (1.14)	29.4 (1.14)
MicroAir, oz./yd^3 (L/m^3)*	5.9 (0.23) or 10.3 (0.40)	8.2 (0.32)	10.3 (0.40)
w/c ratio	0.43	0.43	0.43
*Higher amount of AEA used with Kentucky Kenlite.®			

Table 13 shows the results of the tests on the freshly mixed concrete. The addition of either of the LWAs had virtually no affect on the unhardened characteristics of the concrete. Table 14 shows the results of tests on the hardened concrete. Improvements were observed in concrete with the LWA additions for all the physical characteristics that were measured. Of particular note are improvements in both the compressive and tensile strength and also in the resistance to chloride ion penetration as measured by ASTM C 1202 (AASHTO T 277) “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride-Ion Penetration”. Experience with small additions of crushed lightweight aggregate as a replacement for normal weight aggregates in concrete typically shows some strength improvement because the vesicular surface of the LWA allows penetration of the cement binder into the aggregate with a resulting improvement in the transition zone (22,23). The improvements in the coulomb ratings indicate a denser matrix that is attributed to the additional hydration products that formed because of the availability of water from the LWA fines.

Table 13 Summary of Test Results on Unhardened Concrete for Refs. 19 and 20

Physical Test	Normal Paving Mixture	Companion New York Solite®	Normal Paving Mixture	Companion Kentucky Kenlite®
Slump, in. (mm)	1.5 (38)	2.0 (51)	2.0 (51)	2.0 (51)
Air Content, %	5.5	6.1	6.2	5.9
Unit Weight, lb/ft^3 (kg/m^3)	149.2 (2390)	146.7 (2350)	147.2 (2360)	145.8 (2335)
Temperature, ^{o}F (^{o}C)				
Air	75 (23.9)	75 (23.9)	72 (22.2)	72 (22.2)
Concrete)	69 (20.6)	69 (20.0)	68 (20.0)	66 (18.9)

Table 14 Summary of Physical Test Results on Hardened Concrete (Refs. 19,20,21)

Physical Test	Normal Paving Mixture	Companion New York Solite®	Normal Paving Mixture	Companion Kentucky Kenlite®
Compressive Strength, psi (MPa)				
7-days	4480 (30.9)	5200 (35.8)	4290 (29.6)	4420 (30.5)
28-days	5770 (39.8)	6420 (44.3)	4750 (32.7)	5400 (37.2)
56-days	6190 (42.7)	6880 (47.4)	5300 (36.5)	5630 (38.8)
84-days	6280 (43.3)	6880 (47.4)	5570 (38.4)	6180 (42.6)
Splitting Tensile Strength (28-days), psi (MPa)	500 (3.45)	530 (3.65)	500 (3.45)	540 (3.72)
Flexural Strength, psi (MPa)*				
3-days	580 (4.0)	675 (4.6)	-----	-----
7-days	755 (5.2)	780 (5.4)	-----	-----
28-days	860 (5.9)	890 (6.1)	-----	-----
Modulus of Elasticity (28-days), psi x 10^6 (GPa)	4.77 (32.9)	5.35 (36.9	4.77 (32.9)	5.51 (38.0)
Permeability, coulombs				
28-days	2985	2375	2985	-----
56-days	2460	1825	2460	-----
84-days	-----	-----	-----	1745
Durability Factor, % (avg.), 300 Cycles of Freeze/Thaw,				
ASTM C 666-Procedure A	-----	-----	-----	96.2
ASTM C 666-Procedure B	82.4	84.0	82.4	-----
Unit Weight, lb/ft^3 (kg/m^3)	149.2 (2390)	146.7 (2350)	149.2 (2390)	145.8 (2335)
* Flexural beams made from a different series of mixtures but the same proportions (20).				

An additional test program was begun in 2001 to compliment the original Northeast Solite work. This program examined the partial replacement of cement with fly ash and a reduction in the water-binder ratio to produce a high-performance paving mixture.

Mitigation strategies for reducing or eliminating autogenous shrinkage cracking and self-desiccation have also been proposed and discussed by the U.S. National Institute for Standards and Technology (NIST) (24, 25). Bentz and Jensen (24) noted that the pore structure of aggregate particles may have a strong effect on self-desiccation shrinkage and that aggregate particles containing water in coarse pores may provide internal curing for the hydrating cement paste. In this case, the formation of empty pores due to chemical shrinkage takes place first in the coarser aggregate pores and does not involve the fine pores in the cement paste. They also noted that active use of this principle had been carried out with saturated lightweight aggregate particles (6,26,27) and that it had been demonstrated by both computer simulation (10) and experiments (14) that self-desiccation shrinkage is best minimized by the use of fine saturated lightweight aggregates as opposed to coarser ones. The fine saturated lightweight aggregates result in a more uniform distribution of the needed curing water throughout the microstructure. They suggest that by using this technique, self-desiccation shrinkage could be completely eliminated.

A NIST study (25) of mortars was conducted using a low-alkali cement and a water-binder mass ratio (w/(c+sf)) of 0.35 with a mass replacement of the cement (c) with silica fume (sf) of 8%. For two of the mortars, either 8% or 20% of the sand by mass was replaced by saturated lightweight aggregates of size less than 5/32-in. (4-mm). Mortar cylinders of 2.4-in. diameter and 4.7-in. height (60 by 120 mm) were cured at 86 $\pm$ 0.9 ^{o}F (30 $\pm$ 0.5 ^{o}C) under sealed conditions. Compressive strength, internal relative humidity (RH), and autogenous deformations were measured at ages up to 28-days. Regardless of which amount of saturated lightweight aggregate sand was used, the internal RH was at 94-95% at 15 to 18 days age whereas the companion mixture without the saturated fines had a RH of 87-88% at 18 days age thus indicating an internal curing benefit from the saturated lightweight fines. Autogenous shrinkage was completely eliminated for the 20% replacement and, for the 8% replacement, was reduced (at 18-days age) to 50% of the no-lightweight fines shrinkage. At 28-days age, both mortars containing the lightweight fines had slightly improved compressive strengths (up to 500 psi (3.5 MPa) more) than the no-lightweight mortar.

STRENGTH CONTRIBUTIONS BY THE LWA

In general, LWAs are less stiff and strong than normal weight aggregates and thus may or may not slightly reduce the concrete strength depending on a number of considerations. Their contribution to strength depends on the type and quality of the LWA, the size fraction used, the amount of aggregate used, and the type and quality of the binder in the concrete. In general, crushed LWAs provide a better surface for binder interaction than do LWAs with a sealed surface that often results from a pelletizing process. The vesicular surface resulting from the crushing operation allows paste penetration and provides more surface area for any reaction between the aggregate and paste to occur. It is believed that the transition zone associated with a crushed aggregate has advantages over a more smooth and sealed surface. It has been demonstrated by both computer simulation (10) and experiments (13) that self-desiccation shrinkage is best minimized by the use of fine saturated lightweight aggregate particles (6,11,24) as opposed to coarser particles, as the fine particles result in maximizing distribution of the needed curing water throughout the microstructure. This should completely eliminate self-desiccation. The use of soft or friable lightweight fines may result in some reductions of strength. Consequently, it is helpful to perform a mortar cube strength test (ASTM C 109C/109M) of the lightweight fines being considered for use. Small amounts of lightweight fines replacement generally increase the modulus of elasticity of the concrete whereas larger replacement amounts may decrease the modulus of elasticity. Slight reductions in the modulus of elasticity of the concrete can be beneficial in reducing cracking. Table 14 shows the influence of both the size fraction and the amount of lightweight fines replacement of the normal weight sand in the normal weight concrete mixture.

Table 14 Effect of Lightweight Fines on Modulus of Elasticity*

Modulus of Elasticity, psi x 10^6 (GPa)						
Normal Weight Concrete (No LWA)	LWA Fines Replacement, 3/8 in. to #8 (9 mm to 2.36 mm) lb/yd^3 (kg/m^3)			LWA Fines Replacement, #4 to 0 (4.75 mm to 0) lb/yd^3 (kg/m^3)		
	100 (59)	200 (119)	300 (178)	100 (59)	200 (119)	300 (178)
4.891 (33.7)	5.298 (36.5)	4.691 (32.3)	4.441 (30.6)	5.246 (36.2)	5.307 (36.6)	4.427 (30.5)
4.658 (32.1)	5.020 (34.6)	5.415 (37.3)	4.163 (28.7)	5.454 (37.6)	4.797 (33.1)	4.832 (33.3)

* Data from Northeast Solite® Corp.

While the moisture contained in any size of saturated LWA will contribute to the continued hydration of the binder, larger size aggregates are not as effective as small size fractions because of the difference in spatial distribution. Excellent internal curing results have been obtained by using saturated LWAs in the size #4 (4.75 mm) with 2-4% retained on the #4 (4.75 mm).

The amount of LWA used to achieve substantial internal curing is a function of the type of LWA used, its size and amount, the degree of moisture preconditioning the LWA receives, the amount and type of binder(s) in the mixture, the water-binder ratio at mixing, and the amount and duration of external moist curing provided to the concrete element. An optimization between the need for internal moisture in the concrete to reduce autogenous shrinkage while also obtaining the desired strengths and other mechanical properties must be achieved and can usually be obtained by trial mixtures.

PRACTICAL CONSIDERATIONS

Introducing LWA does not substantially change the mixing procedure or time of mixing provided the LWA is adequately pre-wetted. The most economical way to do this is to have the aggregates shipped SSD from the aggregate supplier, and then regaining any moisture lost during shipping by sprinkling for 24-hours or until the SSD condition is regained. Continued sprinkling may be necessary to maintain the needed moisture conditioning of the aggregate during prolonged periods of concrete production.

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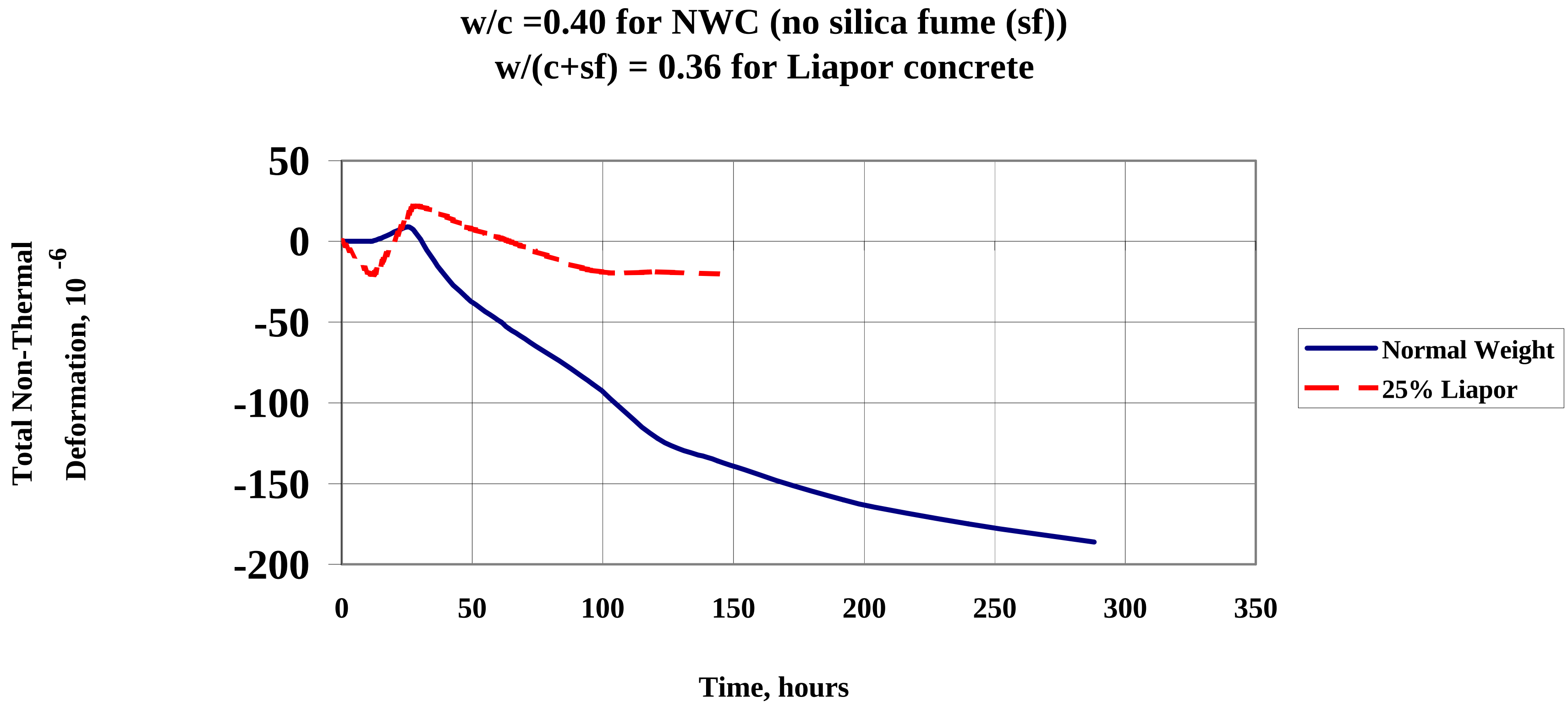

Fig. 1 Non-Thermal Deformation versus Age Relationship for Normal Weight Concrete (NWC) and Liapor Concrete (Ref. 11)

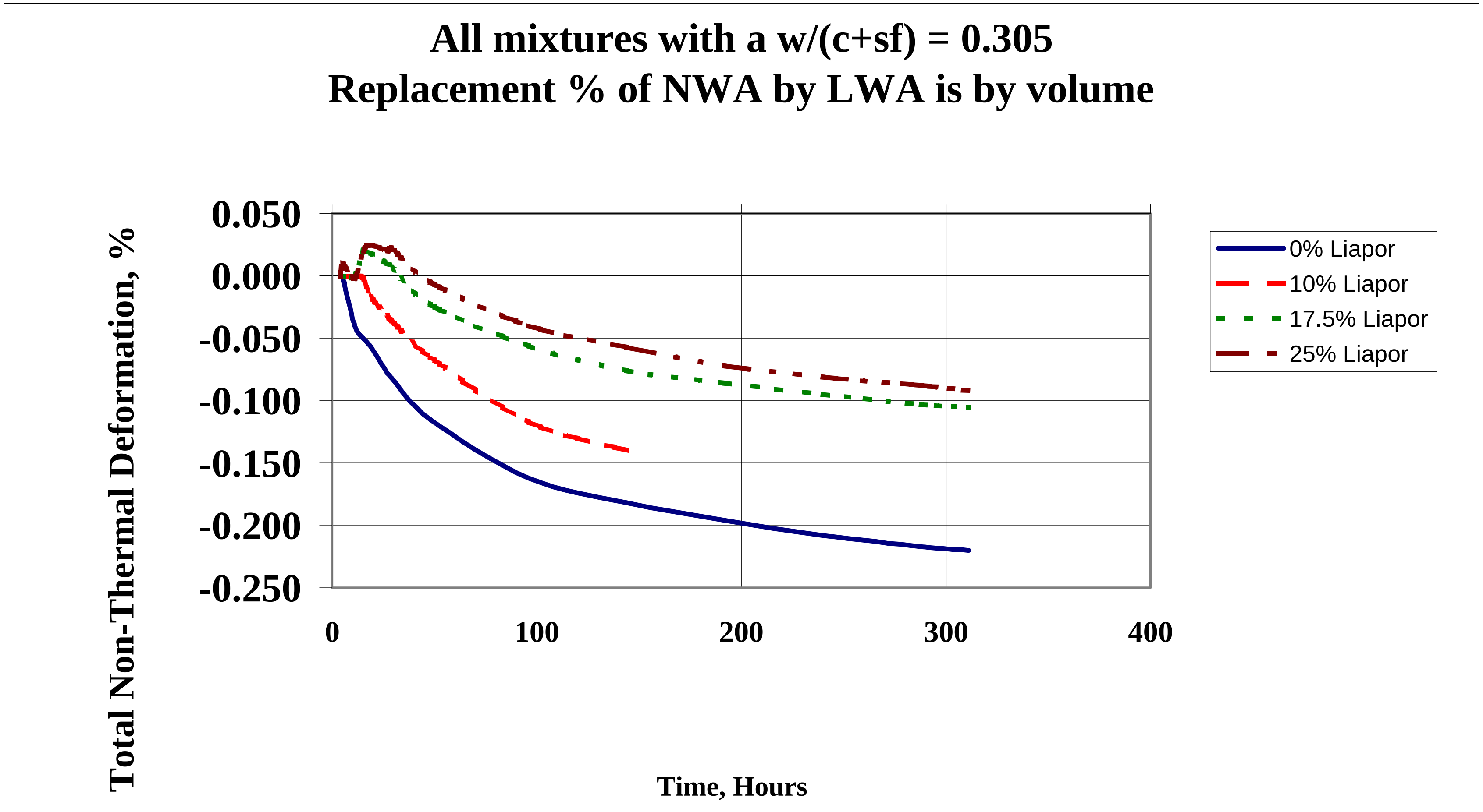

Fig. 2 Effect of Lightweight Aggregate Replacements of Normal Weight Aggregates on Total NonThermal Deformations (Ref. 11)

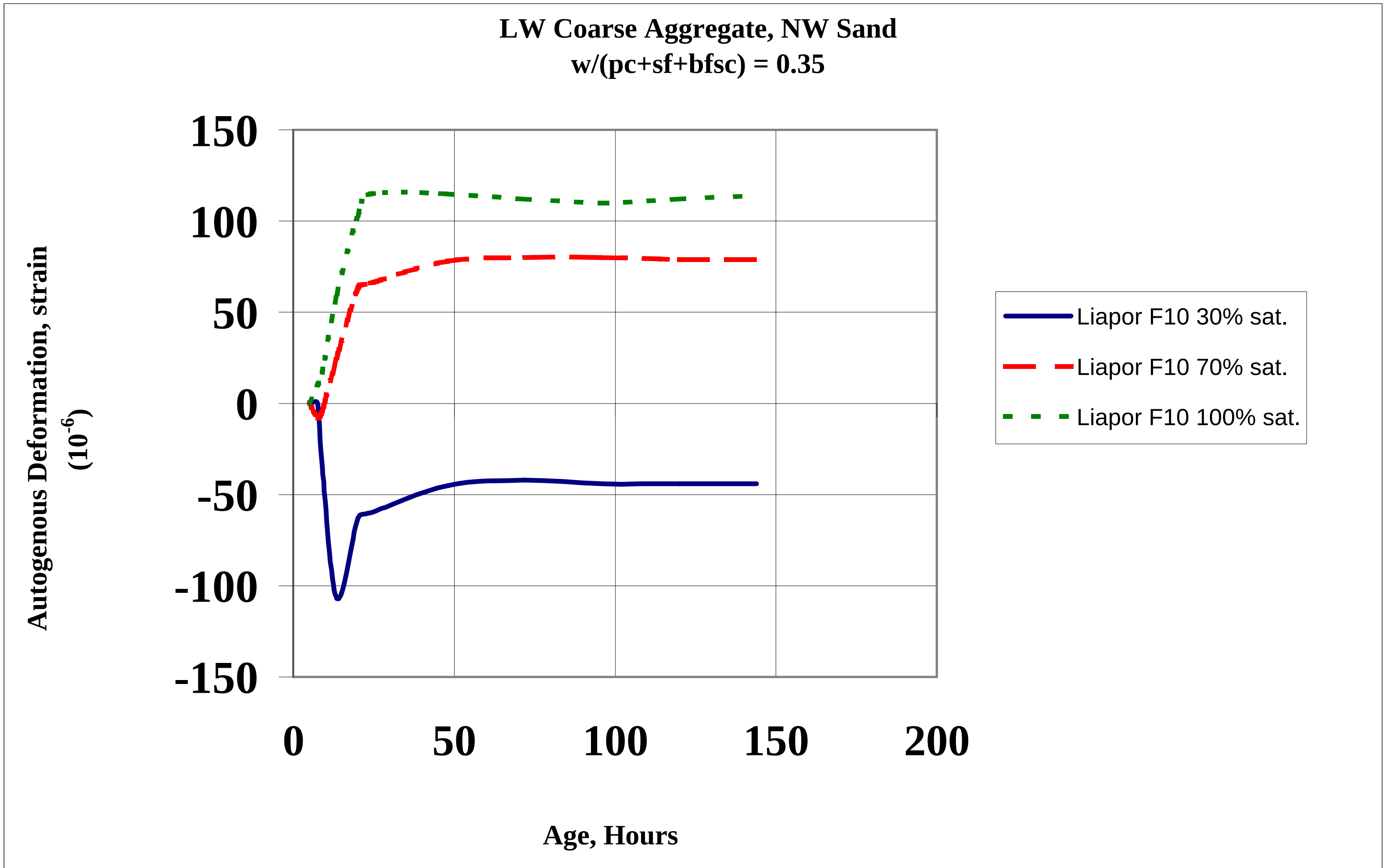

Fig. 3 Effects of Degree of Lightweight Aggregate Saturation on Amount of Autogenous Shrinkage (Ref. 13)

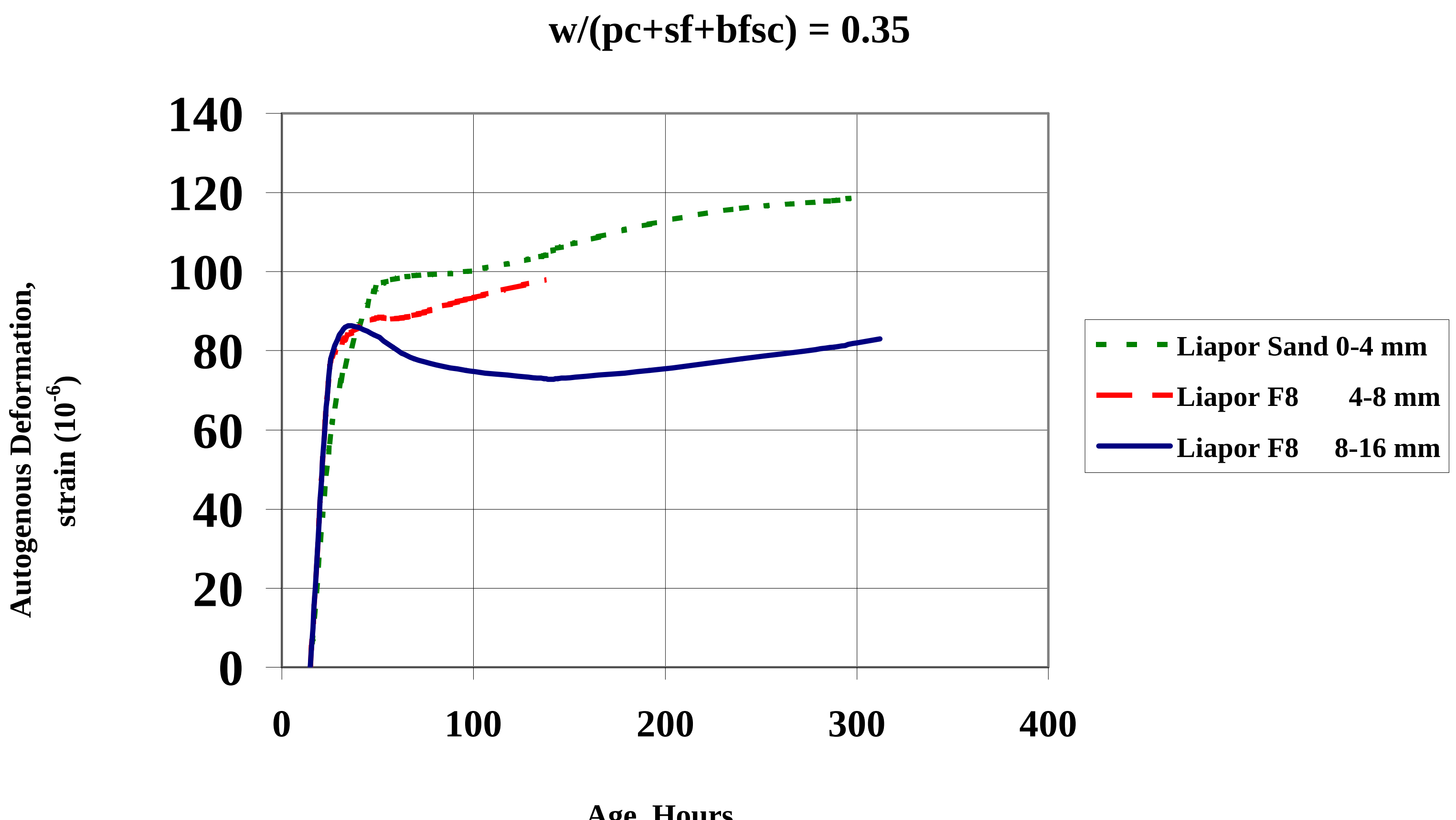

Fig. 4 Effects of Lightweight Aggregate Size Fractions on Amount of Autogenous Shrinkage (Ref. 13)

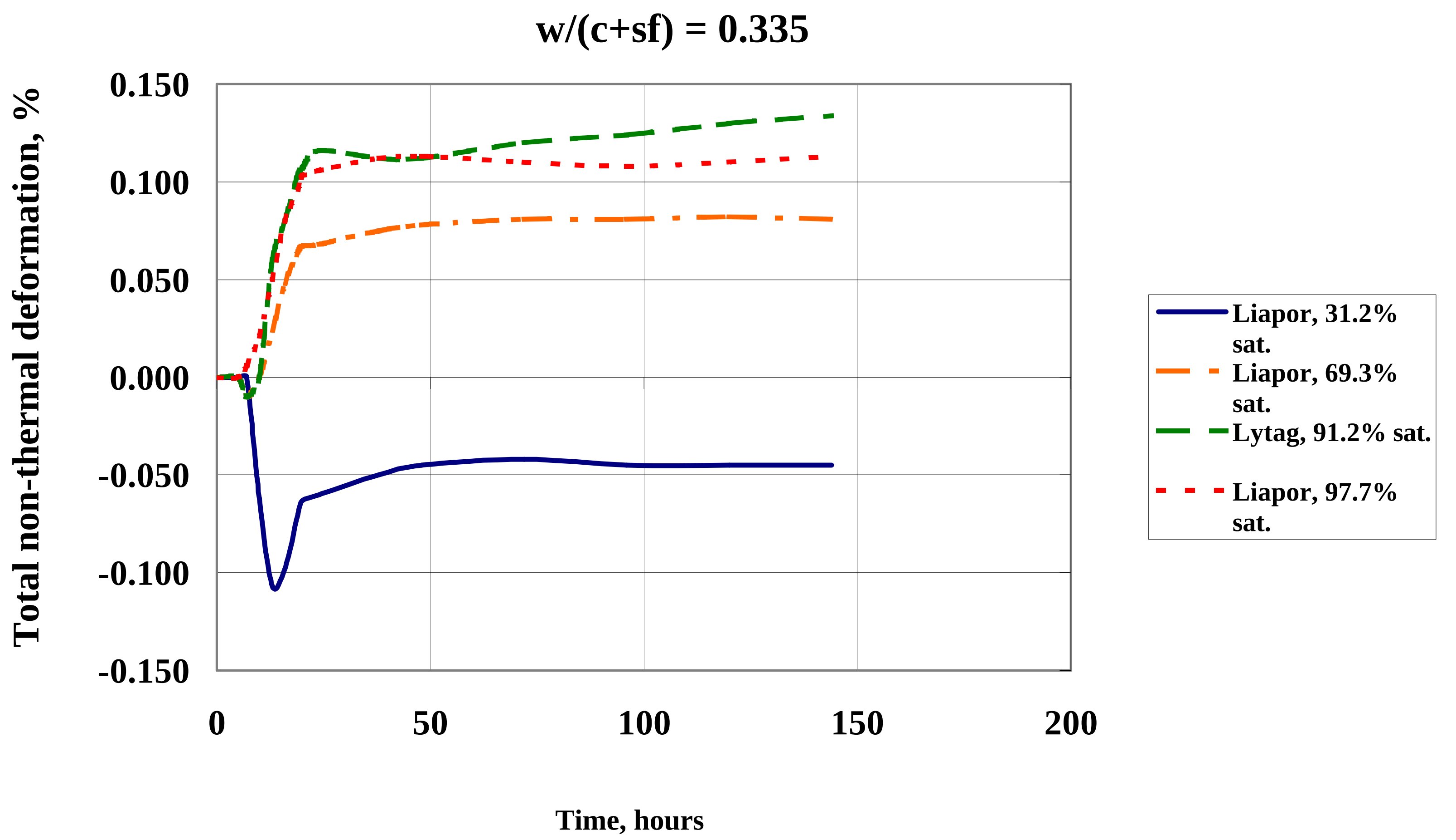

Fig. 5 Effects of Degree of Lightweight Aggregate Saturation on Amount of Non-Thermal Deformations (Ref. 14)

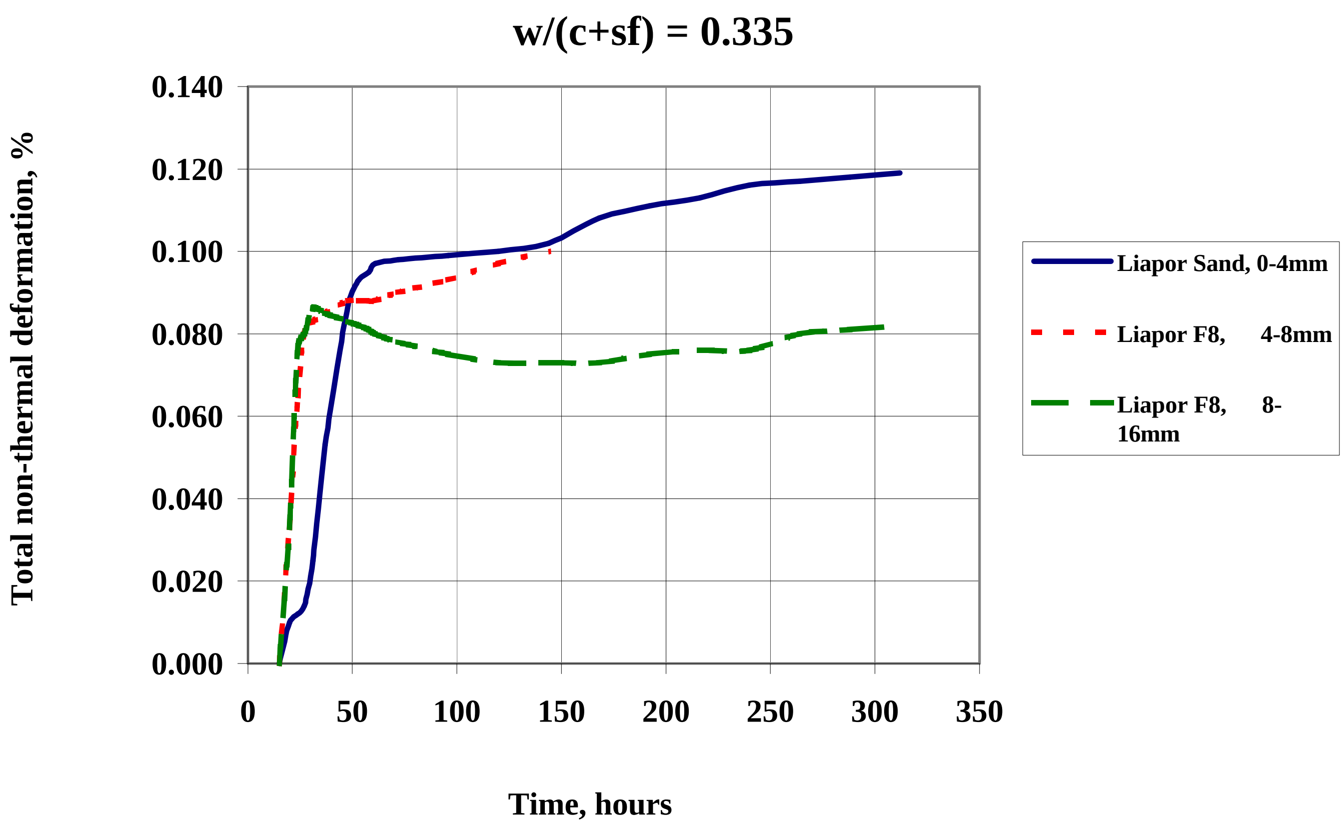

Fig. 6 Effects of Lightweight Aggregate Size Fractions on Amount of Non-Thermal Deformations (Ref. 14)

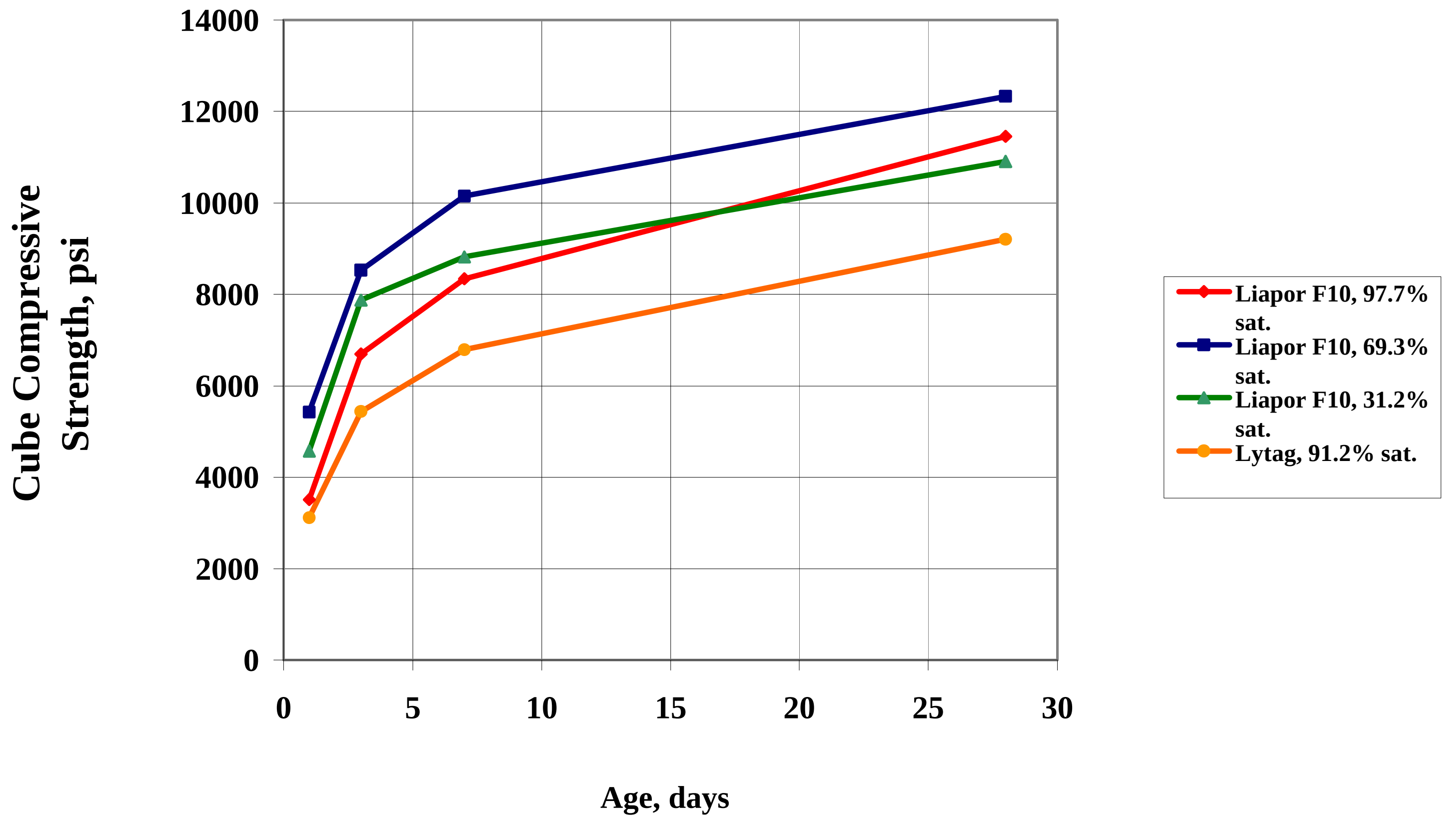

Fig. 7 Effects of Degree of Lightweight Aggregate Saturation on Cube Compressive Strength with Time (Ref. 14)

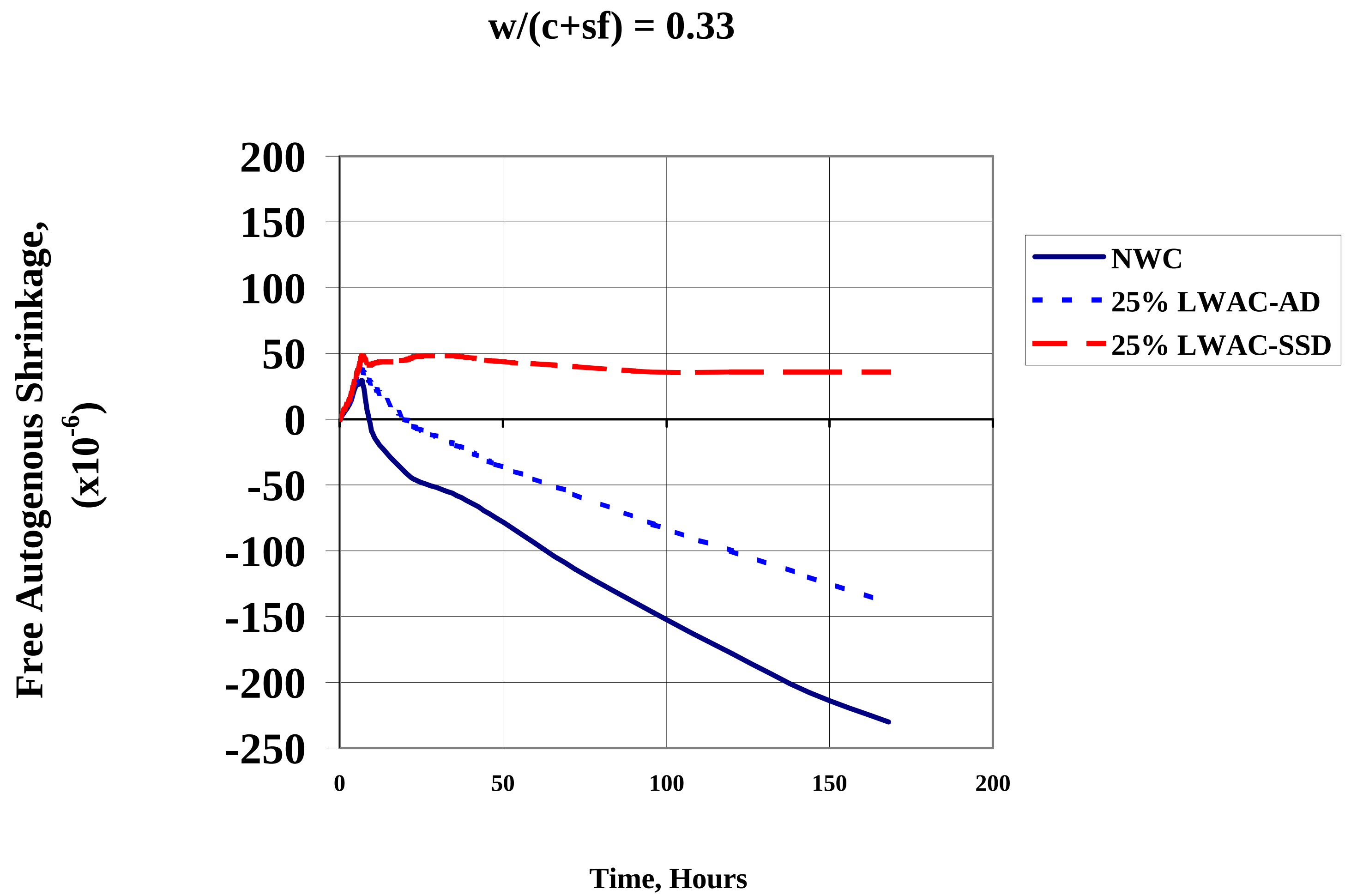

Fig. 8 Effect of Lightweight Aggregate Pre-Conditioning on Free Autogenous Shrinkage with Time (Ref. 17)

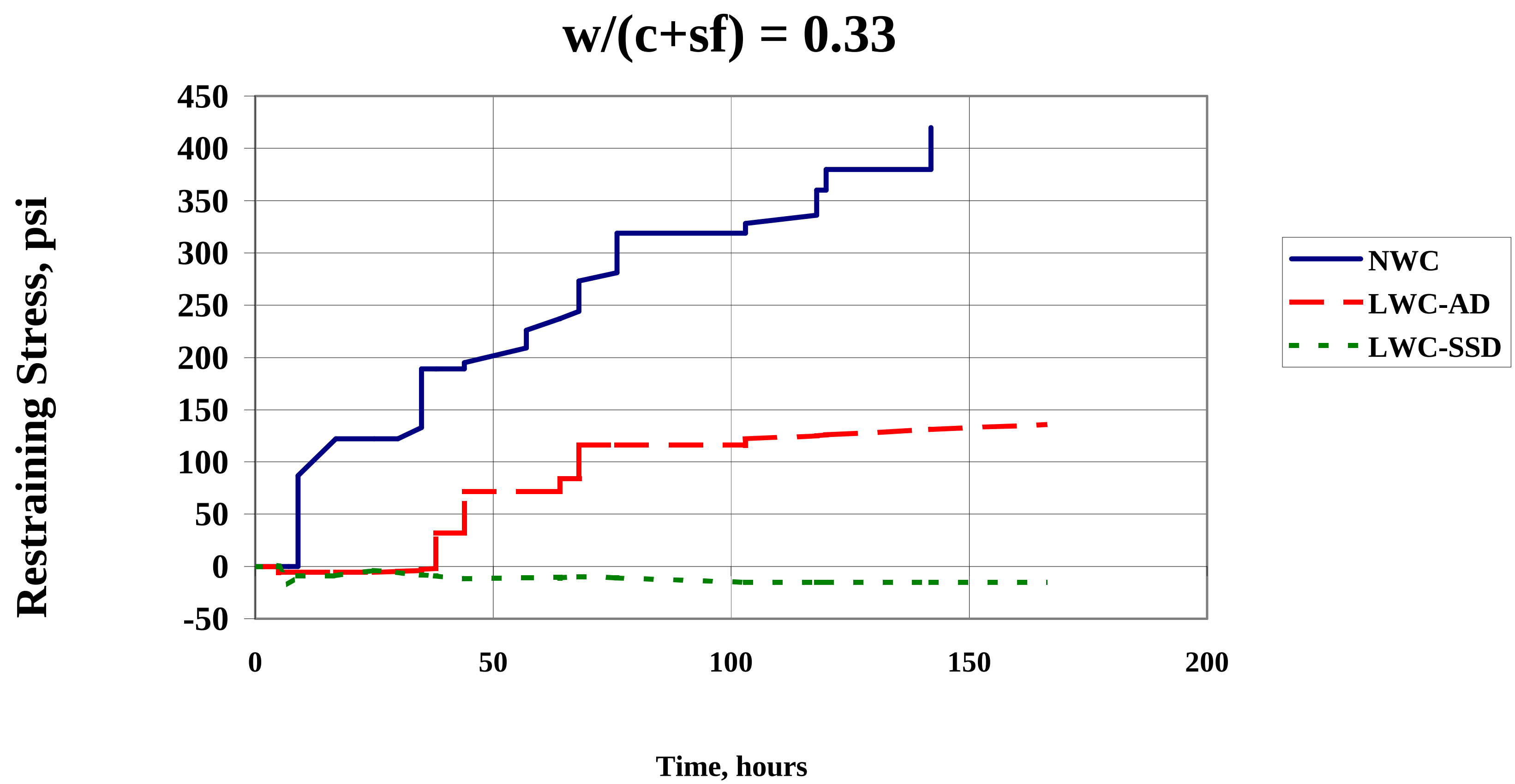

Fig. 9 Effect of Lightweight Aggregate Pre-Conditioning on Restraining Stress Development with Time (Ref. 17)

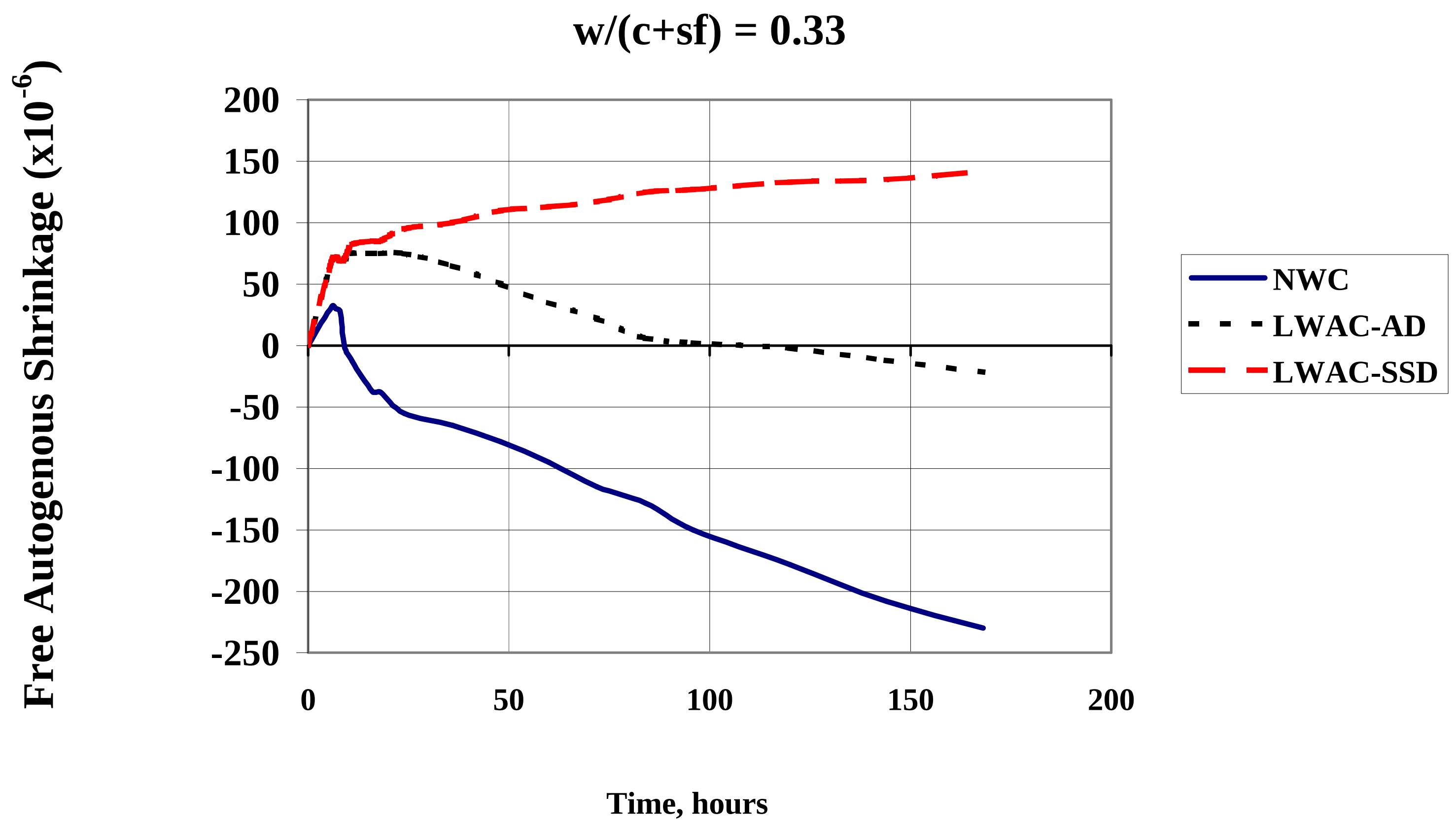

Fig. 10 Effect of Lightweight Aggregate Pre-Conditioning and Partial Replacement of Normal Weight Aggregate on Free Autogenous Shrinkage with Time (Ref. 17)

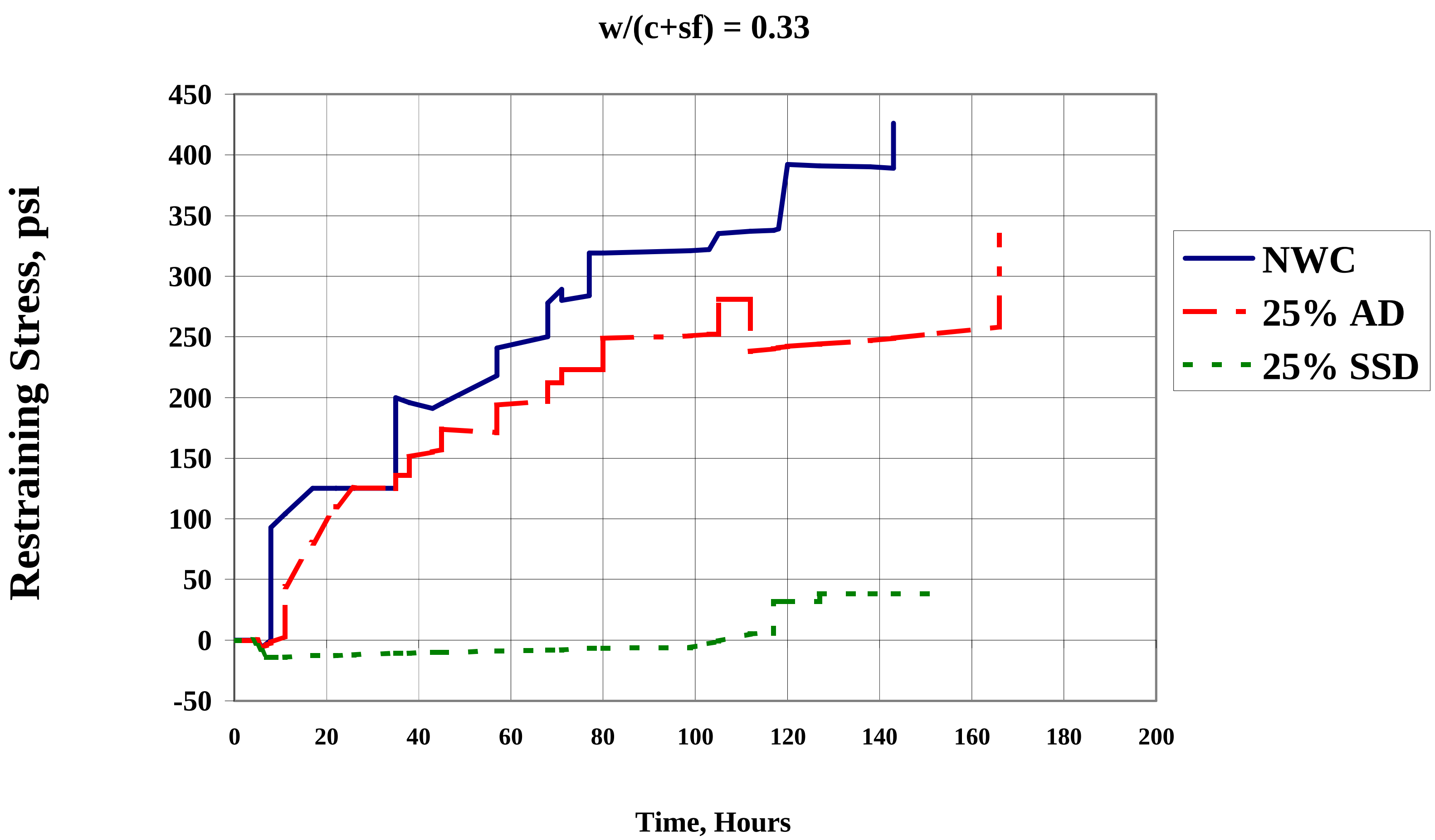

Fig. 11 Effect of Lightweight Aggregate Pre-Conditioning and Partial Replacement of Normal Weight Aggregate on Restraining Stress Development with Time (Ref. 17)

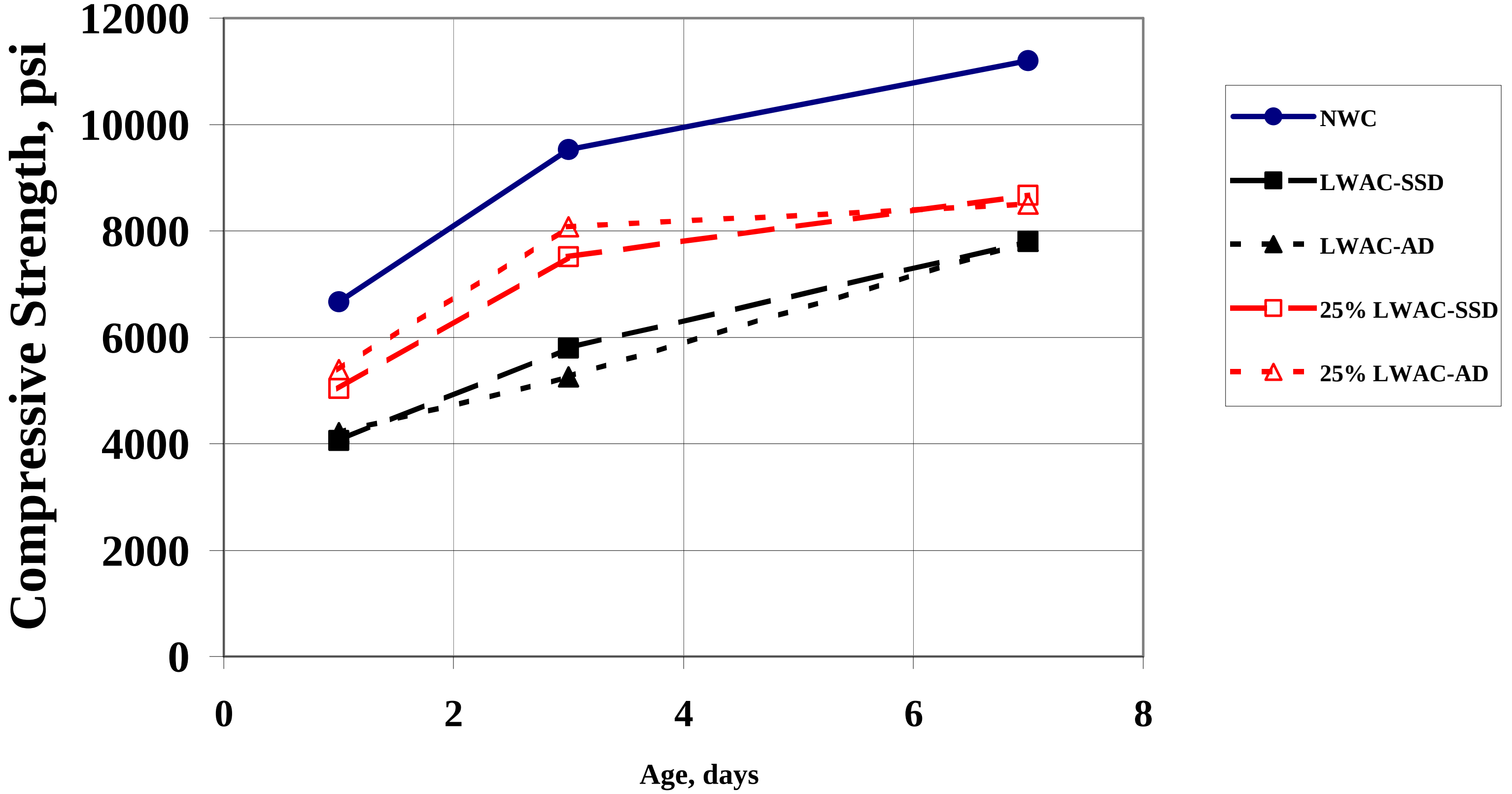

Fig. 12 Compressive Strength versus Time Relationship for Varying Degrees of Lightweight Aggregate Pre-Conditioning and Aggregate Replacements (Ref. 17)

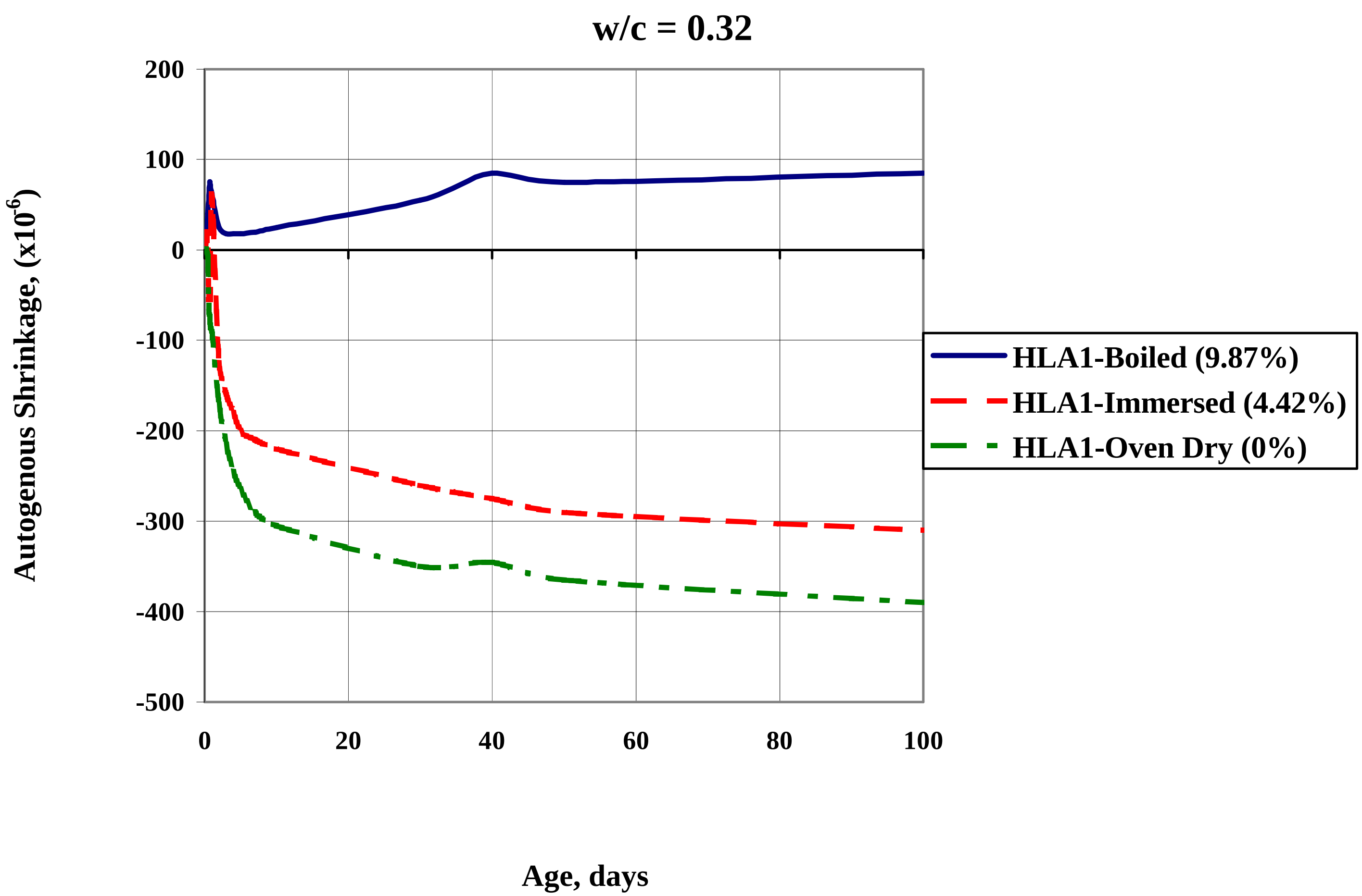

Fig. 13 Effect of Degree of Saturation of Pelletized and Coated Lightweight Coarse Aggregate on Autogenous Shrinkage with Time (Ref. 18)

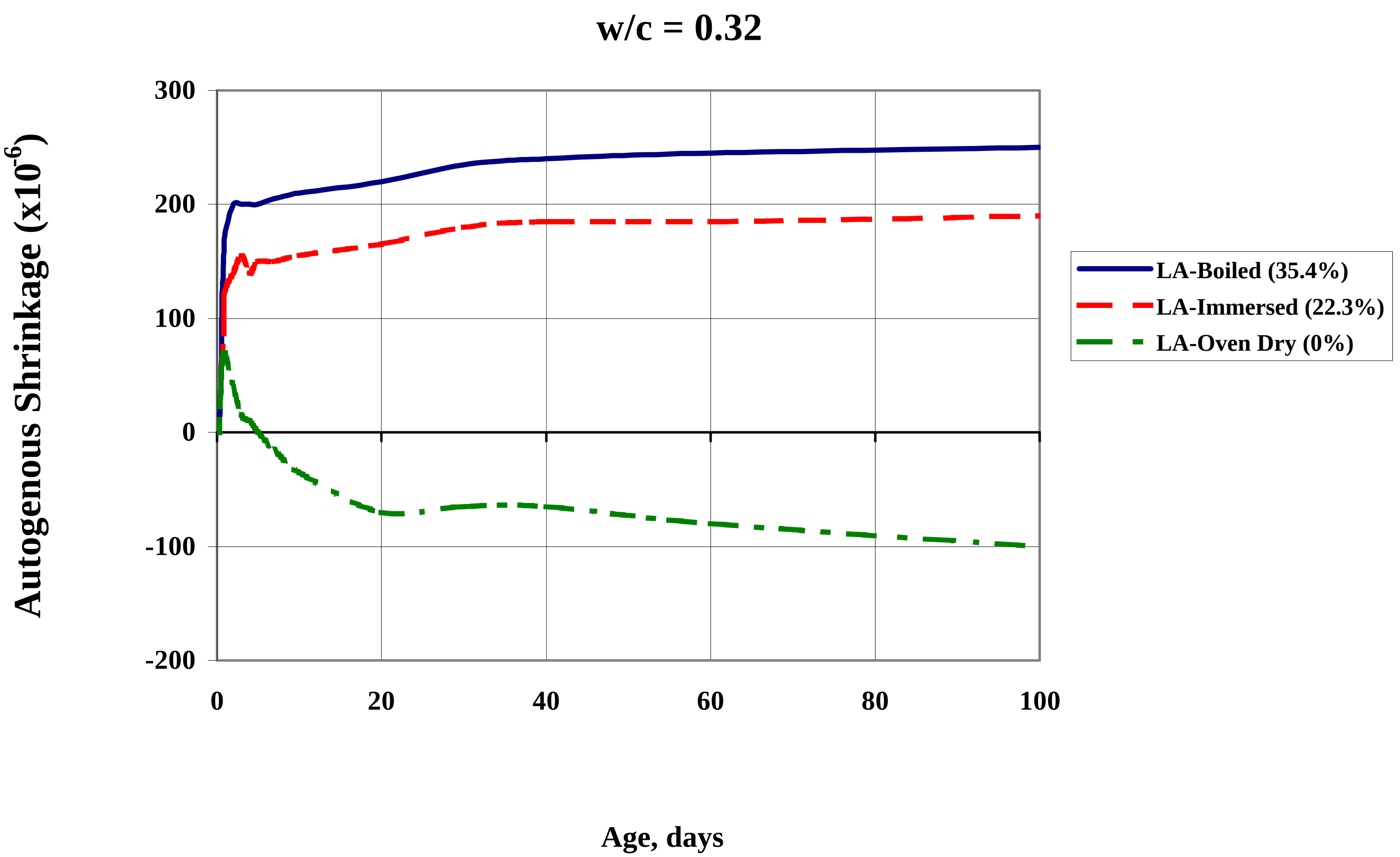

Fig. 14 Effective of Degree of Saturation of Crushed and Coated Lightweight Coarse Aggregate on Autogenous Shrinkage with Time (Ref. 18)

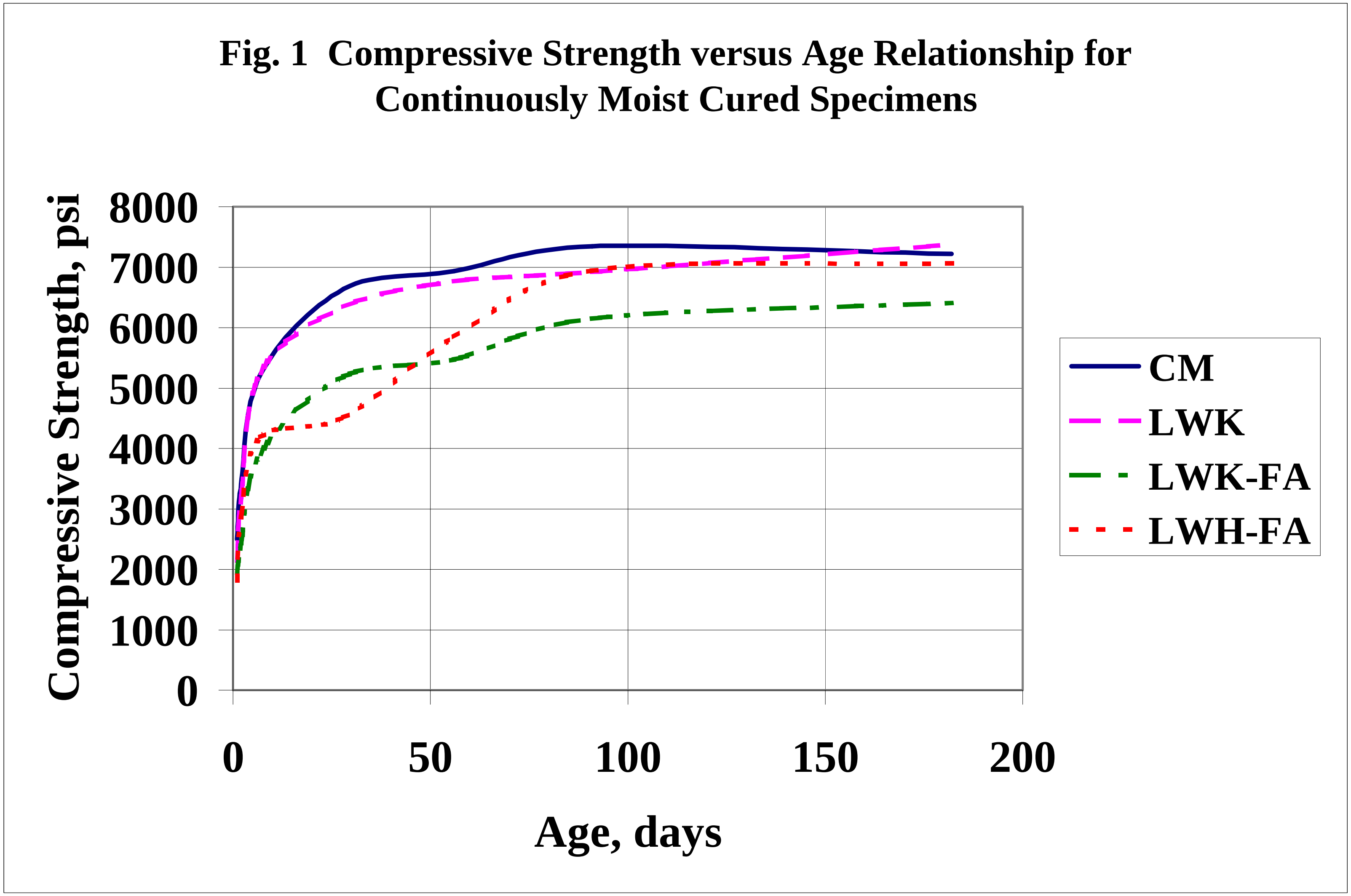
Fig. 1 Compressive Strength versus Age Relationship for
Continuously Moist Cured Specimens
Compressive Strength, psi
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
Age, days
CM
LWK
LWK-FA
LWH-FA

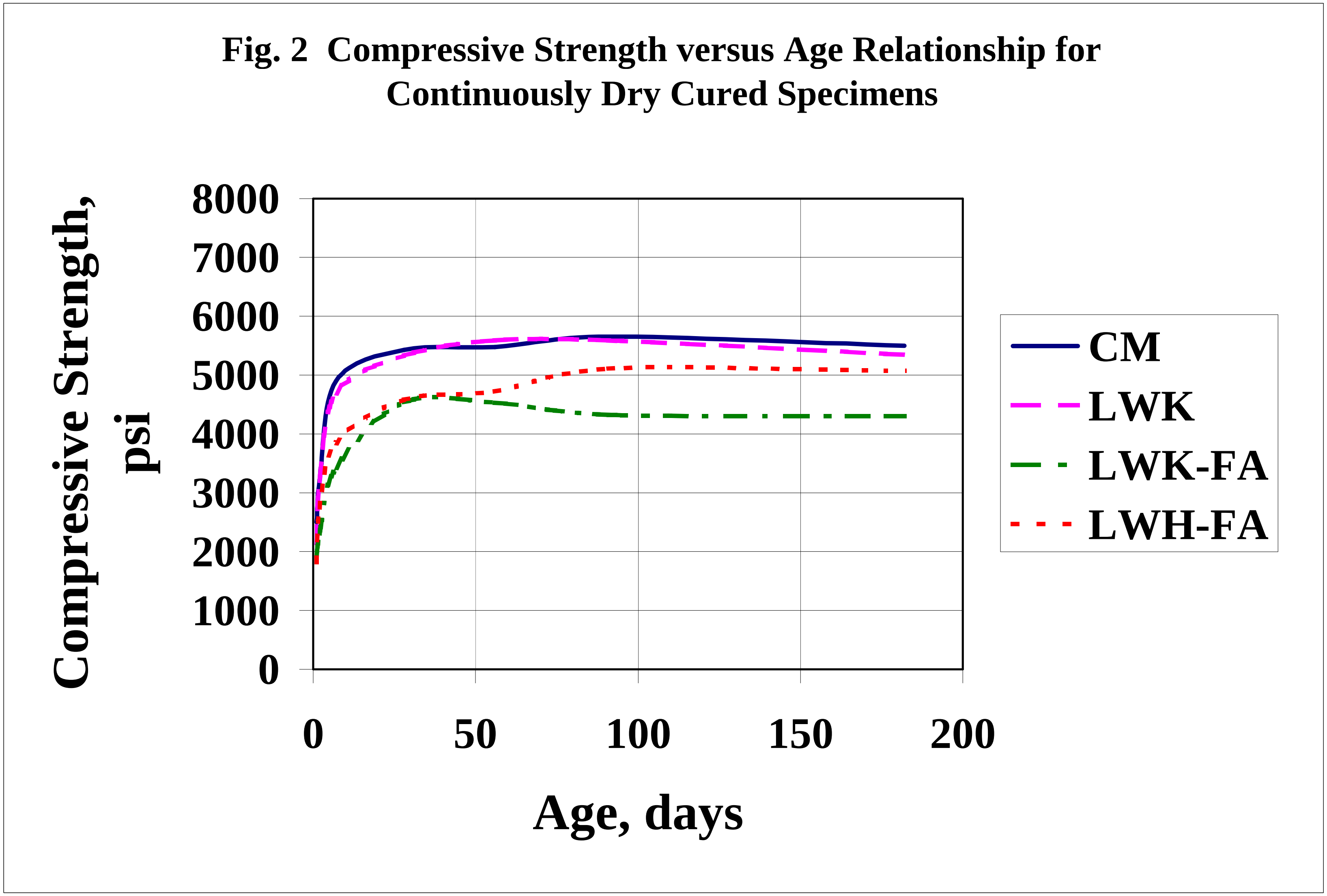
Fig. 2 Compressive Strength versus Age Relationship for
Continuously Dry Cured Specimens
Compressive Strength, psi
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
Age, days
CM
LWK
LWK-FA
LWH-FA

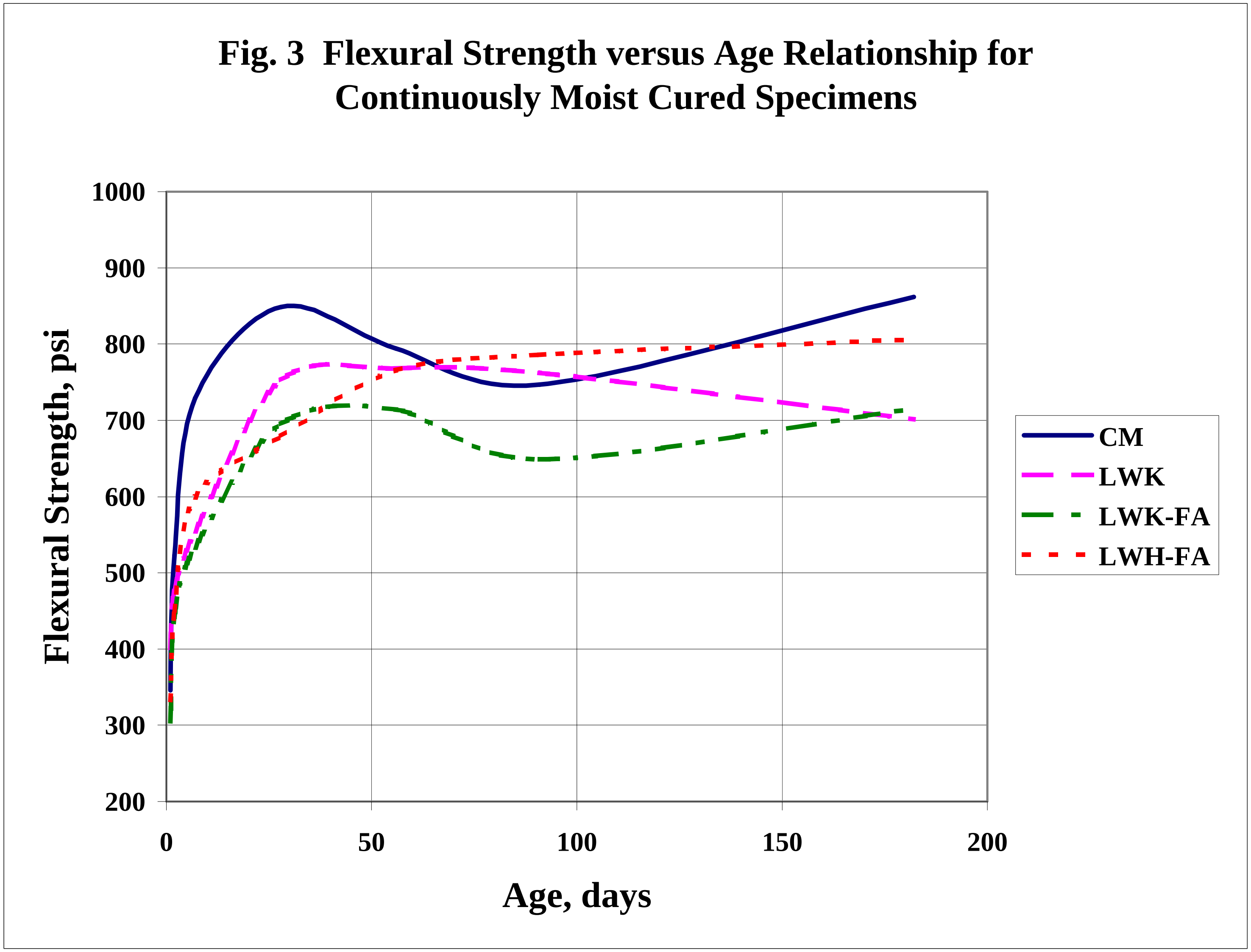
Fig. 3 Flexural Strength versus Age Relationship for
Continuously Moist Cured Specimens
1000
900
800
700
600
500
400
300
200
0
50
100
150
200
Flexural Strength, psi
Age, days
CM
LWK
LWK-FA
LWH-FA

Fig. 4 Flexural Strength versus Age Relationship for Continuously Dry Cured Specimens