

Autogenous Control of Autogenous Shrinkage

by A. Durán-Herrera, N. Petrov, O. Bonneau, K. Khayat,
and P.-C. Aïtcin

Synopsis: The partial substitution of natural sand by lightweight sand has been used to reduce autogenous shrinkage in concretes with a low water/binder ratio, but when this substitution is combined with quasi-adiabatic curing conditions during the first 24 hours, it has been found that autogenous shrinkage can be mitigated and controlled.

During an experiment done at Sherbrooke University on large concrete blocks measuring $0.6 \times 0.6 \times 0.6$ m ($2 \times 2 \times 2$ ft) where 28% by volume of the natural sand in the concrete was replaced by the same volume of saturated lightweight sand, with absorption of about 20%, it was found that autogenous shrinkage was mitigated within the concrete blocks. Moreover, it has been found that the compressive strength and the elastic modulus of the substituted concrete were not affected by this substitution.

For the first time in large concrete specimens, it can be reported that autogenous shrinkage can be mitigated and controlled without the help of any chemical product added to the concrete to induce an initial expansion to neutralize autogenous shrinkage. It seems that quasi-adiabatic conditions favor the development of large crystals that result in swelling of the apparent volume of the concrete block, and that the temperature increase also contributes to reduce chemical shrinkage. This could explain why Le Chatelier found more than 100 years ago that when a paste was cured under water, after a certain time, it swells enough to break the vase in which it had been placed.

Keywords: autogenous shrinkage; quasi-adiabatic curing; swelling; total shrinkage

Biography:

Alejandro Durán-Herrera, FACI, is Professor of Civil Engineering at the School of Civil Engineering and Researcher at the Center of Innovation, Research and Development in Engineering and Technology (CIIDIT) at the Universidad Autónoma de Nuevo Leon, Monterrey, Nuevo León, México. He received the ACI Young Member Award for Professional Achievement in 2004. His research interests include concrete materials and durability of concrete.

ACI member **Nikola Petrov** is the Technical Director of Concrete in Béton Provincial, Québec, Canada. His research interests include concrete durability (shrinkage, creep, and delayed ettringite formation).

ACI member **Olivier Bonneau** is a Research Assistant at the Université de Sherbrooke and coordinator of the Research Centre on Concrete Infrastructure bringing together six universities in Quebec, Canada. His research interests include self-compacting concrete and concrete repair.

Kamal Khayat, FACI, is Professor of Civil Engineering at the Université de Sherbrooke. He serves on numerous ACI committees. His research interests include self-consolidating concrete, high-performance concrete, rheology of cement-based mixtures, and concrete repair.

ACI Honorary Member **Pierre-Claude Aïtcin** is Professor Emeritus in the Department of Civil Engineering at Université de Sherbrooke, Sherbrooke, Québec, Canada.

INTRODUCTION

The recent development of low water-to-cement ratio (w/c) concretes (high performance concretes) has generated a new interest in studying autogenous shrinkage. Autogenous shrinkage was first discovered in the 1930s¹ but was not given much attention at this time because for uncured concrete autogenous shrinkage remained negligible in comparison to drying shrinkage. The concretes used at that time had higher water-to-cement (w/c) ratios (≥ 0.50). But, as concretes having w/c ratios lower than 0.4 are commonly used presently, too often without any special curing, autogenous shrinkage cannot be considered to be negligible anymore. In low w/c concretes, the development of uncontrolled autogenous shrinkage can be catastrophic from a durability point of view, because autogenous shrinkage develops as soon as the hydration reaction begins when the concrete is still weak. In uncured concretes, this can result in severe early cracking, and seriously impair the durability of the structure.

Technologies available to control autogenous shrinkage

Autogenous shrinkage originates from the stresses developed within the menisci appearing in the capillaries of the hydrated cement paste due to the development of chemical shrinkage. Up to now, several technologies have been proposed to fight autogenous shrinkage: the use of fogging or water curing, the use of internal curing materials, the use of an expansive chemical compound, or the use of a shrinkage reducing admixture. Next these technologies will be reviewed briefly.

The use of fogging or water curing minimizes the autogenous shrinkage problem of low w/c concretes only at the surface of concrete, because as the hydration reaction progresses due to the water curing of the surface, the concrete becomes more and more impervious. This additional hydration results in an increase of the absolute volume because the curing water is external to the paste.² This phenomenon leads to the healing of cracks and is usually referred to as autogenous healing. Unfortunately, the increased imperviousness limits the beneficial action of fogging or superficial water curing to the first centimeters of the concrete surface. Practically, it seems that the efficiency of fogging or superficial water curing is limited to the first 50 mm (2 in.) of concrete skin for a 0.35 w/c concrete. However, this beneficial action of fogging or superficial water curing is very important because this depth of penetration corresponds to the depth of the first rank of reinforcing steel which will benefit from this additional protection.

The use of an expanding chemical product to counteract early-age shrinkage has been known for decades and is a common practice in some countries like Japan.³ The introduction of dead burn lime with a specific grain size distribution during mixing has been proposed recently by Collepardi and his co-workers.⁴ The amount of dead burn lime is selected so that during the first 2 or 3 days swelling is equal to the total shrinkage of the concrete. This

method is very efficient and practical to implement, but requires a full control of concrete preparation and cannot be implemented by inexperienced personnel.

The principles and theoretical background of superabsorbent polymers and their use to temporarily store water within a mix has been proposed by Kovler and Jensen.^{5,6,7} Because of the great absorption capacity of these materials this method is very attractive, but to the best of our knowledge it has been used only once in a structure in Germany.⁸

The introduction of a shrinkage reducing admixture during mixing is also used to reduce the development of autogenous shrinkage.⁹ When using a shrinkage reducing admixture, the idea is to decrease these stresses by decreasing the surface tension and/or the angle of contact of the interstitial solution present within the capillary system. This method is currently prescribed to decrease autogenous shrinkage of low w/c concretes, but may induce early-age expansion in specimens cured in sealed conditions.^{4,10} It is also a simple and efficient method but it has a non negligible cost and it does not totally eliminate autogenous shrinkage since the surface tension of the pore solution cannot be reduced to zero.

The use of saturated lightweight aggregates to internally water cure concrete is not a new idea. It was proposed for normal concrete by P. Klieger¹¹ as early as 1957 and in 1997 by Weber and Reinhardt¹² for high performance concrete. These authors proposed a partial substitution of saturated coarse lightweight aggregates. It is only recently that a partial substitution of sand by saturated lightweight sand starts to be considered more seriously as a practical way to create the conditions of an efficient internal water curing. The use of a partial sand substitution was proposed first by R.E. Philleo.¹³ This type of treatment will be called in the following internal water curing.

The idea of using only a partial replacement of sand is to limit the negative effects of this replacement on the mechanical properties of the substituted concrete such as compressive strength (f'_c), flexural strength (f'_r) and modulus of elasticity (E'_c). Moreover, when lightweight sand is more porous than a coarse lightweight aggregate, a lesser quantity of lightweight aggregate is required to store a given volume of water. Through this sand, internal curing water will also be more finely distributed throughout the concrete volume. This approach has proven to be very successful in reducing the development of autogenous shrinkage. It is easy to implement in the field and efficient to improve compressive strength, shrinkage mitigation and construction related aspects such as placing time, fuel savings and equipment wear.¹⁴ However, it has not been found to always be able to counteract 100% the development of autogenous shrinkage in high performance concrete where a residual autogenous shrinkage is still often observed.¹⁵

It is possible to implement more than one of these methods simultaneously to obtain better results, but it complicates the process and causes a supplementary financial burden.

RESEARCH SIGNIFICANCE

Recent developments at the University of Sherbrooke

During a recent experimental work done at the University of Sherbrooke, it was found that a partial substitution of sand by a saturated lightweight sand in a concrete cast in an insulated form resulted in the mitigation of total (long term) shrinkage. This type of concrete will be referred to in this paper as the substituted concrete.

EXPERIMENTAL CONDITIONS

This experiment was performed on $600 \times 600 \times 600$ mm ($24 \times 24 \times 24$ in.) cubic samples casted in forms insulated with a 240 mm (9.5 in.) thick Styrofoam sheet (Figure 1), the development of the total strain within the concrete blocks at 300 mm (12 in.) from the surface was compared for a reference (Ref) and a substituted (Light) concrete. The placement of a vibrating wire strain gauge and a thermocouple at a depth of 300 mm (12 in.) are illustrated in Figure 2. These concretes had the same cement dosage, the same w/c and contained approximately the same amount of superplasticizer as seen in Table 1. They were cast at the same temperature and had almost the same temperature history during the experiment as seen in Figures 3 and 4. After their casting, they remained all the time at room temperature, in the isolated moulds during the first 24 hours, immersed in water for the following 7 days and thereafter in the laboratory. For the same concretes, the thin lines in figures 3 and 4, present the temperature

history monitored in $100 \times 100 \times 400$ mm ($4 \times 4 \times 16$ in.) prisms that were water cured after demolding at 24 hours and then maintained at quasi-isothermal conditions.

EXPERIMENTAL RESULTS

In Fig. 3, we observe that during the first 24 hours before demolding, when the temperature of the concrete increased, the substituted concrete block experienced swelling two to three times greater than that of the reference concrete block (Figure 5). This significant increase of swelling was not found for substituted concrete in a first experiment under quasi-isothermal conditions (thin lines in Figures 5 and 6), because $100 \times 100 \times 400$ mm ($4 \times 4 \times 16$ in.) prisms water cured after demolding at 24 hours were tested¹⁵. The maximum temperature reached within these small cast prisms was not very high (30 to 33 °C or 85 to 95 °F). However, it was noticed that initial swelling of the substituted concrete was greater than that of the reference concrete, but not significant enough to focus special attention on it. Figure 4 presents the temperature history of the blocks and prisms during the first 7 days. After 24 hours, they were placed in water basins at room temperature for 7 days.

The total strain curve of the reference block in Figure 5 shows that the early development of autogenous shrinkage limits the thermal expansion of the reference blocks so that its expansion starts to decrease after 13 to 14 hours. On the contrary, the expansion of the substituted block continues to increase until 24 hours when the block was demolded.

Figure 6 presents the total strains measured up to 7 days. After a significant rate of shrinkage that took place after demolding at 24 hours, prisms and the blocks of both concretes did not experience any volumetric changes. In the reference concrete block the autogenous shrinkage was controlled by the external water curing, and in the substituted concrete block, in addition to the external water curing, the autogenous shrinkage was also controlled by the internal water contained in the pores of the lightweight sand. At 7 days, the reference concrete block presented a total shrinkage of 380 microstrains, and the substituted concrete block presented a total shrinkage of 250 microstrains, representing a reduction of 130 microstrains, attributed to internal water curing. In this case, the reference concrete was already too impervious to allow the curing water to penetrate at a depth of 300 mm (12 in.) from the surface.

After 7 days, the reference and substituted concrete prisms were air cured [23 °C (73 °F), R.H. = 50%], so they experienced some drying shrinkage as illustrated by the thin lines in Figure 7. The presence of some uncombined water in the substituted concrete prism resulted in a decrease of drying shrinkage.

In Figure 7, it is seen in both blocks that after the initial significant rate of shrinkage, they did not experience any significant volumetric variation. At 91 days, total shrinkage stabilized at about 260 microstrains in the reference block, and the substituted block still experienced a slight expansion. The development of some autogenous shrinkage between 7 and 91 days resulted in a shrinkage of 70 to 80 microstrains. After 91 days, the substituted block had not reached its original dimensions of $600 \times 600 \times 600$ mm ($24 \times 24 \times 24$ in.) while the reference block presents a total shrinkage of 260 microstrains.

DISCUSSION OF THE RESULTS

It is the combination of hydration with an external source of water (external to the cement paste), in our case the water contained in the lightweight sand, and the heat developed during this hydration in adiabatic conditions that significantly increases the well known early swelling of a water cured cement paste discovered by Le Chatelier¹⁶ more than a hundred years ago. This phenomenon has been reproduced with modern cements at the University of Sherbrooke (Figure 8). The glass flasks containing pastes (water + cement) with w/c of 0.30, 0.36 and 0.50 that appear in Fig. 8 show the sealed cracks on the surface of the flasks developed as a result of the expansion induced by autogenous swelling. The flask with cement 4 (w/c = 0.30) does not exhibit any cracks, because in this case, the cement paste was covered with a very fluid oil.

The increase in swelling observed during the first 24 hours before demolding between the substituted and reference concretes, was almost equal to the thermal contraction and autogenous shrinkage developed in the substituted concrete during its cooling. Under the curing conditions employed in this study, the substituted concrete

did not experience any further significant autogenous shrinkage, due to the presence of the water still contained in the lightweight sand.

In this experiment, the use of insulated forms created hydration conditions that are different from those created by an external source of heat because the temperature of the concrete within the forms is quasi-uniform. When using a conventional external source of heat, thermal gradients are developed during heating, and then thermal gradients are created again during cooling, therefore, hydration conditions are far from being uniform within the concrete when using an external source of heat. Moreover, the use of an external source of heat implies the release of some greenhouse gas, but when using insulated forms the hydration reaction develops its own heat at its own path, possibly without the emission of any greenhouse gas. To determine the possible greenhouse gas reduction a comparison between an external source of heat and insulated forms are recommended. In adiabatic conditions, the hydration reaction is a self-activating chemical reaction governed by an Arrhenius law which can be called autogenous heating. From a practical point of view, it is only necessary to insulate the forms or to insulate the concrete element during the first 24 hours.

It is legitimate to argue that demolding a concrete block, which has a uniform temperature of 60 °C (140 °F), and suddenly exposing its surface to 20 °C (68 °F) creates a superficial thermal shock. This thermal shock can result in severe microcracking of the surface. This is why it is important to superficially water cure the concrete for a few days after deforming in order to favor an autogenous healing of the surface. As many cement particles are not yet hydrated at 24 hours, this external water curing favors hydration of some of the superficial cement particles and the healing of the microcracks generated during thermal shock. As previously said, in such conditions, the hydration of cement particles results in an increase of the absolute volume of the paste because water is coming from a source external to the initial system.

Even in winter in a northern country like Canada, the use of insulated forms is not widespread. But as the use of slow hardening blended cements will increase drastically in the very near future to limit the emission of CO₂ associated with the use of concrete, all the forms used, even in hot countries, will have to be insulated to provide a quasi-uniform temperature environment within the blended cement concrete and minimize superficial thermal shock. Insulating forms favors, at a very low cost, the development of an increased early strength. Moreover, in the case of a slipforming operation, a mathematical simulation done by Lachemi and Elimov¹⁷ has shown the benefits of using insulated forms. In this case, it is the most efficient method to be sure that the concrete within the forms hydrates uniformly, which is essential to have a smooth slipforming operation. The part of the forms exposed to a chilly wind or to a hot sun does not alter the development of hydration reaction, as the concrete is isolated from any external influence. Consequently, when the concrete is released from the slipping form it has reached exactly the same consistency and strength, which is essential to have a smooth slipforming operation.

Implementation of the autogenous control of autogenous shrinkage

First, it is quite simple to implement such a method. First, it is necessary to substitute some normal sand by saturated lightweight sand (in our case, lightweight sand with an absorption of about 20% in replacement of 28% by volume of normal weight sand). If the ready-mix plant does not have 2 sand bins, one of which can be used to store the lightweight aggregate, large bags of lightweight sand can be used. To have freeflowing lightweight sand, a partially saturated lightweight sand having water content 3 to 5% lower than its saturation can be used with the missing 3 to 5 % of water being added in the mixer.

Second, it is necessary to use insulated forms with 240 mm (9.5 in.) insulating foam sheets. When it is not practical, insulating blankets like the ones used in Canada to protect concrete works in winter, can be used during the first 24 hours.

Third, when the concrete has been demolded, it is important to implement immediately superficial water curing at least for 6 days as is presently prescribed for all high performance concrete in the city of Montréal, Québec, and to specifically pay contractors to do it.

CONCLUSIONS

By combining a 28% substitution of natural sand with the same volume of saturated lightweight sand and the use of insulated forms it was possible to mitigate and control the autogenous shrinkage of a 0.35 w/c ratio concrete without the help of any expanding chemical. The autogenous expansion generated by the autogenous heating of the concrete and the internal curing, resulted in the autogenous control of autogenous shrinkage. This method can be easily implemented in the field to increase the life cycle of high performance concrete structures. The use of the heat of hydration to heat the concrete during the first 24 hours is very interesting as it favors the development of pozzolanic reactions when blended cement is used and it increases early compressive strength.

The mitigation of autogenous shrinkage and the reduction of drying shrinkage are two interesting features for a designer because prestressing losses should be decreased significantly.

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REFERENCES

1. Lynam, C.G., *Growth and Movement in Portland Cement Concrete*, Oxford University Press, London, UK, 1934, pp. 1-139.
2. Morin, R.; Haddad, G.; and Aïtcin, P.C., "Crack-Free, High-Performance Concrete Structure," *Concrete International*, V. 24, No. 9, Sept. 2002, pp. 51-56.
3. Nagataki, S., and Gomi, H., "Expansive Admixtures (Mainly Ettringite)," *Cement and Concrete Composites*, V. 20, 1998, pp. 163-170.
4. Collepardi, M.; Borsoi, A.; Collepardi, S.; Ogoumah Olagot, J.J.; and Troli, R., "Effects of Shrinkage-Reducing Admixture in Shrinkage-Compensating Concrete under Non-wet Conditions," *Cement and Concrete Composites*, V. 27, 2005, pp. 704-708.
5. Jensen, O.M., and Hansen, P.F., "Water-Entrained Cement-Based Materials I. Principles and Theoretical Background," *Cement and Concrete Research*, V. 31, 2001, pp. 647-654.
6. Jensen, O.M., and Hansen, P.F., "Water Entrained Cement-Based Materials II. Experimental Observations," *Cement and Concrete Research*, V. 32, 2002, pp. 973-978.
7. Kovler, K., and Jensen, O. M., "Novel Technique for Concrete Curing," *Concrete International*, V. 27, No. 9, Sept. 2005, pp. 39-42.
8. Mechtcherine, V.; Dudziak, L.; and Schulze, J., "Internal Curing by Super Absorbent Polymers (SAP)--Effects on Material Properties of Self-Compacting Fibre-Reinforced High-Performance Concrete," *Proceedings of the International RILEM Conference---Volume Changes of Hardening Concrete: Testing and Mitigation*, O.M. Jensen, P. Lura, and K. Kovler, eds., RILEM Publications S.A.R.L., 2006, pp. 87-96.
9. Nmai, C. K.; Tomita, R.; Hondo, F.; and Buffenbarger, J., "Shrinkage-Reducing Admixtures," *Concrete International*, V. 20, No. 4, Apr. 1998, pp. 31-37.
10. Maltese, C.; Pistolesi, C.; Lolli, A.; Cerulli, T.; and Salvion, D., "Combined Effect of Expansive and Shrinkage Reducing Admixtures to Obtain Stable and Durable Mortars," *Cement and Concrete Research*, V. 35, 2005, pp. 2244-2251.
11. Klieger, P., "Early High-Strength Concrete for Prestressing," *Proceedings World Conference on Prestressed Concrete*, San Francisco, CA, 1957, pp. AJ (1) -AJ (14).
12. Weber, S., and Reinhardt, H.W., "A New Generation of High-Performance Concrete : Concrete with Autogenous Curing," *Advanced Cement-Based Materials*, V. 6, No. 2, 1997, pp. 59-68.
13. Philleo, R.E., "Concrete Science and Reality," *Materials Science of Concrete II*, J. Skalny and S. Mindess, eds., American Ceramic Society, Westerville, OH, 1991, pp. 1-8.
14. Villarreal, V.H., and Crocker, D.A., "Better Pavements through Internal Hydration," *Concrete International*, V. 29, No. 2, Feb. 2007, pp. 32-36.

15. Durán, A.; Aïtcin, P.C.; and Petrov, N., "Effect of a Saturated Lightweight Sand Substitution on Shrinkage in a 0.35 w/b concrete," *ACI Materials Journal*, V. 104, No. 1, Jan. 2007, pp. 48-52.
16. Le Chatelier, H., "Recherches expérimentales sur la constitution des mortiers hydrauliques," *Dunod*, Paris, 1909, pp. 163-167.
17. Lachemi, M., and Elimov, R., "Numerical Modeling of Slipforming Operations," *Computers and Concrete*, V. 4, No. 1, 2007, pp. 33-47.

Table 1 – Composition of concrete used to cast the 600 mm (24 in.) cubic blocks

	Reference	Substituted
w/cm	0.35	
Water, kg/m ³ (lb/yd ³)	144 (243)	144 (246)
Type GUB-SF cement, kg/m ³ (lb/yd ³)	423 (713)	424 (715)
Superplasticizer, L/m ³ (oz/yd ³)	4.25 (110)	4.26 (110)
Coarse aggregate (2.5-10 mm), kg/m ³ (lb/yd ³)	965 (1 627)	952 (1 605)
Standard sand, kg/m ³ (lb/yd ³)	759 (1 279)	589 (993)
Lightweight sand, kg/m ³ (lb/yd ³)	-----	147 (248)

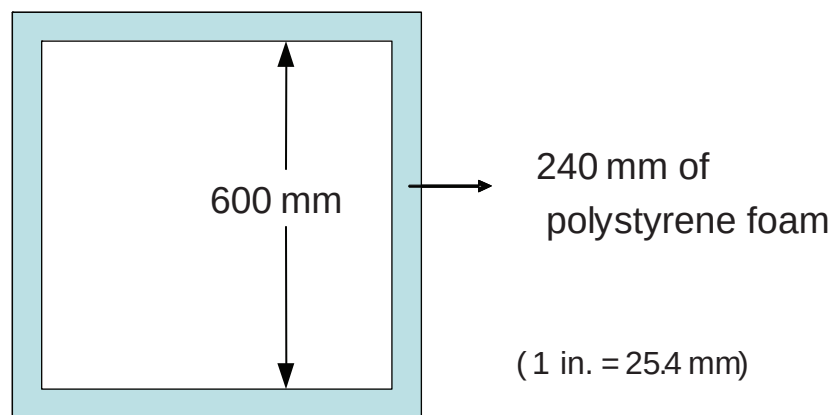


Fig. 1---Insulated form.

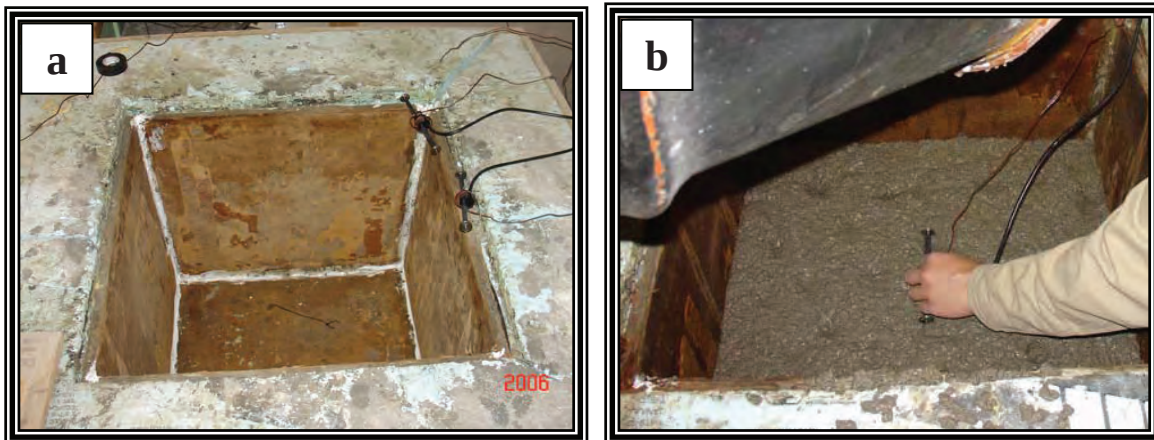


Fig. 2---Casting $600 \times 600 \times 600$ mm ($24 \times 24 \times 24$ in.) blocks in a 250 mm (10 in.) polystyrene 13 insulated form; (a) prior to concrete casting, and (b) placement of vibrating wire gauge and thermocouple at the center of the block and at a depth of 300 mm (6 in.).

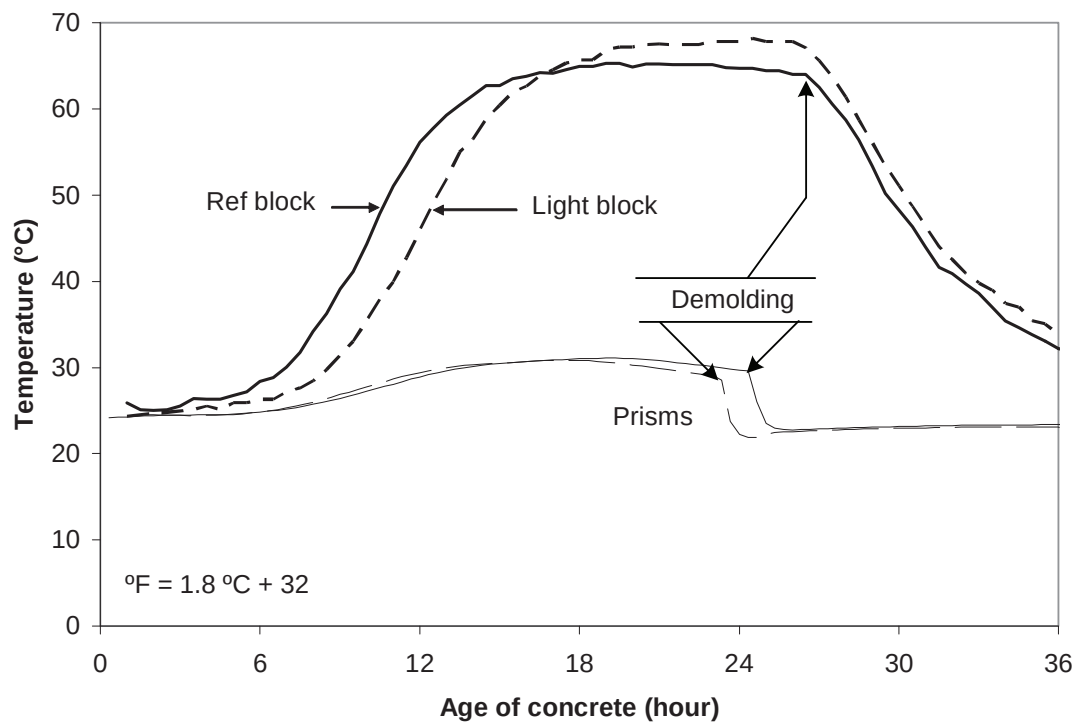


Fig. 3---Temperature rise during the first 36 hours.

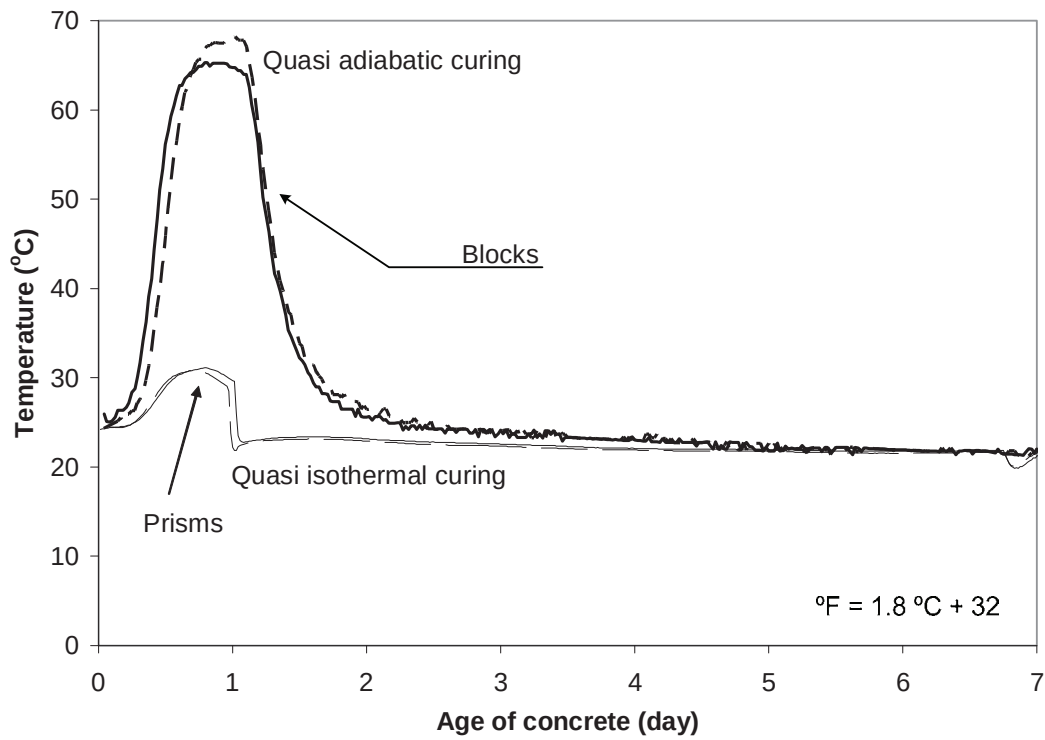


Fig. 4---Temperature during the first 7 days.

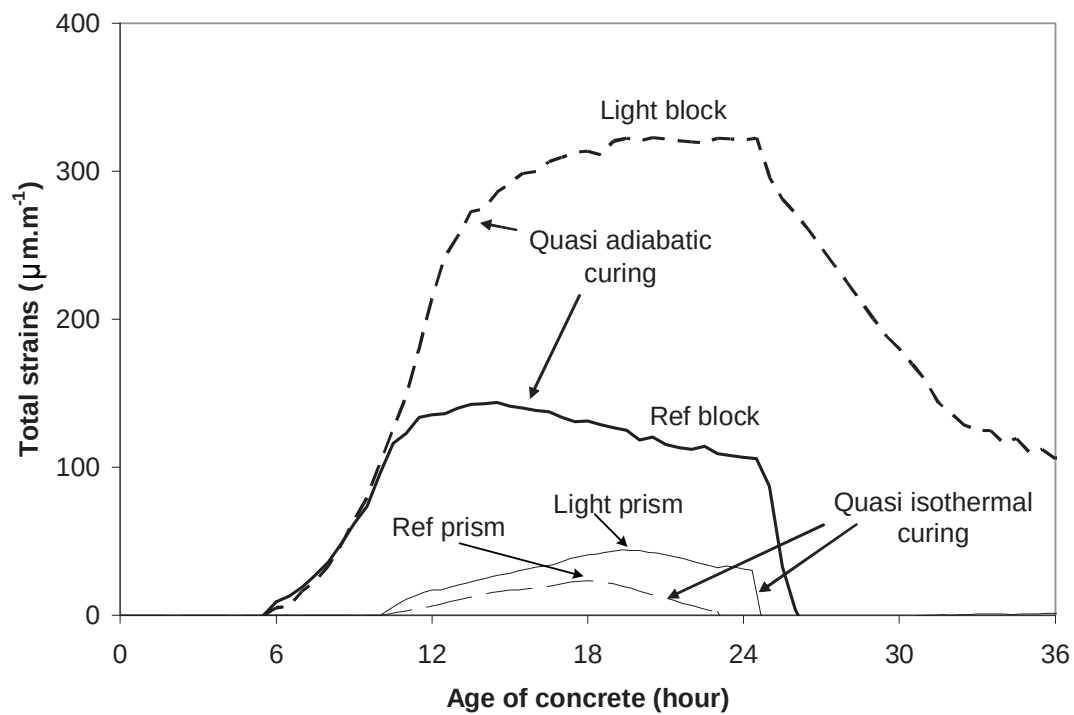


Fig. 5---Total strain during the first 36 hours.

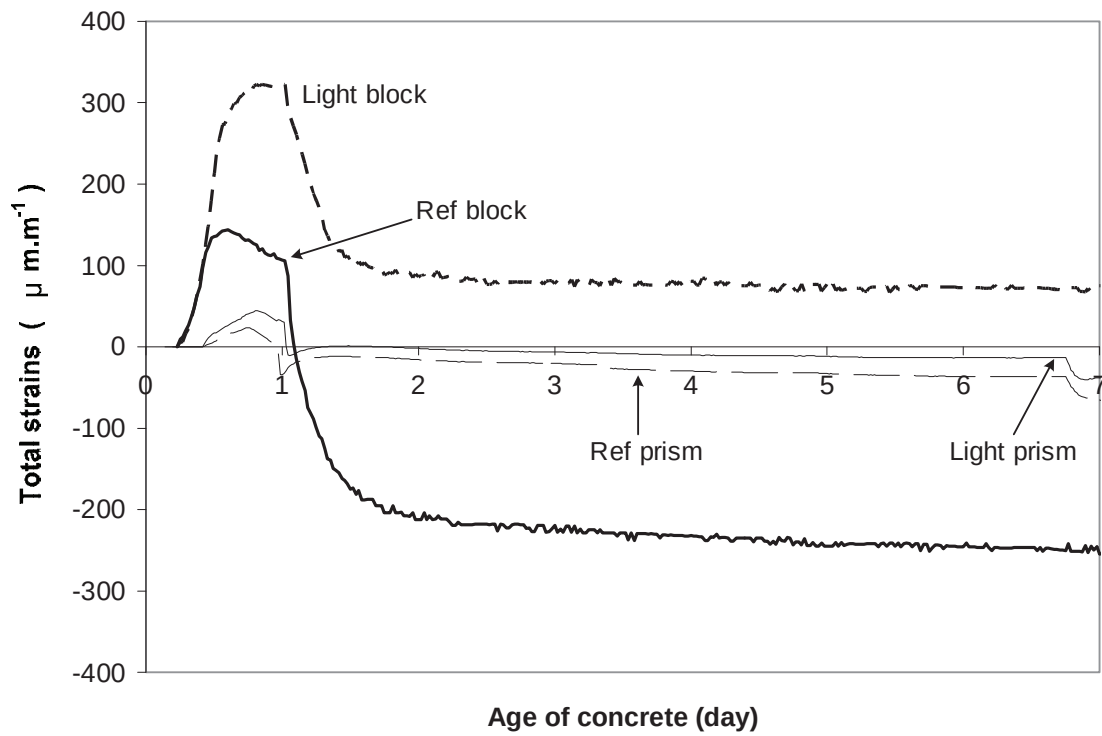


Fig. 6---Total strain during the first 7 days.

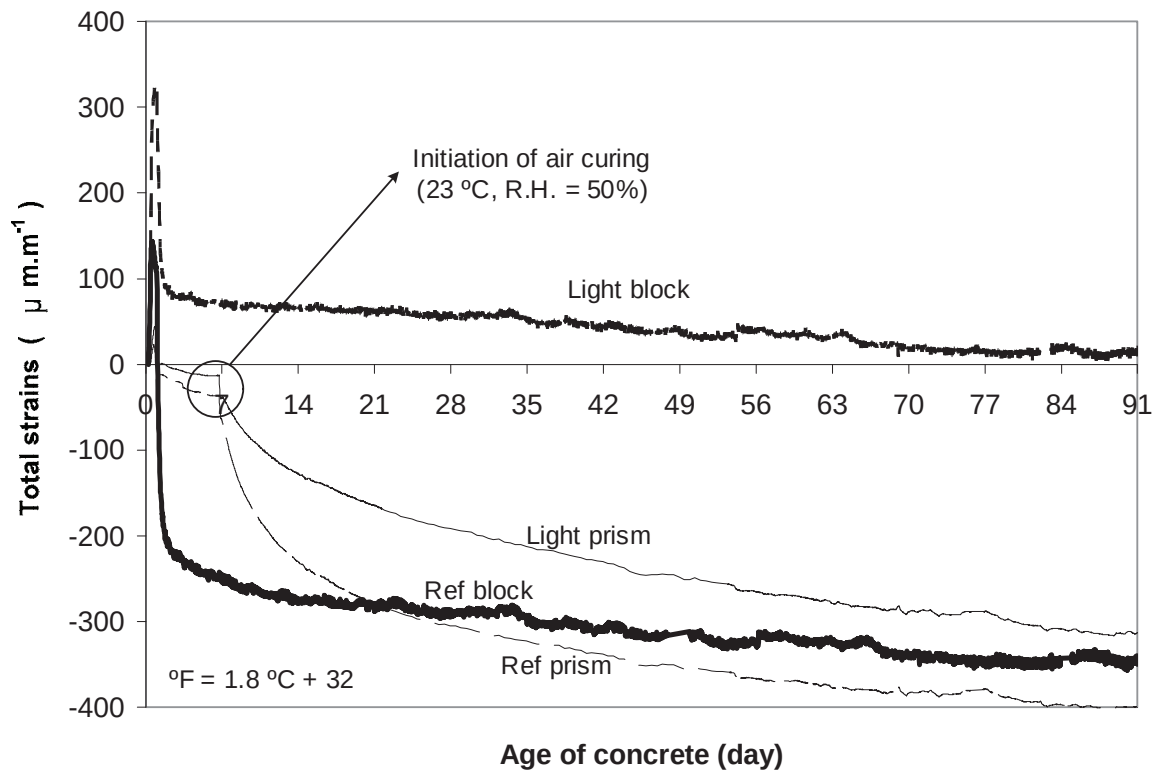


Fig. 7---Total strain until 91 days.



Cement 1
0.50

Cement 2
0.36

Cement 3
0.30

Cement 4
0.30

Fig. 8---Reproduction of Le Chatelier experiment with modern cement.

Internal Curing Study with Intermediate Lightweight Aggregate

by W.A. Pyc, M.A. Caldarone, D. Broton, and D. Reeves

Synopsis: The purpose of this study was to quantify the degree to which moisture-bearing lightweight aggregate can contribute to cement hydration in low, intermediate and high water/cement ratio “normal” density concrete. This was accomplished using chemical testing methods (x-ray fluorescence and thermal gravimetric analysis) supplemented by physical strength testing. To study the influence of lightweight aggregate as a function of paste density (water/cement ratio), three cement contents were chosen to represent low, intermediate, and high water/cement ratio concrete. The three water/cement ratios examined were 0.37, 0.47, and 0.57. Each series consisted of a control mixture containing no lightweight aggregate, and a test mixture containing 6 ft³ of presoaked 3/8 in. to No. 8 intermediate lightweight aggregate used in substitution of a portion of the coarse and fine aggregate. The results of this study provide quantitative validation to the theory that the addition of an effectively preconditioned lightweight aggregate will provide moisture for cement hydration in the concrete. The significance of the findings present an improvement of the performance characteristics of concrete by providing additional internal moisture minimizing the effect of self-desiccation by maintaining a fairly high degree of saturation during the critical strength gain period.

Keywords: concrete; internal curing; lightweight aggregate

Biography:

W. Agata Pyc is an Associate II at the Materials Evaluation Group at CTLGroup, Skokie, IL. She received her BS/MS from the Technical University of Gdansk, Gdansk, Poland, and her MS and PhD from the Virginia Polytechnic Institute & State University, Blacksburg, Virginia. Her research interests are concrete durability, performance, and development of innovative applications. Her experience includes investigation of premature concrete deterioration, determination of expected performance, developing concrete mix design, and materials testing.

Mike Caldarone, FACI, is a Principal Engineer at the Materials Evaluation Group, CTLGroup, Skokie, IL. He received his BS from the University of Illinois at Chicago. He is former Chair of the ACI Committee 363 (High-Strength Concrete), and a member of ACI Committees 201 (Durability of Concrete), 211 (Proportioning Concrete Mixtures), 213 (Lightweight Aggregates and Concrete), and 325 (Concrete Pavements).

Don Broton is Senior Materials Scientist at CTLGroup, Inc. (formally Construction Technology Laboratories and a wholly owned subsidiary of the Portland Cement Association). He received his B.S from University of Illinois in 1984 and has been employed at CTLGroup since 1988. He is a member of ASTM C01 (Cement) and C09 (Concrete and Aggregates). His research interests are reverse engineering of concretes and mortars using x-ray fluorescence spectrometry and ASR reduction through chemical treatments.

ACI member **Don Reeves** is a Customer Representative for the Expanded Shale and Clay Division of TXI Operations, LP. He is a Graduate of the State University of New York and currently serving on The Expanded Shale Clay and Slate Institute (Structural Committee), and The American Concrete Institute's 213 Committee (Lightweight Aggregates and Concrete).

INTRODUCTION

ACI 308R-01 describes curing as a process during which hydraulic-cement concrete develops hardened properties through the hydration of the cement in the presence of water and heat. Hardened cement paste reacts as a porous matrix that bonds aggregates. "As the hydration process continues, the strength of the inter-particle bonding increases, and the inter-particle porosity decreases. The rate and extent of the hydration depend on the availability of water."⁽¹⁾ Proper curing will allow concrete to develop desired strength, low permeability, resistance to stress, abrasion, and freezing and thawing.⁽²⁾

External moist curing of concrete is an important and well known practice in construction of concrete structures. It has been demonstrated that proper external moist curing will prevent loss of moisture from concrete necessary for cement hydration and help to produce a good durable concrete.

All concretes benefit through effective curing practices; however, when concretes with low water-cementitious materials ratios (w/cm) are made, external moist curing may not protect concrete from self-desiccation and autogenous shrinkage. For this reason, internal moist curing takes on significant importance.

Internal moist curing is a method in which additional moisture for cement hydration is provided from within the concrete with no effect on the initial water-cement (w/c) ratio.⁽²⁾ Internal moist curing can be accomplished by the use of water saturated coarse or fine lightweight aggregate or super absorbent polymers.⁽³⁾ Introduction of these materials into concrete will provide a source of water within the concrete matrix and better hydration of cement particles. Additional moisture in concrete becomes available through slow release of water absorbed by the pores within the lightweight aggregate.⁽⁴⁾ In principle, any material that is used to provide a source of internal moisture has to be effectively saturated before it can be introduced into concrete mixture.

The benefits of internal curing were demonstrated through the reduction of autogenous shrinkage in cement mortars with w/cm ratio of 0.35 and 8% silica fume replacement by the use of saturated low-density fine aggregate or saturated super-absorbent polymer.⁽⁵⁾ Previous research also demonstrated that the most beneficial mechanism for internal curing would be a well dispersed system of lightweight fine aggregate.⁽⁶⁾

RESEARCH SIGNIFICANCE

The purpose of this research was to evaluate internal curing of concrete with intermediate lightweight aggregate by physical testing and chemical analysis. In order to examine the influence of internal curing, concrete mixtures with w/c ratios of: 0.37, 0.47 and 0.57, were prepared and tested at ages of 1, 3, 7, 14, 28, and 90 days. Additionally, samples of plastic concrete from the 0.37, 0.47, and 0.57 mixes were placed in a one-liter container filled with 17 fl oz (500 ml) of water, capped, and continuously tumbled end over end. These samples were used to produce a value corresponding to maximum hydration amount at 28 and 90 days. These samples also validated the relative maximum amount of hydration products that the mixtures could attain.

EXPERIMENTAL PROCEDURE

Three sets of concrete mixtures were prepared. Each set consisted of a control mix without lightweight aggregate, and a test mix – with lightweight aggregate. Three cement contents were studied: 658 lb/yd³ (390 kg/m³), 564 lb/yd³ (334 kg/m³), and 470 lb/yd³ (279 kg/m³). No supplementary cementitious materials or chemical admixtures were used.

Materials

The normal weight coarse aggregate used in the concrete mixtures was oven-dried, immersed in water for a period of 24 hours, and then drained immediately prior to mixing, a procedure known as “wet batching.” By knowing the absorption of the coarse aggregate and the weight of the water drained off prior to batching, the amount of mix water contributed by the coarse aggregate can be precisely determined. The free moisture content of the sand was measured prior to mixing.

The lightweight aggregate was preconditioned prior to mixing. First, it was dried in an oven and an oven-dry loose unit weight was determined according to ASTM C29-97, *Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate*. The lightweight aggregate was then quenched in cold water and kept immersed until the wet loose unit weight reached a minimum value of 58 lb/ft³ (0.086 kg/m³). Drained, saturated lightweight aggregate was used for the concrete mixtures.

The constituent materials used in this study are presented in [Table 1](#).

Concrete Mixtures

Concrete mixtures, 2 ft³ (0.06 m³) each, were prepared in a Lancaster pan mixer, according to ASTM C192-98, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. The following fresh concrete properties were determined for all mixes:

- Temperature, ASTM C1064-05, *Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete*
- Slump, ASTM C143-05, *Standard Test Method for Slump of Hydraulic-Cement Concrete*
- Air Content, ASTM C173-01, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*
- Density (Unit Weight), ASTM C138-01a, *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*

Mix proportions and fresh properties are presented in [Tables 2 to 4](#).

Specimens

Specimen fabrication was conducted according to ASTM C192-98. Thirty (30) 4x8-in. cylinders were made for every mix. Six (6) cylinders were used for chemical analysis, six (6) for density determination and eighteen (18) for strength testing. Upon completion of the initial curing period, 24 ± 8 hours, all cylinders were demolded and stored in a room maintained at a relative humidity of 50 ± 4 % and a temperature of 73 ± 3 °F (23 ± 2 °C) until tested.

TEST PROCEDURES

Testing of Base Materials

All materials were tested by CTLGroup prior to mixing concrete. The following tests were performed:

- ASTM C 136-06, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate*
- ASTM C 127-04, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*
- ASTM C 128-04, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate*
- ASTM C 29-97, *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*
- X-Ray Fluorescence (XRF) elemental analysis
- Thermogravimetric Analysis (TGA).

Testing of Concrete

Compressive strength was tested according to ASTM C39-04, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* on three (3) 4x8-in. cylinders at 1, 3, 7, 14, 28, and 90 d for every mix.

Oven-dry density was determined according to ASTM C567-05, *Standard Test Method for Determining Density of Structural Lightweight Concrete* for one (1) 4x8-in. cylinder at 1, 3, 7, 14, 28, and 90 d for every mix.

Chemical analysis was performed on one (1) 4x8-in. cylinder at 1, 3, 7, 14, 28, and 90 d for every mix. Testing included XRF analysis and TGA.

EXPERIMENTAL RESULTS

Testing of Physical Properties of Materials

Sieve analysis was performed in accordance with ASTM C136-05 on all the aggregates used for concrete mixtures. Coarse aggregate, 1 in. to No. 4 crushed limestone, met the requirements of ASTM C33-03, *Standard Specification for Concrete Aggregate*, for size 3/4 in. to No. 4. Fine aggregate, concrete sand, met the requirements of ASTM C33-03. Lightweight aggregate, 3/8 in. to No. 8 intermediate, met the requirements of ASTM C330-04, *Standard Specification for Lightweight Aggregates for Structural Concrete*, for size 3/8 in. to No. 8. Results are presented in [Tables 5 to 9](#).

Specific gravity and absorption of aggregates was also determined according to ASTM C127-04 and C128-04. Coarse aggregate, 1 in. to No. 8 crushed limestone, had a SSD bulk specific gravity of 2.65 and absorption of 1.38%. Fine aggregate, concrete sand, had a SSD bulk specific gravity of 2.62 and absorption of 1.52%. Lightweight aggregate, 3/8 in. to No. 8 intermediate, had an average bulk density of 51.47 lb/ft³ (824 kg/m³).

Testing of Physical Properties of Concrete

Results of compressive strength testing at 1, 3, 7, 14, 28, and 90 days are presented in [Figure 1](#).

An increase in compressive strength for the 0.37 with lightweight aggregate in comparison to the control 0.37 mix was observed at 1, 3, 14 and 28 days. The 0.47 mix with lightweight aggregate had an increase in compressive strength in comparison to the 0.47 control mix, at later ages: 14, 28 and 90 days. An increase in compressive strength for the 0.57 mix with lightweight aggregate in comparison to the 0.57 control mix was observed at 28 and 90 days.

As presented in [Figures 2 to 4](#), all lightweight mixes demonstrated higher moisture loss in time in comparison to the mixes with normal weight aggregates. Change in moisture was determined based on the difference between the initial weight at 1 day and weights at ages of 3, 7, 14, 28, and 90 days.

Chemical Analysis

The materials used for concrete as well as each concrete at various ages were analyzed using thermal and x-ray techniques. The mass losses at 221°F (105°C), 1022°F (550°C) and 1742°F (950°C) corresponding to free moisture, combined water and carbonates were measured. Additionally, the materials were analyzed for 14 chemical elements and expressed as the oxides. The analytical scheme is presented in the flow chart, see [Figure 5](#). Additionally, unit weight measurements according to ASTM C 1084 were used to calculate batch weights.

Results of chemical and thermal analyses of cement and aggregates used in concrete mixtures are presented in [Tables 10 and 11](#).

Unit Weight Measurement

Measurements for unit weight were in accordance with ASTM C 1084. Each sample was allowed to soak under water for a period of 48 hours. The sample was then weighed under water and at saturated surface dry condition. The sample was then transferred to a forced air convection oven and dried for 48 hours. The sample was allowed to cool and then weighed. Calculations for Saturated Surface Dry (SSD) unit weight, and Dry unit weights as well as free moisture percent were used in the calculations of total water content. Unit weight measurements were also taken by combining the initial SSD weights of the concrete when demolded at 24 hrs and the cured weights taken at various ages. Calculation of SSD, dry unit weight and free moisture contents are reported in [Table 12](#). As presented in [Table 12](#), all lightweight mixes demonstrated lower initial and oven-dried densities in comparison to the regular mixes. Few outlier results were observed in oven-dry densities especially for the 0.37 mixes with and without lightweight aggregate, and 0.47 mixes with and without lightweight aggregate at 14 days, as well as at 7 days for the 0.57 mixes with and without lightweight aggregate. These outliers are likely attributed to low slump and poor workability of the fabricated mixes.

Thermogravimetry was obtained on a LECO Model TGA 601 multi specimen analyzer and weight losses obtained at 221, 1022 and 1742°F (105, 550 and 950°C). Traditionally the amount of hydration was measured by drying the sample at 221°F (105°C) and then the total loss on ignition was used. For the concrete tested, carbonate from limestone was present and contributed substantially to the total loss. Therefore the amount of hydration product formed (combined water) was measured using the losses between 221°F (105°C) and 1022°F (550°C). The samples were then analyzed using a regression-based program to obtain the amounts of cement, normal weight aggregate and lightweight aggregate. The combined water content from the TGA as well as carbonate was used in the calculations to determine the mix proportions. The loss at 1022°F (550°C) was used for calculating hydration and total water content. The formula for calculating total water content was:

$$[(SSD_{pcf} \times \text{free water \%} * 27/100) + (Dry_{pcf} \times \text{combined water \%} * 27/100)] = \text{total water content.}$$

This value is reported in pounds per cubic yard.

X-ray fluorescence (XRF) analysis meets the precision and accuracy of ASTM C 114 for rapid methods of analysis. Each sample was taken after TGA analysis (ignited sample) and fused using five parts of a borate flux to one part ignited sample to obtain a glass bead. A three place Claisse Fluxy was used to complete the fusion of the material into a glass bead. The bead was then polished on a 30 micrometer diamond impregnated metal wheel with water used as a lubricant. XRF analysis followed using an Applied Research Labs (ARL) Model 8410 wavelength dispersive-scanning x-ray spectrometer and analyzed for 12 elements which were then expressed as the oxides. The ignited results were tabulated and brought to oven dry weight basis using the TGA values. These values were input to a mix evaluation program which allowed for calculations of percent cement, normal weight aggregate and lightweight aggregate based on best fit of the mix components composition to the composition of the concrete.

Regression and Calculations

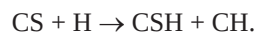
Spreadsheet calculations involve the use of minimizing the differences between the determined composition of the concrete and the calculated best fit of the mass percentages of the ingredients oxide values. These values were obtained for the cement and aggregates samples from bulk and analyzed using XRF. These values are multiplied by the determined percentages of each component (cement, aggregates) that best fit the concrete composition. The difference between the calculated amount of cement and actual batch values are shown in [Table 13](#). The calculated amounts of each ingredient using XRF and regression are presented in [Table 14](#). As indicated above, the differences between the determined amounts and actual batch weights may be attributable to the “dryness” of the batches made with such low w/c containing no admixtures. Most cylinders could not be well consolidated using just the rodding technique but required additional vibration to obtain test cylinders. This may also account for some of the other test cylinder result deviations. The amount of actual water compared to the calculated water was lower than expected for the lightweight aggregate mixes. It may be that the air drying of the specimens removes the water from the lightweight aggregate such that 48 hour soaking (used to determine unit weights) will not reconstitute the lightweight aggregate moisture content.

DISCUSSION

“Hydration” occurs because of the combination of portland cement and water and can be represented as the general formula:



In cement chemist notation:



The hydrates can be decomposed using thermal analysis. By measuring the losses between 221 and 1022°F (105 and 550°C) the amount of hydration product can be determined. This assumes that no appreciable amount of calcium hydroxide has carbonated. There is no appreciable thermal loss associated with the calcium silicate or other clinker minerals.

In terms of hydration the total amount of water that can be consumed by portland cement hydration is approximately 23% by weight and the loss from Ca(OH)_2 decomposition is a fairly direct measure of cement hydration. This can be achieved by mixing portland cement with abundant water and allowing hydration to occur. In this study the tumbled concrete in 50% water places confidence in this measurement. In normal concrete, however, water is usually not that abundant. At a w/c of about 0.23, the cement can not become fully hydrated as the hydration products would occupy more space than the original cement and water occupy. Using water to cement ratio of about 0.35 the hydration products can fill the space formally from the cement and water however for full hydration it must occur in a moist environment. A 0.45 water-cement ratio supplies the space and moist environment for full hydration to occur although in practice full hydration does not occur for many years. Higher water to cement ratio concrete will typically show more hydration product compared to concrete with lower w/c at similar ages and similar curing conditions.

This study shows the importance of water in the curing process. Concrete that is allowed to dry due to low humidity, high wind, or heat will slow the hydration process and may show distress such as drying shrinkage cracks. Self-desiccation may occur if the initial water is depleted during the hydration process and no additional curing water is used. By providing an internal source of “moisture” using lightweight aggregate with high absorption, concrete can be allowed to cure using “internally” supplied moisture. This additional moisture is not available to increase the initial water to cement ratio as the initial moisture is absorbed into the aggregate and available for “moist curing”. The absorbed water does not occupy space in the paste as it is internal to the aggregate and appears to be released readily when subjected to curing conditions used in this project, 50% RH and 70°F (21°C). Additional testing could amplify the effects shown if cured under higher temperatures, lower humidity or both. Petrographic examination could yield insight into differences in paste properties at the surface compared to the body of the concrete. The unit weight measurements at the various ages studied show that once the aggregate releases the water it does not appear to be able to “re-hydrate” itself during the 2-day soak used for unit weight measurements and thus shows lower calculated total water content. This could imply that once emptied during internal curing, the voids in

the lightweight aggregates are not easily re-saturated and may thus function effectively as part of concrete's air void system.

CONCLUSIONS

Significant benefits from using saturated intermediate lightweight aggregate for internal curing were observed. Internal curing is most beneficial at early ages (i.e. within the first few days). During that time, hydraulic cement concrete is particularly vulnerable to stresses developed as a result of early age volume changes, especially in concretes proportioned at very low w/cm ratios and in elements having high ratios of surface area to volume, such as pavements.

Benefits of using saturated lightweight aggregate in pavements are not only due to the provision of additional moisture for cement hydration but also due to increased skid resistance (low polishing characteristics).

Additional study is necessary to evaluate the most effective batch weight of lightweight aggregate in concrete. This study used approximately 350 lb/yd³ (208 kg/m³) SSD of lightweight aggregates in the concrete. Based on site conditions a higher or lower percentage may be more beneficial and it may be possible to optimize the amount used in any concrete depending on the expected concrete exposure conditions. Additionally, the effects of the use of admixtures and supplementary cementitious materials require further study.

REFERENCES

1. ACI Committee 308, "Guide to Curing Concrete (ACI 308R-01)," American Concrete Institute, Farmington Hills, MI, 2001, 30 pp.
2. Kosmatka S. H.; Kerkhoff, B.; and Panarese, W.C., *Design and Control of Concrete Mixtures*, 14th edition, *Engineering Bulletin 001*, PCA, Skokie, IL, 2002.
3. Duran-Herrera A., Aitcin, P.C.; and Petrov, N., "Effect of Saturated Lightweight Sand Substitution on Shrinkage in 0.35 w/b Concrete," *ACI Materials Journal*, V. 104, No. 1, Jan.-Feb. 2007, pp. 48-52.
4. "Guide for Structural Lightweight Aggregate (ACI 213R-03)," American Concrete Institute, Farmington Hills, MI, 2003, 38 pp.
5. Geiker, M.; Bentz, D.P.; and Jensen, O.M, "Mitigating Autogenous Shrinkage by Internal Curing," *High-Performance Structural Lightweight Concrete*, SP-218, American Concrete Institute, Farmington Hills, MI, 2004, pp.143-154.
6. Bentz D.P., and Snyder, K.A., "Protected Paste Volume in Concrete: Extension to Internal Curing Using Saturated Lightweight Fine Aggregate," *Cement and Concrete Research*, V. 29, No. 11, 1999, pp. 1863-1867.

Table 1 — Materials.

Material	Type	ASTM Specification
Cement	Type I/II	C 150
Coarse Aggregate	1" - #4 Crushed Limestone	C 33
Fine Aggregate	Concrete Sand	C 33
Intermediate Aggregate	$\frac{3}{8}$ " - #8 Expanded Shale LWA	C 330
Water	Municipal - Potable	C 1602

Table 2 — Mix proportions and fresh properties for mix 0.37 and 0.37-LWT.

Mix	0.37	0.37-LWT
<u>SSD Mix Design, lbs (kg):</u>	Per 1 yd³ (1 m³)	Per 1 yd³ (1 m³)
Cement	658.0 (390.4)	658.0 (390.4)
Coarse aggregate	1750.0 (1038.3)	1350.0 (801.0)
Fine aggregate	1433.0 (850.2)	1231.0 (730.4)
Lightweight aggregate	0.0 (0.0)	336.0 (199.3)
Water	246.4 (146.2)	246.4 (146.2)
<u>Fresh Properties:</u>		
Fresh density, lbs/ft ³ (kg/m ³)	150.6 (2412.4)	142.4 (2281.0)
Slump, in. (mm)	0.00 (0)	0.50 (13)
Air content, %	2.3	2.5
w/c	0.37	0.37

Table 3 — Mix proportions and fresh properties for mix 0.47 and 0.47-LWT.

Mix	0.47	0.47-LWT
<u>SSD Mix Design, lbs (kg):</u>	Per 1 yd³ (1 m³)	Per 1 yd³ (1 m³)
Cement	564.0 (334.6)	564.0 (334.6)
Coarse aggregate	1750.0 (1038.3)	1350.0 (801.0)
Fine aggregate	1512.0 (897.0)	1310.0 (777.2)
Lightweight aggregate	0.0 (0.0)	348.0 (206.5)
Water	265.0 (157.2)	265.0 (157.2)
<u>Fresh Properties:</u>		
Fresh density, lbs/ft ³ (kg/m ³)	148.2 (2373.9)	140.6 (2252.2)
Slump, in. (mm)	1.50 (38)	2.25 (57)
Air content, %	2.5	2.5
w/c	0.47	0.47

Table 4 — Mix proportions and fresh properties for mix 0.57 and 0.57-LWT.

Mix	0.57	0.57-LWT
<u>SSD Mix Design, lbs (kg):</u>	Per 1 yd³ (1 m³)	Per 1 yd³ (1 m³)
Cement	470.0 (278.9)	470.0 (278.9)
Coarse aggregate	1750.0 (1038.3)	1350.0 (801.0)
Fine aggregate	1540.0 (913.7)	1340.0 (795.0)
Lightweight aggregate	0.0 (0.0)	348.0 (206.5)
Water	267.9 (158.9)	267.9 (158.9)
<u>Fresh Properties:</u>		
Fresh density, lbs/ft ³ (kg/m ³)	148.8 (2383.5)	141.4 (2265.0)
Slump, in.	0.75 (19)	1.25 (32)
Air content, %	2.0	2.0
w/c	0.57	0.57

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Table 5 — Results of testing of coarse aggregate sample #1, ASTM C136.

Weight of Sample After Oven Drying, g: 6005.6

Sieve No.	Coarse Aggregate				ASTM C 33 Requirements (3/4 in. to No. 4)
	Wt. Ret. on Ind. Sieve	% Ret on Ind. Sieve	Cum. % Ret. Ind Sieve	Cum. % Pass Ind Sieve	
3-1/2					
3					
2-1/2					
2					
1-1/2					
1					100
3/4	379.0	6.3	6.3	93.7	90 - 100
1/2	975.8	16.2	22.6	77.4	---
3/8	1352.9	22.5	45.1	54.9	20 - 55
#4	2682.2	44.7	89.7	10.3	0 - 10
#8	547.3	9.1	98.9	1.1	0 - 5
Pan	68.4	1.1	100.0	0.0	---

Table 6 — Results of testing coarse aggregate sample #2, ASTM C136.

Weight of Sample After Oven Drying, g: 5346.7

Sieve No.	Coarse Aggregate				ASTM C 33 Requirements (3/4 in. to No. 4)
	Wt. Ret. on Ind. Sieve	% Ret on Ind. Sieve	Cum. % Ret. Ind Sieve	Cum. % Pass Ind Sieve	
3-1/2					
3					
2-1/2					
2					
1-1/2					
1					100
3/4	235.5	4.4	4.4	95.6	90 - 100
1/2	1071.1	20.0	24.4	75.6	---
3/8	1209.5	22.6	47.1	52.9	20 - 55
#4	2312.9	43.3	90.3	9.7	0 - 10
#8	468.5	8.8	99.1	0.9	0 - 5
Pan	49.2	0.9	100.0	0.0	---

Table 7 — Results of testing of lightweight aggregate sample #1, ASTM C136.

Weight of Sample After Oven Drying, g: 1560.9

Sieve No.	Coarse Aggregate				ASTM C 330 Requirements (3/8 in. to No. 8)
	Wt. Ret. on Ind. Sieve	% Ret on Ind. Sieve	Cum. % Ret. Ind Sieve	Cum. % Pass Ind Sieve	
3-1/2					
3					
2-1/2					
2					
1-1/2					
1					
3/4					
1/2					100
3/8					80 - 100
#4	1109.7	71.1	71.1	28.9	5 - 40
#8	373.7	23.9	95.0	5.0	0 - 20
Pan	77.5	5.0	100.0	0.0	---

Table 8 — Results of testing of lightweight aggregate sample, ASTM C136.

Weight of Sample After Oven Drying, g: 941.5

Sieve No.	Coarse Aggregate				ASTM C 330 Requirements (3/8 in. to No. 8)
	Wt. Ret. on Ind. Sieve	% Ret on Ind. Sieve	Cum. % Ret. Ind Sieve	Cum. % Pass Ind Sieve	
3-1/2					
3					
2-1/2					
2					
1-1/2					
1					
3/4					
1/2					100
3/8					80 - 100
#4	633.6	67.3	67.3	32.7	5 - 40
#8	256.4	27.2	94.5	5.5	0 - 20
Pan	51.5	5.5	100.0	0.0	---

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Table 9 — Results of testing of fine aggregate sample, ASTM C136.

Weight of Sample After Oven Drying, g: <u>468.5</u>					
Sieve No.	Fine Aggregate				ASTM C 33 Requirements % Passing
	Wt. Ret. on Ind. Sieve	% Ret. on Ind. Sieve	Cum. % Ret. Ind. Sieve	Cum % Pass. Ind. Sieve	
#4	1.7	0.4	0.4	99.6	95 - 100
#8	61.9	13.2	13.6	86.4	80 - 100
#16	102.6	21.9	35.5	64.5	50 - 85
#30	67.9	14.5	50.0	50.0	25 - 60
#50	133.5	28.5	78.5	21.5	5 - 30
#100	80.6	17.2	95.7	4.3	0 - 10
#200	4.4	0.9	96.6	3.4	
Pan	15.9	3.4	100.0	0.0	
FM= 2.74					

Table 10 — Results of XRF analysis of materials used in concrete mixtures.

	Fine Aggregate	Coarse Aggregate	Lightweight Aggregate	Cement
Analyte	Wt. %			
SiO ₂	45.60	1.22	68.89	19.67
Al ₂ O ₃	1.38	0.23	15.10	4.61
Fe ₂ O ₃	0.29	0.14	5.31	3.66
CaO	27.79	54.08	2.61	64.10
MgO	0.57	0.38	2.63	1.35
SO ₃	0.04	0.01	0.46	3.49
Na ₂ O	0.11	<0.01	0.99	0.16
K ₂ O	0.61	0.06	2.81	0.56
TiO ₂	0.03	0.01	0.64	0.21
P ₂ O ₅	0.03	0.02	0.18	0.17
Mn ₂ O ₃	0.01	<0.01	0.07	0.43
SrO	0.05	0.05	0.01	0.16
Cr ₂ O ₃	<0.01	<0.01	0.03	0.06
ZnO	<0.01	<0.01	0.04	0.01
L.O.I (950°C)	23.72	43.21	0.20	1.11
Total	100.23	99.42	99.98	99.76
Alkalies as Na ₂ O	0.51	0.04	2.84	0.53

Table 11 — Results of TGA analysis of materials used in concrete mixtures.

	Fine Aggregate	Coarse Aggregate	Lightweight Aggregate	Cement
Free Moisture, ambient - 221°F (105°C)	0.11	0.10	0.21	0.64
Combined Water , 221°F (105°C) – 1022°F (550°C)	0.29	0.23	0.15	0.66
CO ₂ , 1022°F (550°C) – 1742°F (950°C)	23.41	42.94	0.04	0.44

Table 12 — Determined unit weight using ASTM C 1084 methodology.

Age, days	Mix ID	Unit Weight, lbs/ft ³ (kg/m ³)		Free Moisture, weight %	Mix ID	Unit Weight, lbs/ft ³ (kg/m ³)		Free Moisture, weight %
		SSD	Dry			SSD	Dry	
1	0.37-LWT	141.3 (2263.4)	130.7 (2093.6)	7.5	0.37	151.3 (2423.6)	143.2 (2293.8)	5.3
3		142.1 (2276.2)	133.1 (2132.1)	6.3		152.5 (2442.8)	145.0 (2322.7)	4.9
37		140.5 (2250.6)	131.3 (2103.2)	6.5		151.4 (2425.2)	143.5 (2298.6)	5.2
14		138.9 (2225.0)	129.9 (2080.8)	6.5		145.9 (2337.1)	135.2 (2165.7)	7.3
28		141.3 (2263.4)	133.2 (2133.7)	5.8		151.0 (2418.8)	143.9 (2305.1)	4.7
90		139.2 (2229.8)	130.7 (2093.6)	6.1		150.3 (2407.6)	142.9 (2289.0)	4.9
1	0.47-LWT	141.9 (2273.0)	130.6 (2092.0)	8.0	0.47	149.8 (2399.6)	140.8 (2255.4)	6.0
3		141.2 (2261.8)	130.9 (2096.8)	7.3		150.6 (2412.4)	142.0 (2274.6)	5.7
37		140.7 (2253.8)	130.9 (2096.8)	6.9		150.3 (2407.6)	142.0 (2274.6)	5.5
14		141.7 (2269.8)	132.3 (2119.2)	6.7		149.9 (2401.2)	141.5 (2266.6)	5.6
28		140.8 (2255.4)	131.5 (2106.4)	6.6		149.7 (2398.0)	141.2 (2261.8)	5.7
90		140.9 (2257.0)	132.0 (2114.4)	6.3		149.2 (2390.0)	140.8 (2255.4)	5.7
1	0.57-LWT	144.0 (2306.7)	132.3 (2119.2)	8.1	0.57	150.1 (2404.4)	141.3 (2263.4)	5.9
3		142.9 (2289.0)	132.8 (2127.3)	7.1		149.9 (2401.2)	141.2 (2261.8)	5.8
37		141.9 (2273.0)	132.0 (2114.4)	7.0		148.4 (2377.1)	139.7 (2237.8)	6.7
14		142.0 (2274.6)	132.9 (2128.9)	6.4		149.0 (2386.8)	140.5 (2250.6)	5.7
28		141.4 (2265.0)	132.1 (2116.0)	6.6		149.2 (2390.0)	141.0 (2258.6)	5.5
90		140.6 (2252.2)	131.6 (2108.0)	6.4		147.7 (2365.9)	139.5 (2234.6)	5.6

Table 13 — Calculated cement contents using regression based analysis.

		Cement Content, lb/yd ³ (kg/m ³)							Calculated Average
Age, days		0	1	3	7	14	28	90	
Mix ID	0.37-LWT	0	613 (364)	532 (316)	696 (413)	588 (349)	619 (367)	572 (339)	603 (358)
	0.37	0	776 (460)	541 (321)	692 (411)	639 (379)	616 (365)	585 (347)	641 (380)
	Actual	658	658	658	658	658	658	658	658 (390)
	0.47-LWT	0	548 (325)	513 (304)	518 (307)	538 (319)	471 (279)	530 (314)	520 (309)
	0.47	0	590 (350)	507 (301)	506 (300)	485 (288)	519 (308)	428 (254)	506 (300)
	Actual	564	564	564	564	564	564	564	564 (335)
	0.57-LWT	0	495 (294)	430 (255)	477 (283)	516 (306)	429 (255)	447 (265)	466 (276)
	0.57	0	479 (284)	448 (266)	469 (278)	401 (238)	472 (280)	516 (306)	464 (275)
	Actual	470	470	470	470	470	470	470	470 (279)

Table 14 — Mix reconstructions based on TGA, Unit Weight and XRF analyses.

Mix ID	Test Age	1	3	7	14	28	90	28 tumble	90 tumble
0.37	Cement	776	541	692	693	616	585		
	Coarse	1968	2384	2119	1901	2298	2189		
	Fine	1156	1005	1071	1109	981	1158		
	Water,add'd	227	209	237	314	213	223		
	105-550 loss	1.56	1.6	1.98	2.05	1.95	2		
calculated	% hydrated	29	46	46	50	51	54		
0.37-LWT	Cement	613	532	696	588	619	572		
	Coarse	1374	1771	1405	1591	1587	1629		
	Fine	1248	1022	1114	1076	1147	1034		
	30% moisture	LightWt	380	319	386	298	317		
		Water,add'd	215	193	204	205	182		
		105-550 loss	1.74	1.96	2.47	2.14	2.29	3.35	3.23
calculated	% hydrated	42	55	54	54	56	60	90	98
0.47	Cement	590	507	506	485	519	530		
	Coarse	2048	2146	2112	2135	2145	1869		
	Fine	1165	1177	1211	1199	1119	1355		
	Water,add'd	257	242	234	237	238	240		
	105-550 loss	1.78	1.68	1.68	1.71	1.89	1.89		
calculated	% hydrated	47	51	51	54	57	55		
0.47-LTW	Cement	548	513	518	538	471	428		
	Coarse	1712	1704	1602	1804	1677	1922		
	Fine	1053	1024	1150	930	1054	933		
	30% moisture	LightWt	277	385	342	394	376		
		Water,add'd	253	205	206	190	193		
		105-550 loss	1.66	1.74	1.88	2.05	2.1	2.85	2.85
calculated	% hydrated	44	50	54	58	66	61	89	91
0.57	Cement	479	448	469	401	472	516		
	Coarse	2189	2031	2124	2277	2191	1775		
	Fine	1166	1357	1208	1148	1119	1417		
	Water,add'd	231	231	238	227	223	248		
	105-550 loss	1.29	1.38	1.54	1.44	1.71	1.66		
calculated	% hydrated	39	46	50	53	56	63		
0.57-LTW	Cement	495	430	477	516	421	447		
	Coarse	1725	1887	1752	1589	1748	1693		
	Fine	1105	1019	1032	1146	1109	1063		
	30% moisture	LightWt	325	321	411	435	369		
		Water,add'd	242	200	187	171	179		
		105-550 loss	1.37	1.4	1.71	1.99	1.7	2.33	2.4
calculated	% hydrated	40	46	53	58	58	66	83	91

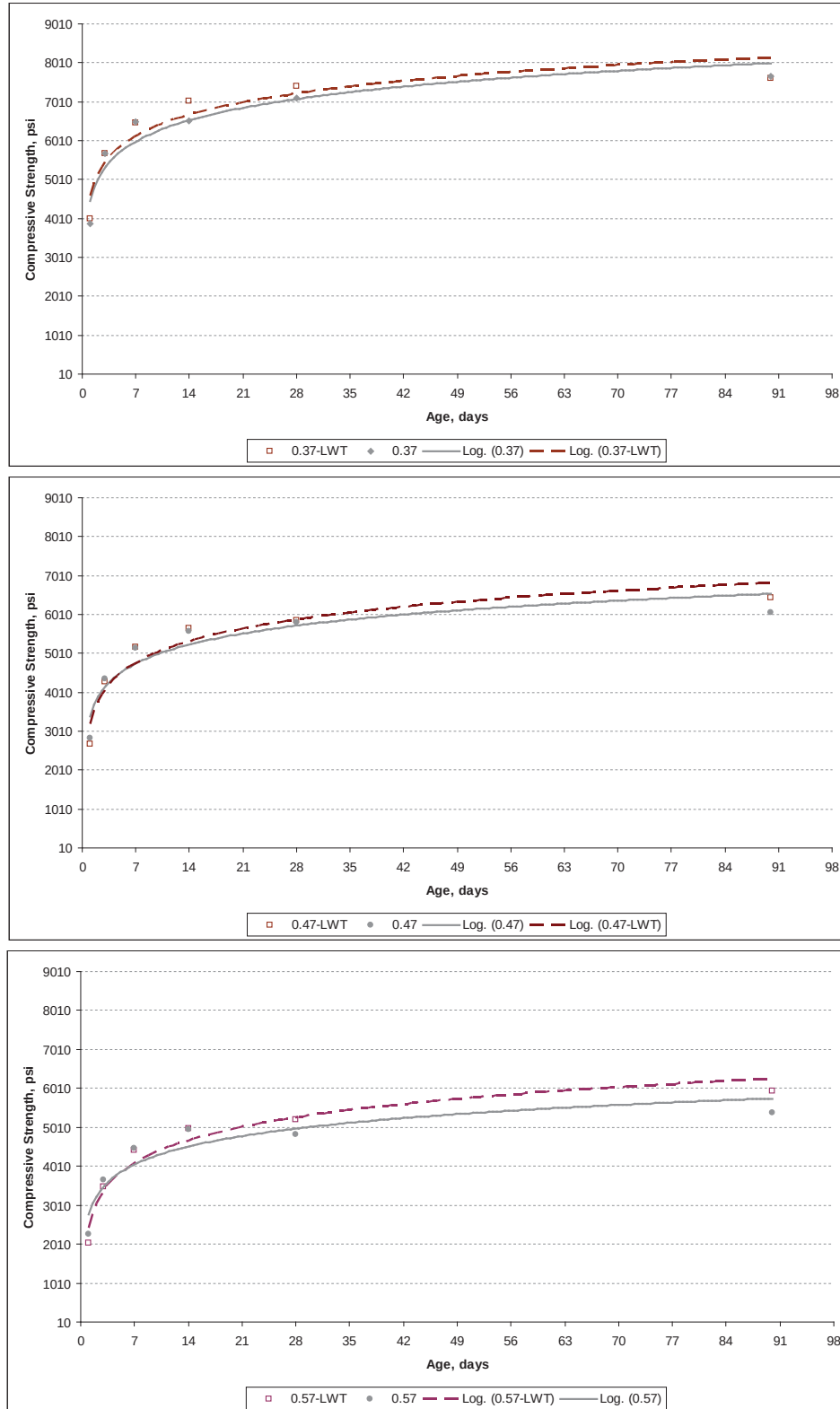


Figure 1 — Compressive strength results with trend lines.

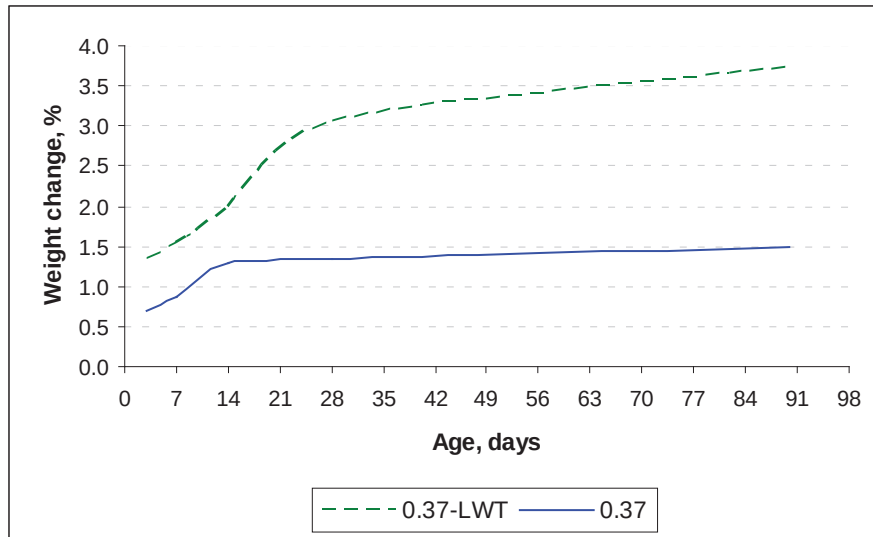


Figure 2 — Percentage moisture loss over time based on initial weights and weight at various ages: 0.37 and 0.37-LWT mixtures.

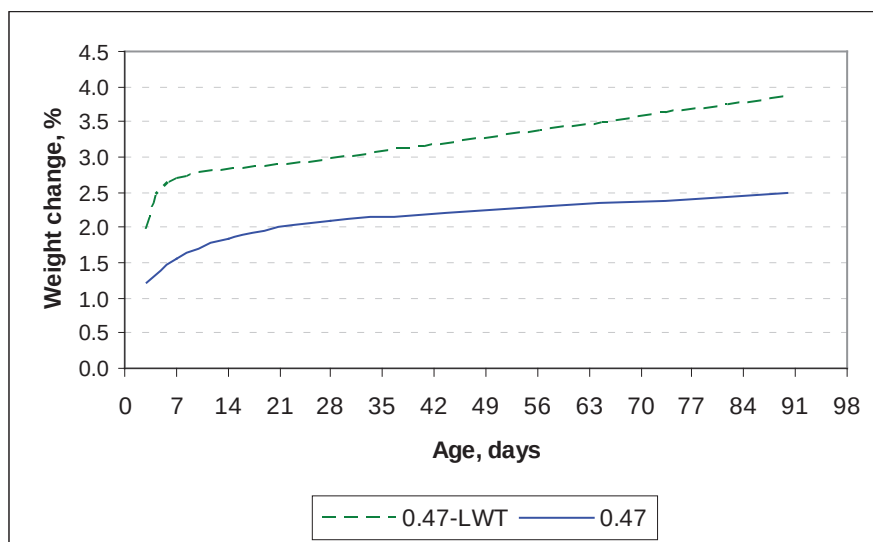


Figure 3 — Percentage moisture loss over time based on initial weights and weight at various ages: 0.47 and 0.47-LWT mixtures.

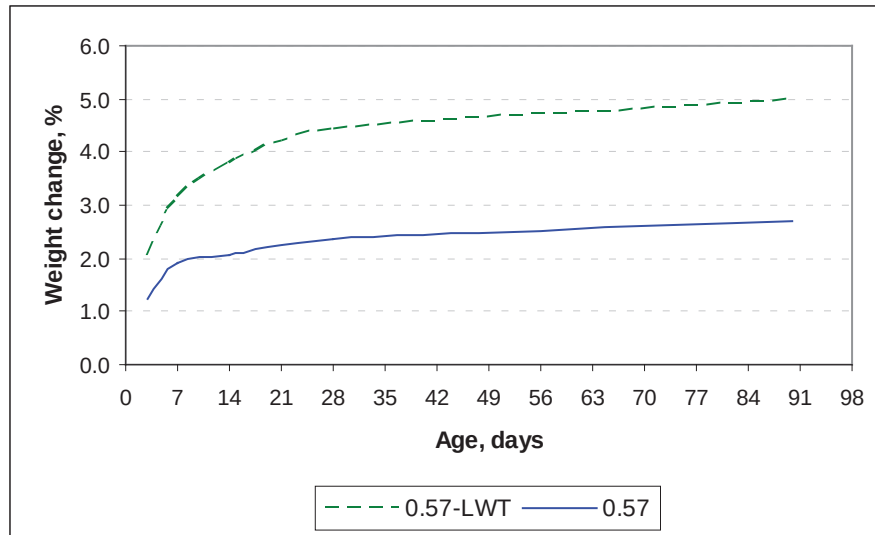


Figure 4 — Percentage moisture loss over time based on initial weights and weight at various ages: 0.57 and 0.57-LWT mixtures.

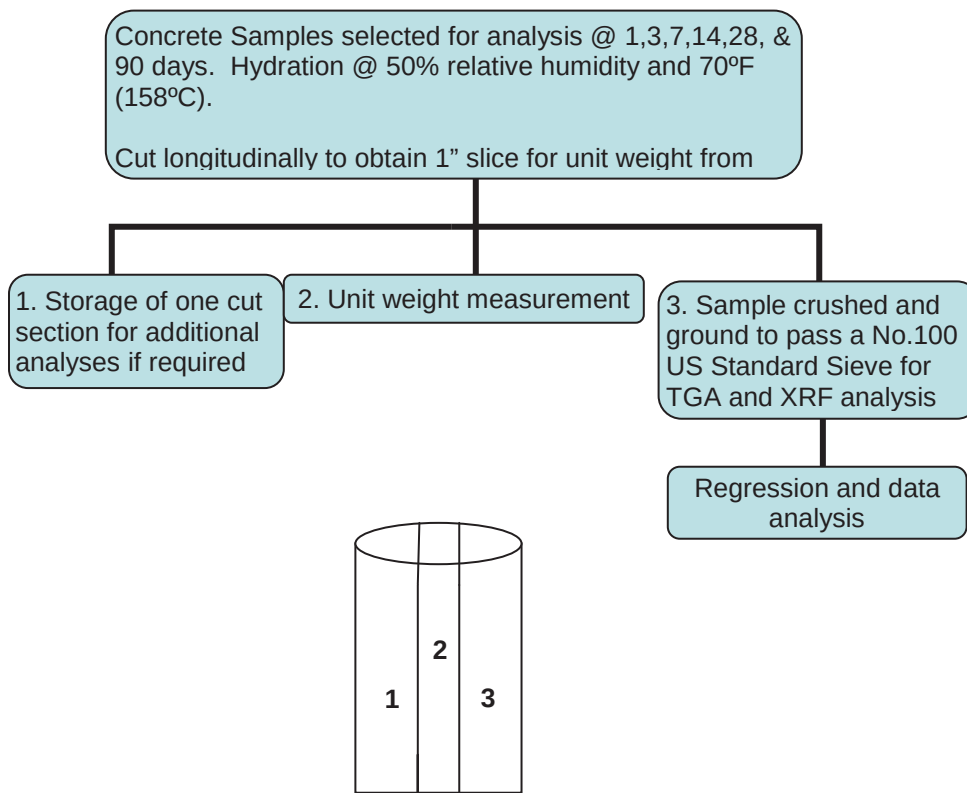


Figure 5 — Cutting layout of cylinders used for test at each age.

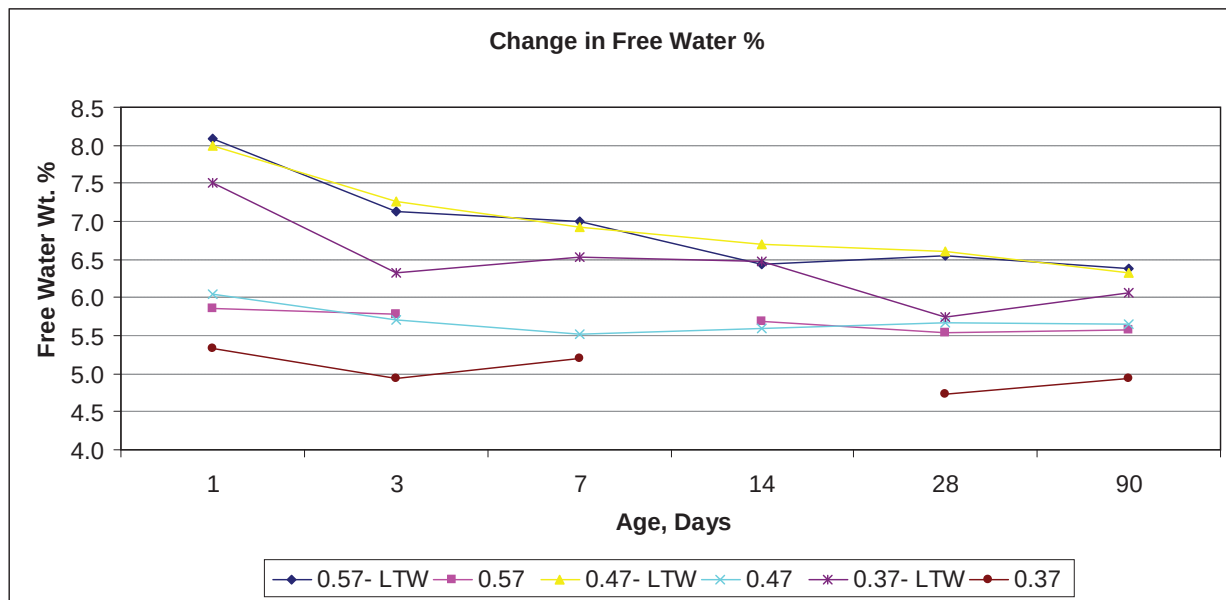


Figure 6 — Change in free water percent stored at 50% RH and 70°F.

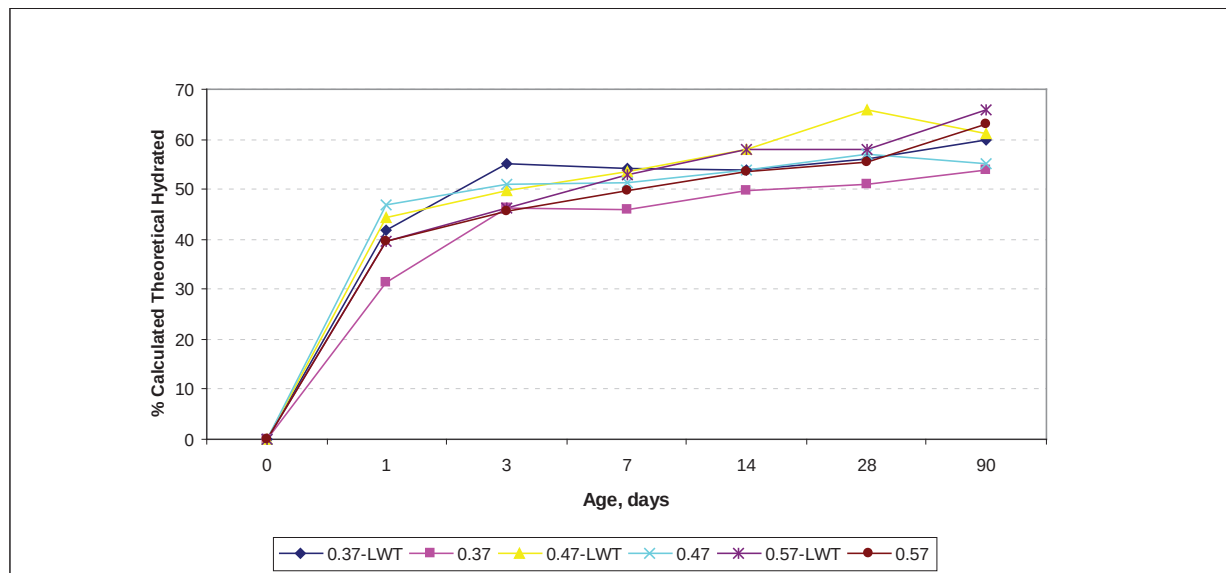


Figure 7 — Calculated percent hydration based on combined water contents and determined cement content.

Pre-soaked Lightweight Fine Aggregates as Additives for Internal Curing in Concrete

by Y. Wei and W. Hansen

Synopsis: High-performance concrete (i.e. water-cementitious ratio below 0.40) for bridge-deck applications has been shown to develop shrinkage-related cracking. This study explores the concept of internal curing using pre-soaked lightweight fine aggregate (LWFA) as partial replacement of sand for mitigating autogenous shrinkage and moisture warping. Concretes with water-cementitious ratios (w/c) of 0.35 and 0.45 containing LWFA to sand ratios of 20% and 40% by volume were investigated. Results show that pre-soaked LWFA is effective in mitigating autogenous shrinkage but also reduces slab uplift from moisture warping due to combined drying shrinkage at the top surface and wetting at the bottom surface.

Keywords: autogenous shrinkage; internal curing; moisture warping; self-desiccation shrinkage; self-induced stress

Biography:

Ya Wei is a PhD candidate at The University of Michigan, Ann Arbor, MI. Her research interests include early-age properties, curling, and warping analysis in pavement. She received her BEng from Chang'an University, China, and MSc from Southeast University, China.

Will Hansen, Ph.D., FACI, is a Professor of Civil Engineering at The University of Michigan, Ann Arbor, MI. He is currently Chairing ACI Committee 231, Properties of Concrete at Early Ages, and is a member of Committees 209, Creep and Shrinkage, and 224 Cracking.

INTRODUCTION

Autogenous shrinkage is the macroscopic volume reduction of cementitious systems without moisture transfer to the environment. This property is a result of self-desiccation of pores within the hydrating cement paste thus increasing with degree of hydration.

Within days after pouring, the hydrating cement paste develops capillary discontinuity.^{1, 2} This has been found to hinder moisture transport in cross sections greater than about 80 mm (3.2 in.).³ Once this happens a moisture gradient can develop within the cross section any time the concrete is exposed to water at the free surface. Consequently, warping deformation can result in slabs if poor base-drainage conditions exist.^{4, 5}

This paper presents new experimental results and test methods for quantifying autogenous shrinkage and warping and the effectiveness of internal curing by using pre-soaked LWFA in mitigating the shrinkage and associated tensile stresses.

RESEARCH SIGNIFICANCE

Low w/c (less than 0.40) bridge-deck concrete often develops shrinkage-related cracking. Cracking can affect the durability, especially in wet-freeze climate zones in North America, where deicing salts are used extensively during the winter. Low w/c mixes develop larger autogenous shrinkage. If this property can be mitigated through internal curing procedures, the advantages of using low w/c concrete can be better realized. Even higher w/c concretes such as highway mixes (w/c between 0.40 and 0.45) can benefit from internal curing procedures if they counteract self-desiccation by maintaining high internal pore humidity. In this study the use of water-soaked lightweight fine aggregate for internal curing and autogenous shrinkage control is further explored.

EXPERIMENTAL PROGRAM

Materials and experimental methods

A type I portland cement was used throughout. The chemical compositions of this type of cement are listed in **Table 1**. The sand-size expanded shale lightweight aggregate was obtained from a local manufacturer. This type of LWFA was found to have a bulk specific gravity of 1.8 and water content of 15% by weight obtained in a 24-hour pre-soaked condition. Two w/c ratios (0.35 and 0.45) and two LWFA contents (20% and 40%) by volume were used. The mix proportions for the 0.35 w/c concrete without LWFA and with 40% LWFA sand-volume replacement are shown in **Table 2**. For mix proportions of concrete with w/c = 0.45 (which is not listed in **Table 2**), the aggregate volume was maintained the same as w/c = 0.35 concrete.

Tests included heat of hydration of the portland cement paste, free and restrained autogenous deformation of concrete with a maximum aggregate size of 12.5 mm (1/2 in.), and moisture warping of concrete beams. Preliminary free autogenous deformation tests on concrete containing 25 mm (1 in.) maximum aggregate size were inconclusive. It was decided to remove the largest aggregate particles as they hindered the macroscopic measurement of autogenous shrinkage, probably due to particle to particle proximity.

Measurement of heat of hydration

Long-term (up to 21 days) isothermal heat rate was obtained for 0.35 and 0.45 w/c cement pastes at 23 °C (73 °F). Two specimens were tested for each mix and the average results were reported.