

Optimizing the Sustainability of Concrete Through Internal Curing

by: Benjamin E. Byard and John Ries

Abstract: The internal curing process is often referred to as “curing concrete from the inside out”. This process is accomplished by using materials that absorb water, such as lightweight aggregate, to replace some of the normalweight aggregate in the freshly placed concrete mixture. This absorbed water can then be released from the aggregate into the paste fraction as the paste begins to desiccate. By doing this the hydration reactions of cement and supplementary cementitious materials are enhanced, and capillary stresses are reduced as the water is readily released from the absorbent materials.

This paper gives a general overview of internal curing, and will show how internal curing plays a practical and economical role in today’s move toward sustainable concrete. The paper will explain how internal curing works, why internal curing is used, summarize the modern history of internal curing, and how it affects the carbon footprint of a concrete mixture. In addition, how to adjust the concrete mixture to provide appropriate amount of internal curing, and reduce the life-cycle costs of the concrete. Examples of real projects that have used internally cured concrete will then be highlighted.

Keywords: Internal curing, life-cycle cost, lightweight aggregate, mixture proportioning, performance, sustainability,

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INTRODUCTION

The internal curing (IC) process is often referred to as “curing concrete from the inside out”. This process is accomplished by using materials that absorb water, such as lightweight aggregate (LWA) or super absorbent polymer, to replace some of the aggregate in the freshly placed concrete mixture. This absorbed water can then be released from the aggregate into the paste fraction as the paste begins to desiccate. By doing this the hydration reactions of cement and supplementary cementitious materials (SCM) are enhanced, and capillary stresses are reduced as the water is readily released from the absorbent materials.

Internal curing is not a new process, and occurs naturally in conventional lightweight concrete; which has been used since 3000 B.C. when the Sumerians used LWA concrete to build Babylon¹. In addition, Romans used LWA concrete in building their empire including the Pantheon and the aqueducts¹. What is new, however, is a better understanding of the internal curing process. This better understanding has resulted in IC being intentionally incorporated into normalweight concrete to improve its properties and performance in an economical and practical way.

How internal curing works

The reaction products formed from cement hydration occupy a smaller volume than the initial components². The reduction of the volume of the reactants due to hydration is chemical shrinkage. Before setting, this phenomenon results in a volumetric change but generates no stress because the concrete is still plastic³. At setting, enough hydration products have formed to provide a self-supporting skeletal framework in the paste. Within the framework of solids are water-filled capillary voids. As water is consumed by the ongoing hydration process, the voids desiccate and capillary tensile stresses are generated, which results in a volumetric shrinkage. The concrete volume change that occurs without moisture transfer to the environment or temperature change is called autogenous shrinkage. When wetted LWA is introduced into the mixture, it can desorb water from its pores into the paste maintaining high moisture levels, limiting capillary stresses and increasing the ultimate degree of hydration⁴.

To date, in North America almost all IC research and construction projects use expanded shale, clay or slate (ESCS), which is a porous, low density, strong and durable lightweight aggregate. The pore structure of this aggregate will allow it to absorb water, and readily release it to the hydrating cementitious paste. Research by Castro et al.⁵ has shown that ESCS will release over 85% of its absorbed water at relative humidity of 94%. This has been found to be the optimal level of desorption for IC to occur. To be most beneficial the internal curing water needs to be released from the aggregate at high relative humidity, like that of the paste fraction in concrete at early-ages⁵. The performance of other absorbent materials is not covered in this paper as they are still in various stages of research and development.

Why internal curing is used

Durability - Internal curing increases the performance of concrete by increasing the amount of cement hydration^{6, 7, 8}. The improvement in degree of hydration is seen even at higher w/cm of 0.45, as the illustrated in Figure 1. This increase in hydration is attributed to the additional moisture provided by the lightweight aggregate. Increased degree of hydration improves the microstructure of the paste fraction; which, increases paste density and strength⁹. This increased degree of hydration and strength has also been shown with mixtures containing SCM¹⁰. The SCM reactions generally require more time than ordinary cement reactions. Thus, the increased strength of internally cured SCM mixtures has been attributed to the longer periods of high moisture allowing for their long-

term hydration and pozzolanic reactions to take place⁴. In addition, internal curing has been shown to provide a denser and more homogeneous interfacial transition zone (ITZ) between LWA particles and paste, when compared to the ITZ of normalweight aggregate particle¹¹. Generally, the ITZ region is less dense than the bulk hydrated cement paste, and provides a preferential pathway for the ingress of potentially deleterious chloride ions¹². The improved ITZ, provided by LWA, greatly reduces the transport properties at the LWA⁴.

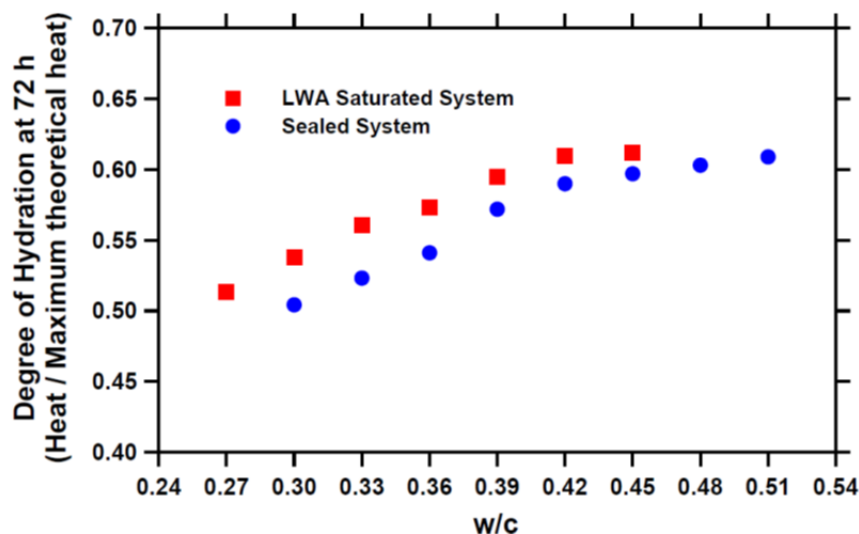


Figure 1 — Degree of hydration of sealed specimen⁶

Stress development - The additional water provided by IC minimizes the internal autogenous stresses caused by self-desiccation^{4, 13, 14}. This reduced autogenous stress reduces the total state of stress, and can improve the cracking performance¹⁴. Internally cured concrete also benefits from reduced modulus of elasticity and coefficient of thermal expansion (CTE) when compared to non-internally cured concrete, all of which lower stresses within the concrete, and improve the cracking performance of the concrete. The increased cracking performance of the internally cured concrete compared to non-internally cured is illustrated in Figure 2. The combined effect of the reduced CTE, modulus of elasticity, and autogenous stress results in an increased time to cracking of the internally cured sample. In field placements, this increased cracking performance may be in the form of increased crack spacing, decreased crack widths or fewer cracks.

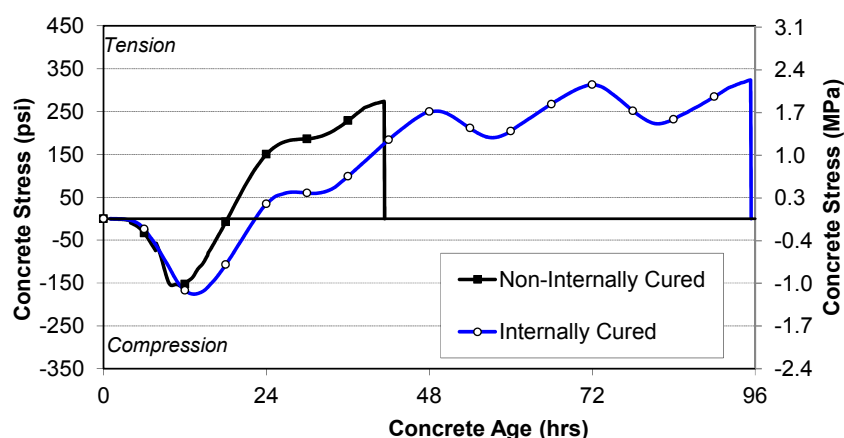


Figure 2 — Stress development of bridge deck concrete¹⁴

Surface curing may only penetrate the concrete 0.08 to 0.79 inches (2 to 20 mm), and may be insufficient to maintain adequate moisture throughout the cross section¹³. Properly proportioned internally cured concrete can

provide an even distribution of internal curing water throughout the thickness of the concrete section, which can reduce internal stresses due to warping¹⁵.

Internal curing has also been shown to work well with SCM¹⁶. SCM have increased chemical and autogenous shrinkage^{10, 13}; consequently, they have been found to have increased demand for internal curing water compared to concrete with ordinary portland cement¹⁶. Internal curing has been shown to significantly reduce the increased self-desiccation associated with concrete mixtures containing SCM¹⁶.

Construction - Internal curing was recently described as a way to make conventional concrete more robust for field construction due to its ability to perform well under a wide range of site conditions¹⁷. During construction, internally cured concretes have available water to reduce plastic and drying shrinkage cracking that can occur in higher temperature and lower humidity placements¹⁷. In addition, their decreased CTE and modulus which reduce thermal stresses, and allow for more early-age robustness with respect to thermal shock from form removal, cooling, or diurnal temperature changes^{17, 14}.

Concrete finishers have reported improved workability and finishability, because the additional IC water helps to eliminate some of the stickiness commonly found in concrete utilizing SCM, such as silica fume.

While internal curing does not replace conventional surface curing, it can help compensate for higher temperature, low relative humidity weather conditions and poor conventional curing that is often seen in the real world.

THE HISTORY OF INTERNAL CURING

The first modern awareness of internal curing dates back to the mid 1950's when Paul Klieger¹⁸ wrote, "*Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration.*" Campbell and Tobin¹⁹ confirmed this with a comprehensive program that showed the availability of absorbed moisture in lightweight aggregate will produce a more forgiving concrete that was less sensitive to poor field curing conditions.

In the early 1990s, the benefits of internal curing came to the concrete industry forefront. Robert Philleo²⁰ stated, "*Either the basic nature of Portland cement must be changed so that self-desiccation is reduced, or a way must be found to get curing water into the interior of high-strength structural members. The latter is possible through the use of saturated lightweight aggregate. However, people striving for high strengths are not eager to use lightweight aggregate. A partial replacement of fine aggregate with saturated lightweight fines might offer a promising solution.*"

Structural lightweight aggregate was used on the Hibernia Offshore Platform in Newfoundland, Canada, to improve buoyancy by replacing 50% of the coarse aggregate with wetted ESCS aggregate. The benefits of internal curing quickly became apparent on this innovative use of high-strength lightweight concrete, which spawned new research on the subject in the mid-1990s.²¹

Around 2000, the National Institute of Science and Technology (NIST) started an extensive investigation of IC. Since then, IC has been widely investigated with well over 100 papers published to date. One recent significant report, "Internal Curing: A 2010 State-of-the-Art Review," by Bentz and Weiss⁴ covers the subject in depth.

INTERNAL CURING MIXTURE DESIGN

Generally, autogenous stress development is not considered a concern at w/cm above 0.42⁹. However, internally cured concrete has shown decreased chloride permeability at w/cm up to 0.55²², and has shown to have increased degree of hydration results in mixtures with w/cm up to 0.45⁶.

The IC mixture design is quite simple; typically, a fine LWA replaces a portion of the normalweight mixture's sand fraction. The finer grading provides a more even distribution of IC water than the same amount of water in coarse ESCS aggregate. In hardened concrete, water only travels a limited distance depending on age and w/cm; therefore, it's important the IC water is distributed as evenly as possible. Henkensiefken²³ showed that water from LWA can move 0.07 inches (1.8 mm) into the paste surrounding an aggregate particle. However, more recent research has shown that water from lightweight aggregates travels at least 0.12 inches (3.0 mm) into the paste²⁴. In some mixtures, intermediate size aggregate may optimize total aggregate grading, as well as provide IC¹⁴.

For most practical concrete applications, 7 lbs IC water/100 lbs cementing material (7 kg IC water / 100 kg cementing material) provides an appropriate value for the amount of IC moisture needed. This value is based on the work of Geiker et al.²⁵ who showed most cement have a chemical shrinkage of 7 ml / g of cement. However, the amount of IC water may be increased to accommodate evaporation, or to satisfy the higher internal curing water

demand in mixtures with SCMs. The amount of wetted ESCS aggregate needed is based on the absorption and desorption properties of the aggregate being used, and the desired proportion of IC water.

Knowing the target amount of IC water needed and the aggregate's absorption and desorption, the amount of wetted ESCS aggregate can be determined through the use of ESCSI's "Guide for Concrete Mixture Designs using Wetted ESCS Lightweight Aggregates for Internal Curing,"²⁶ or "Mixture Proportioning for Internal Curing."²⁷

INTERNAL CURING HELPS THE "SUSTAINABILITY" OF CONCRETE

Cusson et al.²⁸ studied the impact of internal curing on the service life of high-performance concrete (HPC) bridge decks by using deterministic analysis of analytical models to predict the times to onset of corrosion, onset of corrosion-induced damage, and failure of bridge decks. Three bridge deck designs were compared in severe environmental conditions: (1) normal concrete deck with 0.40 w/c; (2) HPC deck with SCM and 0.35 w/cm; and (3) HPC deck with SCM and internal curing at 0.35 w/cm. It was found that the use of HPC with SCM extended the service life 18 years compared to normal concrete and that HPC with SCM incorporating internal curing extended the service life of normal concrete bridge decks 41 years. The significant increase in service life using IC is mainly due to a significant reduction in the penetration rate of chlorides in concrete as a result of reduced early-age shrinkage cracking and reduced chloride diffusion.

When compared to normal concrete in bridge decks, Cusson et al.²⁸ estimated life-cycle cost reductions of 40% with conventional HPC and 63% reduction with internally cured HPC. This lower life-cycle cost is despite the fact that the in-place unit cost of internally cured HPC can be 4% higher than that of conventionally cured HPC, which in turn can be up to 33% higher than that of normal concrete. The lower cost is due to a longer predicted service life and less frequent maintenance activities, because the internally cured HPC bridge deck's lower permeability and fewer cracks.

Some additional cost, energy, and emissions will be associated with manufacturing ESCS lightweight aggregate, but these are lower than the savings realized due to its use. In general, 100 lbs (45kg) of ESCS generates about 18 lbs (8kg) of CO₂²⁹, which is roughly equivalent to the amount of CO₂ created by manufacturing 18 lbs (8kg) of portland cement. To determine the carbon footprint, each mixture needs to be individually evaluated based on the balance of CO₂ from cement reduction, increased SCM use and the potential increase in service life.

Through the use of IC, users of concrete structures as well as owners and the overall society will benefit for years to come with a more durable concrete that can have a longer service life²⁸. This helps the economy by lowering the life-cycle cost of structures. The environment benefits from a more efficient use of cementing material and the potential for reducing the carbon footprint of a concrete mixture.

INTERNAL CURING PROJECTS

Since 2003, over 2 million yd³ (1.5 million m³) of internally cured normalweight concrete have been placed, including 1.3 million yd³ (1.0 million m³) of low slump pavements³⁰. Some of the more recent projects that have incorporated wetted ESCS aggregates into a normalweight concrete mixture for the specific purpose of internal curing are provided below.

The Union Pacific Intermodal Terminal, Hutchins, TX³¹

The union pacific intermodal terminal project in Hutchins Texas, started in 2005, and incorporated over 250,000 yd³ (190,000 m³) of internally cured concrete. The mixture used 5 ft³ (0.15 m³) bulk volume of an ESCS intermediate grading (3/8 in. to No. 8) in each cubic yard of concrete to replace a portion of both the normalweight coarse and fine aggregate. This enhanced both the cementitious hydration and overall aggregate grading of the mixture, which resulted in the mitigation or elimination of plastic and drying shrinkage cracking. The average compressive strength gain was about 1000 psi (7 MPa) with a 200 lbs/yd³ (120 kg /m³) reduction in unit weight, which translates to 2000 lbs (900 kg) less weight per 10 yd³ (7.6 m³) load of concrete.

Texas State Highway SH 121³⁰

Texas State Highway SH 121 incorporated 1300 yd³ (1000 m³) of internally cured concrete on one side of a 5 mile (8 km) section near Dallas in November 2006. A 500 ft (150 m) long section of continuously reinforced concrete pavement was evaluated for cracks on February 1, 2007, and again on September 11, 2007. The side with IC showed

21 cracks. In comparison, the normalweight control on the other side of the road showed 52 cracks. In addition, the crack width was considerably smaller on the side with the internally cured concrete.

New York State³⁰

New York State has incorporated the use of wetted ESCS LWA fines into numerous bridge decks throughout the state. Thousands of yards of internally cured concrete were specified to reduce cracking associated with low permeability concrete that incorporated SCMs into the mixture. These structures are exposed to high traffic volumes and have high exposures to de-icing chemicals because of the severe climate.

The State of Indiana³⁰

Indiana began their transition from IC laboratory research to the field testing with two bridge decks near Bloomington, cast in September 2010. The placement of the internally cured bridge deck is shown in Figure 3. The bridges had similar design and were constructed with the same methods and materials supplied from the same ready mix company. One of the bridge decks used non-internally cured, conventional, bridge deck concrete; while the other internally cured bridge deck had approximately 55% of the fine aggregate replaced with wetted lightweight aggregate. One finisher noted that the IC mixture was less “sticky” and easier to work with.

Test results showed similar compressive strengths at 10 days, and at 3 months the internally cured concrete was 20% stronger. Rapid chloride permeability results for the IC mixture was 10% lower at 28 days, and nearly 40% lower after 3 months. The internally cured mixture also showed lower drying shrinkage. It was also notable that cracks developed in the conventional deck after the first few months of service as illustrated in Figure 4, while at nearly one year after placement, the internally cured concrete has no visible cracking as illustrated in Figure 5.



Figure 3—Placement of internally cured bridge deck concrete near Bloomington IN³⁰



Figure 4—Cracking in conventional concrete bridge deck after 3 months of service³⁰



Figure 5—Internall cured bridge deck with no observed cracks after 1 year of service³⁰

SUMMARY

The goal of internal curing is to provide additional curing water with a proper spatial distribution, so that the entire three-dimensional microstructure of hydrating cementitious paste remains saturated and autogenous stress free⁴. Internal curing reduces or eliminates early-age cracking of the concrete and promotes increased of hydration of cementing materials, contributing to increased strength, and reduced transport coefficients. All of which helps concrete achieve its maximum potential as a sustainable building material by extending its service life and improving the economical, environmental, and social aspects of the concrete industry.

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History and Evolution of Internal Curing-Case Studies

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Synopsis: First noticed by T. C. Powers, et al in 1948, [22] as beneficial for hydration by supplying water internally, specifiers and contractors in 2012 have grasped how the process of internal curing is implemented, how hydration behaves, and how improvements in mechanical properties, durability, and cost may be beneficial. To meet the time-dependent hydration needs of the concrete, having sufficient water internally available, when, as, and where needed, is vital for achieving optimum characteristic qualities. There is lower life cycle cost with internal curing (IC) and frequently lower first cost. In 2012, the number of projects using internal curing is increasing at an escalating rate, because the process is simple and economically implemented. Pavements, bridges, buildings, and pervious parking lots are being started now in this recession, because specifiers and contractors are saving dollars, as they build longer lasting structures while costs and interest rates are low. Developed initially to reduce autogenous shrinkage in low water-cement ratio and high performance concretes, internal curing has been found to reduce drying shrinkage. Other benefits found include reduced permeability, increased compressive and flexural strengths, less warping, stronger interfacial transition zones, greater durability, and lower carbonation.

Keywords: Curing, internal curing, long life, low life cycle cost, saturated-surface-dry

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INTRODUCTION

The concrete curing process uses water to keep the outside surface moist, thus reducing drying shrinkage and cracking. [ACI 308 Guide]¹. Bryant Mather, the first chairman of the reconstituted ACI 308 Curing committee said “Curing is the maintaining of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop. Curing is essential in the production of concrete that will have the desired properties. The strength and durability of concrete will be fully developed if it is cured. No action to this end is required, however, when the ambient conditions of moisture, humidity, and temperature are sufficiently favorable to curing. Otherwise, specified curing measures shall start as soon as required. There are cases in which concrete has been greatly assisted in moving toward a self-curing status either inadvertently or deliberately through actions taken in the selection and use of materials.” He cites a case where a curing compound was omitted on two slabs of a motel project, one normal weight⁵, and the other one lightweight⁶. “The next morning the normal-density concrete was virtually destroyed by drying shrinkage cracks. On the other hand, the low-density concrete had practically no cracking. Enough absorbed water had been brought to the concrete, though not included in the water-cement ratio, to effectively compensate for the contractor's failure to apply the prescribed membrane-forming curing compound”²⁰.

In order to achieve high strengths, and reduce drying shrinkage, the industry, starting in the late 1990's, has been attracted to a system using low water-cement (w/c) ratios, called high performance concrete (HPC). The problem is that this intensifies a different shrinkage – chemical and autogenous. To eliminate this, the essential water has been supplied internally from reservoirs in the absorbent lightweight aggregate sand (LWAS) that replaces some of the normal weight sand in the concrete mixture.⁹. This was named "Internal Curing"(IC) and was published in *ACI Concrete Terminology*, August 2010:²

ACI Definition: curing, internal – supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self desiccation.

The genesis of Internal Curing was to reduce or eliminate autogenous shrinkage (9) and cracking and the equation as to how much LWAS to use based on chemical shrinkage was developed by Bentz et al., based on the amount of water needed to overcome chemical shrinkage⁹. The water also has benefits other than correcting shrinkage^{9,22} such as improved hydration¹⁰, provision of early age (4) and later compressive and mortar strength¹⁸, early age flexural strength, reduced permeability¹⁷ and warping²⁸, and improved density of the interfacial transition zone (ITZ)²¹. Even carbonation is reduced. These improvements are causing the IC system to evolve at a fast pace,

because the focus is not just on shrinkage but also on the other characteristics as well, providing long life^{15,16,17} and a low life cycle cost¹². A 2012 example is the North Channel Bridge replacement between Cornwall, Ontario and Cornwall Island, Ontario, Three Nations Bridge Crossing. High Performance Concrete (HPC) is being used at a water/cement ratio of 0.35, Type I cement 453 kg/m³ (755 pcy) and compressive strength is 60 MPa (8700 psi). The wet lightweight aggregate sand (LWAS) has a water absorption capacity of 15%.”



Figure 1—Chesapeake Bay Bridge under construction 1952 Figure 2—Bridge 60 years later. January 2012

THE CHESAPEAKE BAY BRIDGE LED THE WAY

The William Preston Lane, Jr. Memorial Chesapeake Bay Bridge, eastbound, was the world's largest continuous over-water steel bridge at 4.03 miles (6.48 km) when it opened July 1952 (Fig. 1). It was designed with a minimum compressive strength of 3500 psi (24 MPa) at 28 days, and an equilibrium density of 105 pcy (1682 kg/m³). The lightweight concrete achieved the desired compressive strength.[26]

The Maryland Transportation Authority owns, operates, finances and maintains both the 1952 bridge and another westbound bridge constructed 450 feet (137m) to the north in 1973. After the second bridge was completed and opened to traffic, the original bridge was closed for inspection, having been in continuous service for 21 years.

The 2 inch asphalt surface was removed and the bridge deck was inspected. The normal weight causeway decks needed replacing. The lightweight concrete used on the bridge suspension spans was found to be in excellent condition. Not only were the 1/3 of a mile approach causeways replaced with lightweight concrete, so were the steel "half Jersey barriers".

What caused the cited quality improvements on this 60 year old concrete deck (Fig. 2)? The answer is found in the internal curing water reservoirs of lightweight aggregate²⁶, and especially that of fine lightweight aggregate. When batched in a saturated surface dry (SSD) condition,^{17, 18} the absorbed water in its reservoirs can immediately flow through the capillaries to the unhydrated cement particles throughout. The result is that the plastic concrete paste and mortar receive their needed water when, where and how it needed it.

CLEVELAND, OHIO AREA ADDRESSES REDUCTION OF CONCRETE CRACKING USING THREE APPROACHES

The Cleveland Ohio area has been involved with three approaches that use internal curing in reducing shrinkage and cracking of concrete. These are (1) the use of preconditioned absorbent fine lightweight aggregate in a concrete mixture as a replacement of some of the natural sand, (2) the use of crushed stone coarse aggregate that is above 1% in absorption (ASTM C127), and (3) the use of Type K expansive cement.

The Main Avenue Bridge across the Cuyahoga River (Fig. 3) had absorbent lightweight aggregate included in the mixture to provide internal curing, because Type K needs a reliable source of water for at least a week. There is greater assurance that the water is where it is needed by supplying it from the interior as well as from the exterior



Figure 3—No sign of cracking. Main Avenue Bridge



Figure 4—High absorption limestone aggregate bridge concrete.
No sign of cracking.

The Cleveland Ohio area is fortunate in having crushed limestones with above 1% absorption. Dale Crowl¹¹ discovered that high performance concrete bridge decks with a sufficiently high absorption crushed limestone had a much lower autogenous shrinkage and cracking than those with absorptions of less than 1% in 24 hours (Fig. 4).



Figure 5—Saturated lightweight fine aggregate internal curing. Compressive strength is 20% greater. No sign of cracking.

It is pertinent to point out that 1% water of 1500 lbs (681kg) of crushed limestone is 15 lbs (7 kg), and that 15% of 100 lbs of lightweight aggregate is 15 lbs of water.¹⁹ The lightweight concrete bridge, likewise, shows no sign of cracking but the compressive strength is 20% greater.

All three approaches lead to less shrinkage and cracking. The system that incorporates lightweight aggregate fines shows, in addition, higher flexural and compressive strengths (Fig. 6), because the water reservoirs provide water for increased hydration and thereby increased the compressive strength by 20%.⁵ All three approaches were inspected in December 2011 and showed no cracking¹⁵.

PERVIOUS CONCRETE USES INTERNAL CURING TO OBTAIN GREATER FLEXURAL AND COMPRESSIVE STRENGTH

In order to reduce water quality impairment from stormwater, an approach is to combine pervious concrete pavements and infiltration systems to make a “Green Infrastructure”. Through the use of this new approach compared to the traditional approach, water peak flows are managed, the flow is slowed, and the water is allowed to infiltrate, reducing pollutant flows to waterbodies¹⁴.

Lightweight aggregate has been used in “Green Roof” systems for the last ten years and is being proposed for the infiltration system of parking lots as well as for the purpose of increasing the strength of pervious concrete pavements. The EPA’s successful installation at Edison, NJ, triggered a test to ascertain the optimum amount of lightweight aggregate sand to use in order to improve materially the integrity of normal weight concrete pervious pavements. No-fines pavements can be improved by using fine aggregate to reduce ITZ. ITZ is a high porosity zone typically found around coarse aggregate. The use of lightweight aggregate sand (LWAS) can more effectively do that, because of its ability to more effectively hydrate the cement in the mortar.

Table 1 – Pervious Concrete Mixture Designs

	REFERENCE (CONTROL) pcy (kg/m ³)	50 IC pcy (kg/m ³)	100 IC pcy (kg/m ³)	150 IC pcy (kg/m ³)
CEMENT	600 (360)	600 (360)	600 (360)	600 (360)
FINE NORMAL WEIGHT AGGREGATE, 2.61 sg	668 (400)	668 (400)	518 (315)	518 (315)
FINE LIGHTWEIGHT AGGREGATE, 1.80 sg	0	50 (30)	100 (60)	150 (90)
COARSE AGGREGATE, 2.68 sg	2620 (1570)	2620 (1570)	2620 (1570)	2620 (1570)
SIKAMENT 686	6 oz/cwt (3.9 mL/kg)	6 oz/cwt (3.9 mL/kg)	6 oz/cwt (3.9 mL/kg)	6 oz/cwt (3.9 mL/kg)
SIKA AEA-14	2 oz/cwt (1.3 mL/kg)	2 oz/cwt (1.3 mL/kg)	2 oz/cwt (1.3 mL/kg)	2 oz/cwt (1.3 mL/kg)
WATER	166 (75)	166 (75)	166 (75)	166 (75)
AIR CONTENT	6%	6%	6%	6%
W/C RATIO	0.28	0.28	0.28	0.28

Table 2 – 28 Day Comparative Flexural and Compressive Strength

PAD #	Pcy (kg/m ³)	FLEXURAL Psi (mPa)	COMPRESSIVE Psi (mPa)
Pad 1 REFERENCE	0	210 (1.4)	1155(8.0)
Pad 2	50 (30)	315 (2.2)	1225 (8.5)
Pad 3	100 (60)	535 (3.7)	3825 (26.4)
Pad 4	150 (90)	425 (2.9)	2930 (20.2)

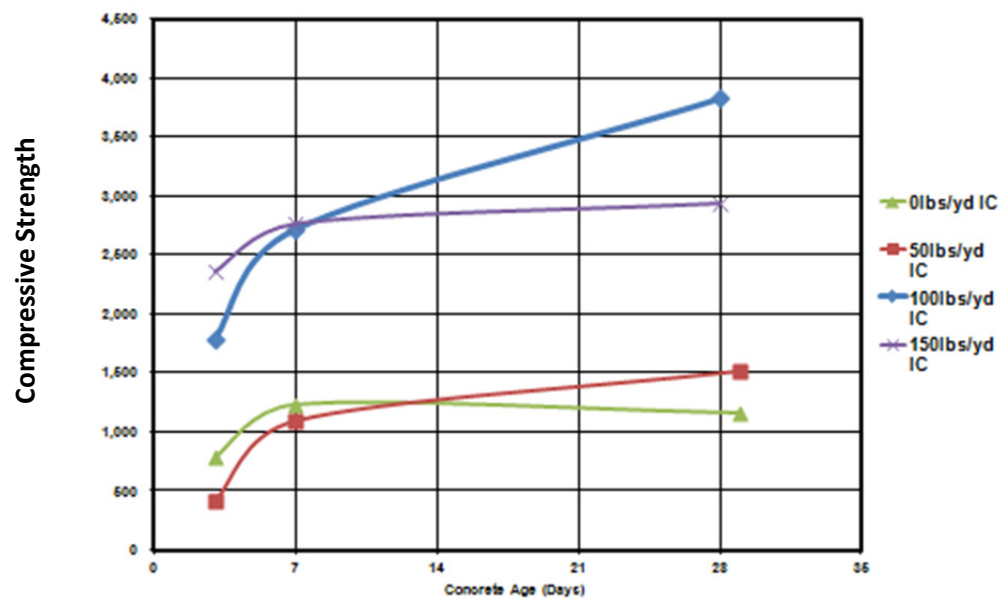


Figure 6—Compressive Strength vs Time, 7-28 Days

A 24 ft (7.32m) by 25 ft (7.62m) slab was poured in 4 strips. The site was prepared by removing existing soil and replacing with 18 in (.46m) of $\frac{3}{4}$ in (19mm) lightweight aggregate to provide the infiltration process. The pervious concrete was placed in one 6 in (15.2cm) layer. The four sections of the pad (Fig. 9) included a Reference (Control) section of the ready mixed concrete company's standard pervious mixture design. The other sections used 50 lb/cy (22.68 kg/m³), 100 lb/cy (45.36 kg/m³), and 150 lb/cy (68.04 kg/m³). The control section received standard curing with a 6 mil poly covering for 14 days. The other three sections did not receive the poly protection or any special curing, other than internal. The compressive strengths and flexural strengths are shown in Table II. The mixture designs are shown in Table I. Figure 6 has the compressive strength vs. time relationship.



Figure 7—Infiltration Beds



Figure 8—Placement

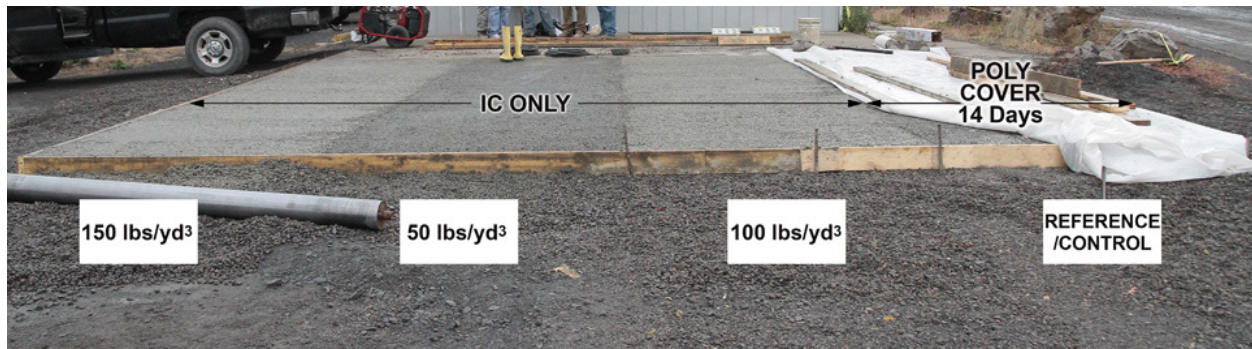


Figure 9—Pads 1- 4

Water permeates through all four pads promptly. As of five months after installation, there is no cracking whatsoever.

DENVER WATER, POST-TENSIONED WATER TANK USING INTERNALLY CURED CONCRETE

Denver Water Authority has its first truly sustainable underground pre-stressed concrete storage tank costing \$7.5 million to store 10 million gallons of water. The engineers (Bates Engineering) used the modern concept of internally curing the concrete to improve the permeability and durability, resulting in a lower life cycle cost. The characteristics of the concrete were achieved through the substitution of 285 pcy (169 kg/m³) in place of m³ of normal weight sand.

The concrete mix was designed for the internal curing benefits of fine lightweight aggregate substitution, which are lower shrinkage and permeability and higher cement hydration. The slab was placed monolithically in 10 hours. The placement was uneventful; not a single truck was rejected (Fig. 10). The contractor decided to use the ICC for the walls and columns as well as the designated slab and roof (Fig. 11). The early age strength was high without a high heat of hydration. Moreover, inspection reported virtually no shrinkage cracks.



Figure 10—Denver Water Storage Tanks. Internally roof. cured monolithic slab placement



Figure 11—Preparing for the internally cured concrete Contractor used IC even though not specified.

DIFFERENT MIXTURE DESIGNS INCORPORATING DIFFERENT SIZES OF LIGHTWEIGHT AGGREGATE

There has been no limit to the different approaches used to incorporate lightweight aggregate in concrete mixture designs. These include 100% lightweight coarse and fine, lightweight coarse and natural fine aggregate, modified density concrete (MDC), with both lightweight and normal weight coarse and fine aggregate and inverted mixes of coarse stone and fine lightweight. They weigh respectively 105pcf (1682 kg/m³), 115pcf (1842 kg/cm), 115-123pcf (1842-1970 kg/m³) to 135pcf (2163 kg/m³). These are used according to the needs of the structural design engineer.

MDC is usually achieved by modifying the coarse fraction of a concrete mix design. This is accomplished by blending a predetermined volume of structural grade (ASTM C 330) lightweight aggregate (LWA) and normal weight aggregate to achieve the proper volume of each in the coarse fraction of the mixture. Occasionally, the fine fraction is modified with a blend of lightweight aggregate sand (LWAS) with natural sand while leaving the coarse fraction all normal weight. The Lincoln Harbor Structure in Weehawken, NJ is an example of the use of MDC. There were 6500 cubic yards of high performance concrete (HPC), modified density (MDC) concrete in that six story, 651 vehicle parking garage.

A 2011 building project which used internal curing to advantage was placed in Tulsa, Oklahoma on a corrugated metal deck in difficult weather conditions, using a pump. Difficult curing conditions were of concern because of record temperatures in Tulsa, when the average daytime temperature was above 100° F and at dawn it was still above 80°F. The concrete was pumped in July 2011 in multiple pours on the 2nd and 3rd floors, starting after midnight. Very few shrinkage cracks were noticed after the pours and the finishers reported very little difference from a normal lightweight pour.

Table 3 – Lightweight Sand Gradation

Sieve Size	Cumulative % Passing	Cumulative % Retained
#4	87	13
#8	57	43
#16	23	77
#30	10	90
#50	4	96
#100	1	99
FM		4.18

For at least two weeks, the surface had a dark color, indicating the presence of moisture in the concrete and that self desiccation had not occurred. Strengths were higher than for a normal lightweight mix. Five months later, the project superintendent stated that all the original cracks were hair-line and originated at columns. Two sizes of lightweight aggregate fines were used to fill the gap grading when combined with the limestone coarse aggregate. No natural sand was used in the mix.

The most important difference encountered between preparing a normal mixture and in inverted mixture is the soaking of the lightweight aggregate. To get saturation in a ready-mixed concrete plant, they used a lawn sprinkler on top of the bunker and turned the stockpile once a shift with a front-end loader. Consequently, the lightweight aggregate supplier should ship the fine-sized material approaching saturated surface dry (SSD) as defined by ASTM C128.⁷

Table 4 – The Concrete in Plastic State, Concrete Temperature and Compressive Strengths at 7 and 28 Days

Date	Air Content %	Slump	Concrete Temperature	7 Day Compressive Strength	28 Day Compressive Strength
7/27/11	2.8	5.0"	83° F	5136 psi	7064 psi
7/27/11	4.0	7.5"	78° F	4190 psi	6440 psi
7/30/11	4.6	7.0"	83° F	3550 psi	4911 psi

LOW CARBONATION OF BRIDGES IN VIRGINIA AND FLORIDA CONTRIBUTES TO LONG LIFE AND LOW LIFE CYCLE COST

Carbonation adversely affects the alkalinity of concrete that protects the reinforcing steel from corrosion. There are 100 year-old structures and 60 year-old bridges that have unblemished reinforcing due to the use of internal curing. There are 80 year old sea-going barges that petrographic analysis classifies as intrinsically sound. The report by the Erlin Company, Latrobe, Pa., [January 2009]²⁷ of the non-air-entrained Boulevard Bridge (Fig 12) in Richmond, Virginia, that used lightweight aggregate, showed the depth of such carbonation to be only 1/4 inch after 50 years.

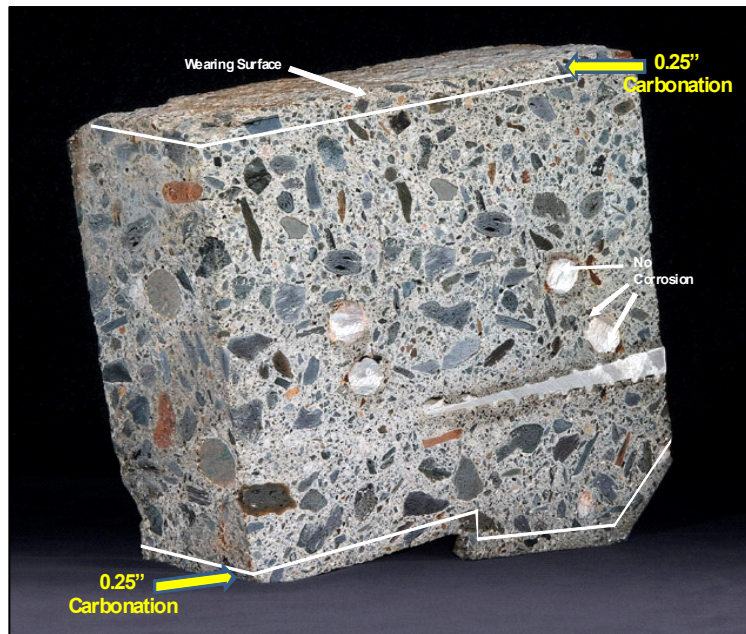


Figure 12—The Boulevard Bridge deck was replaced because of deterioration of the steel superstructure. Carbonation of the deck was only $\frac{1}{4}$ inch (6 mm) after 50 years.



Figure 13—Sebastian Inlet Bridge, FL. Carbonation was less in the lightweight concrete portion of the span.

An example of a long lasting bridge in a salty marine environment is at the Sebastian River Inlet (Fig.13) to the Atlantic Ocean. Forty-two years after its construction, the Florida DOT repeated tests performed in 1997 and 2006 on the depth of carbonation on the top and bottom surfaces, and found it to be negligible in both the normal weight and internally cured lightweight cores. The depth of carbonation on the bottom of the lightweight concrete slab was 0.16 to 0.25 inches (4 to 6.4 mm) and that of the normal weight 0.3 to 0.4 inches (7.6 to 10 mm) or twice the carbonation depth. The chloride content of the cores was well under 2 pounds per cubic yard (1.2 kg/m^3). The 2006 compressive strength of the lightweight concrete (cement 630 lb/cy (374 kg/m^3)) was 4580 psi (31.6 MPa).

Bridges and parking structures too, are two of the most vulnerable concrete structures. Internal Curing can reduce that vulnerability in two ways: (1) the availability of water that improves the hydration of the cement as and where needed, and (2) the voids left in the water reservoirs in the lightweight aggregate serve as an addition to air-entrainment agents.

SUMMARY AND CONCLUSIONS

Sixty years of concrete in service has brought the industry the basic knowledge that enables concrete to be perceived as the material of choice for many types of construction in the 21st Century. When cured properly and throughout the mass, it is able to make its contribution to sustainability

The case studies represent those applications where Internal Curing (IC) can be justified based on life cycle cost analysis and frequently on first cost. They include bridges (long, short, and medium span), buildings (even 3-story ones), highways and parking lots (even pervious pavements), and utilities (such as water tanks)

Geographically, they encompass the United States and Canada from Tulsa to New York City, from Florida to the St. Lawrence.

The case studies presented are representative of those under construction or on the drawing boards. They show the possibility of achieving improvement in the characteristics of concrete, including:

- longer life.
- reduction in shrinkage and cracking
- reduction in permeability
- protection of reinforcing through less carbonation
- increased early age and later age flexural and compressive strength
- provision of greater mortar strength
- provision of more consistency and predictability of interfacial transition zone (ITZ)
- provision of less variation in modulus of elasticity (MOE)
- lower life cycle cost

RECOMMENDATIONS

Starting with an optimum normal weight concrete mix design for a project, choose one or more characteristics that needs improvement, and make comparative tests substituting different amounts of preconditioned absorbent lightweight aggregate sand (LWAS) for an equal volume of the normal weight sand. Simultaneously, run 3, 7, 28, and 90 day compressive and flexural strength tests to make structural design and earlier use decisions. When the optimum replacement is established, apply the benefits to a life cycle cost analysis to ascertain the degree of sustainability enhancement.

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Efficiency of Eucalyptus Pulps for Internal Curing

by: Passarin Jongvisuttisun, Camille Negrello, and Kimberly E. Kurtis

Synopsis: Cellulosic or wood pulp fibers, like pre-wetted lightweight aggregates and superabsorbent polymers, can be used as internal curing agents in cementitious materials to mitigate autogenous shrinkage. While the internal curing abilities of different types of cellulose fibers have been demonstrated in mortar and concrete, relatively little fundamental research has examined the influence of fiber processing or “pulping” on their efficacy as internal curing agents. This is an important topic because even for fibers derived from the same type of wood, the morphology and composition of its pulp can be altered by processing, and these alterations can have important effects on the fibers’ internal curing capacity.

This research examines the effect of variations in pulping process on the internal curing performance of eucalyptus pulp fibers grown in Southeast Asia. Variations in processing produced three fibers – unbleached soda pulp, unbleached kraft pulp, and semi-chemical pulp – which were compared as internal curing agents through standard autogenous shrinkage testing. These data were then compared based on fiber composition and morphology, using results from thermogravimetric analysis (TGA) and scanning electron microscopy, to better understand the complex roles of these factors – as influenced by processing – in providing internal curing to cement-based materials.

Keywords: Autogenous shrinkage, chemical shrinkage, early age, pulping, wood fiber

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INTRODUCTION

The use of chemically inert absorptive materials such as lightweight aggregate and superabsorbent polymers (SAPs) as internal curing agents has been well documented over the last decade (Bentur et al. 2001; Jensen and Hansen 2001; El-Dieb 2007; Bentz and Weiss 2011), but the use of cellulose or pulp fibers, other types of absorptive materials, has only recently been studied (Mohr et al. 2005; Johansen et al. 2009; Kawashima and Shah 2011). The studies have found that pulp fibers not only substantially reduce autogenous shrinkage but also provide additional resistance to shrinkage-induced cracking (Kawashima and Shah 2011). However, the effects of pulp fiber properties (e.g., physical structure, chemical composition) on internal curing capability remain unclear. An improved understanding of the connection between the fiber properties and internal curing efficacy would make the complex problem of selecting and dosing (or even potentially designing) pulp fibers for internal curing more precise.

Pulp fibers derived from various types of wood and pulping processes have different structural and chemical characteristics that can affect the amount of water they hold and other factors, such as the rate of desorption of the water in the fiber, which can affect internal curing. Water can be held in the fiber lumen (or cavity enclosed by the cellulose-rich cell wall) or bound to and within the cell wall itself. The maximum amount of free water which can be held in the lumen could be related to the size of the lumen and its structure, which are in turn related to the type of wood and the processing of the fiber (e.g., pulping, drying, and refining). The pulping process also affects the chemical composition of pulp—cellulose, hemicelluloses, and lignin contents—which vary in their ability to attract and bind polar water molecules. The content of lignin and hemicellulose in the fiber generally decreases as the level of chemical treatment increases. Therefore, based upon their inherent structure and composition which can then be altered through processing, fibers derived from different wood species or subjected to different pulping processes are expected to exhibit different internal curing capabilities.

The effects of different chemical treatment on the internal curing properties were examined in prior research (Mezencevova et al. in press) for a species of softwood fiber, but that investigation concluded that further information about the fiber morphology, along with the known relevant chemical composition (e.g., cellulose-to-hemicellulose ratio), were needed to better understand these complex relationships. This study investigates the effect of the pulping process on the efficiency of hardwood *Eucalyptus camaldulensis* fibers, together with their fiber properties with an aim to comprehensively explain the correlation between the fiber characteristics and the internal curing capabilities of pulp fibers, as they are altered by processing.

MATERIALS AND EXPERIMENTAL METHODS

Materials

The source of the *Eucalyptus camaldulensis* (or River Red Gum) fibers tested and evaluated in this study is Southeast Asia. The average fiber length of these hardwood pulp fibers was approximately 0.6 mm (0.024 in).

Three industrial treatments of this fiber are examined: unbleached soda pulp (USF), unbleached kraft pulp (UKF), and semi-chemical pulp (SCF). These processes vary in the types of chemicals used and whether mechanical treatment is included or not; both of which will affect the fiber morphology and composition, as described below.

The cooking chemical used in the soda pulping process is sodium hydroxide, whereas that of the kraft pulping process is a mixture of sodium hydroxide and sodium sulfide. For the soda pulping process, anthraquinone is used as a pulping additive to decrease carbohydrate (e.g., cellulose, hemicelluloses) degradation. The semi-

chemical pulping process, also known as high yield chemical pulping, involves mild chemical treatment which is a mixture of sodium carbonate and sodium hydroxide solution and is followed by moderate mechanical refining. As a result, both lignin and hemicellulose are only partially extracted from the semi-chemical pulp fiber.

The fiber-cement pastes were prepared by mixing the fibers with ASTM Type I/II portland cement and deionized water (resistivity of 18.2 MΩ.cm) at a fixed water-to-cement ratio (w/c) of 0.30. The oxide analysis and Bogue potential composition of the cement is shown in Table 1.

Table 1—Oxide analysis and Bogue potential composition of ASTM Type I/II Portland cement

Component	Mass %
SiO ₂	19.73
Al ₂ O ₃	4.82
Fe ₂ O ₃	3.16
CaO	62.41
MgO	3.64
SO ₃	2.99
LOI	2.20
Na ₂ O	0.08
K ₂ O	0.48
TiO ₂	0.28
P ₂ O ₅	0.07
MnO	0.08
C ₃ S	59
C ₂ S	12
C ₃ A	7.4
C ₄ AF	10
Gypsum	6.4

Composition and hard-to-remove water analysis of eucalyptus pulp fiber

The compositions of the three fiber types were measured. The lignin content was determined by a kappa number test (TAPPI T236). The total residual lignin content (TRLIC) was calculated according to $TRLIC = \text{kappa number}/6.546$ (Laine et al. 1994). The ratio of cellulose-to-hemicellulose of each fiber was determined by measuring the weight change of samples during thermogravimetric analysis. As-received fibers were dried at $23 \pm 2^\circ\text{C}$ ($73 \pm 4^\circ\text{F}$) in a ventilation hood for 24 hours prior to the test. The nitrogen gas flow rate was 20 mL/min (0.68 oz/min) for balance and sample gas. Samples were heated up from room temperature to 600°C (1112°F) at a constant heating rate of $10^\circ\text{C}/\text{min}$ ($18^\circ\text{F}/\text{min}$). Since the main decomposition temperature of hemicellulose and cellulose which occurs mainly at $220\text{--}315^\circ\text{C}$ ($428\text{--}599^\circ\text{F}$) and $315\text{--}400^\circ\text{C}$ ($599\text{--}752^\circ\text{F}$), respectively (Yang et al. 2007), the cellulose-to-hemicellulose ratio of the fibers was defined as the fraction of the percent weight change at $315\text{--}400^\circ\text{C}$ ($599\text{--}752^\circ\text{F}$) to the percent weight change at $220\text{--}315^\circ\text{C}$ ($428\text{--}599^\circ\text{F}$).

In addition, for the purpose of understanding the use of pulp fibers for internal curing, it is important to assess the relative availability of moisture provided by the fibers. For this, measurements of hard-to-remove (HR) water were made. HR water can be defined as the moisture ratio (g of water per g of oven dry fiber) at the transition between the constant rate zone and the falling rate zone of evaporative change in mass detected by using TGA (Park et al. 2006).^{*} The authors suggested that the amount of HR water can be used as an indicator of the range in

^{*} Water in wet pulp has been classified in various ways such as free water, intra-wall bound water, and inter-wall bound water. However, the term “HR water,” defined by Park et al. (2006), consists of the water associated with fibers at the transition of the constant rate and falling rate zones at the drying rate curve observed from the isothermal drying experiment performed by using high-resolution TGA. HR water is also considered to be located in the fiber cell wall and trapped in the fiber network geometry and expected to have an impact on the fiber drying behavior. When differential scanning calorimetry (DSC) is used to characterize a fiber-water system, cellulose fiber contains three types of water: unbound water (or free water), freezing bound water, and non-freezing bound water. HR water is a combination of both bound water and some amount of free water that can move freely, but it is concentrated in small pores and capillaries, making it difficult to remove from fiber in the drying process. Internal diffusion, which depends on fiber properties such as fiber type, pore volume, fiber wall thickness and moisture ratio, is the key mechanism for removing HR water. Since the determination of HR water is based on the drying experiment, it is proposed here that HR water could be used to analyze the effect of fiber morphology on the internal curing capability of fibers.

moisture content over which moisture loss from the fibers is controlled by internal diffusion; in this research, HR water will be related to fiber properties such as fiber type, pore volume, and fiber wall thickness and measures of autogenous and chemical deformation.

TGA was used to determine the HR water content in each fiber. The nitrogen gas flow rate was 20 mL/min (0.68 oz/min) for balance and sample gas. Measurements of change in mass were made under isothermal conditions at 50°C (122°F), until the weight change was negligible. The resolution of the instrument is 0.001 μg (3.5×10^{-11} oz).

Morphology of eucalyptus pulp fibers

In addition to assessing each fiber's chemical composition, variations in fiber morphology were assessed. The cross-sectional dimensions of the fibers can be assessed by performing an image analysis of scanning electron micrographs (Reme et al. 2002; Chinga-Carrasco et al. 2009). Fibers were dispersed, filtered, and freeze-dried in order to eliminate clumping of the fibers and to preserve their microstructure. Freeze-dried fiber bundles were embedded in a hydrophilic aromatic acrylic resin and heat cured at 60°C (140 °F) for 24 hours. After the acrylic resin was polymerized, samples were ground using silicon carbide paper with a grit size of 320, 600, and 1200, and polished using 1.0 and 0.3 micron (40 and 12 $\mu\text{in.}$) of aluminum oxide powder. Polished samples were observed with a variable pressure scanning electron microscope, from which images were acquired at 600X magnification with 20 kV accelerated voltage and 9-10 mm (0.354-0.393 in.) of working distance. Using the public-domain, Java-based image processing program ImageJ, the gray-scale images were thresholded and converted to binary images. Then, the most likely value of the fiber and lumen diameters were determined by performing statistical analysis of 350 cross-sectional images per fiber type.

Autogenous deformation

The compositions of the control and fiber-cement paste samples for autogenous shrinkage measurement are listed in Table 2. The mix proportions were determined to maintain a constant amount of “entrained” water (e.g., water available for internal curing) with the constant amount of cement (by weight) and the constant w/c at 0.30. Thus, the amount of fiber added to the cement paste depended on the fiber's absorption capacity k , as determined by using isothermal calorimetry, using the method described by Johansen et al. (2009). This method is based on the assumptions that internal curing agents will absorb water from the mix to equilibrate at k , and the internal curing agents neither accelerate nor slow the rate of hydration. Using this method, k can be calculated by comparing the early heat evolution data of the sample with internal curing to those of ordinary cement pastes at similar w/c. Absorption of water by the internal curing agents would be expected to produce calorimetry curves similar to those for ordinary pastes at a lower w/c; thus, the amount of water absorbed can be used to calculate k for an internally cured paste of known composition.

The autogenous deformation of the cement paste containing fibers was measured according to ASTM C1698-09 and compared with that of the control sample, which contained no internal curing agent. After mixing, the pastes were cast and sealed in corrugated polyethylene tubes. The corrugated tubes had an outer diameter of 29 ± 0.5 mm (1.14 ± 0.02 in.) with a length of 420 ± 5 mm (16.54 ± 0.19 in.). The distance between corrugations is 5.8 ± 0.2 mm (0.23 ± 0.008 in.). All of the samples were stored in an environmental chamber at $25 \pm 1^\circ\text{C}$ ($77 \pm 1.8^\circ\text{F}$) during the entire test period. Measurements of the initial deformation were taken when the pastes reached the final set, which was determined according to ASTM C191-08. The amount of entrained water to cement by mass (w_e/c) was 0.01. This entrained water was an additional amount of water provided by pulp fibers and was calculated based on k .

Table 2—Mix designs for the autogenous shrinkage measurements

	Control	Fiber-Cement Paste		
	w/c 0.3	USF	SCF	UKF
As-received moisture content, %	-	487	529	401
k	-	1	1.5	2
Cement, g (lb)	1500 (3.307)	1500 (3.307)	1500 (3.307)	1500 (3.307)
Water, g (lb)	450 (0.992)	391.95 (0.864)	412.08 (0.908)	434.93 (0.959)
Dry fiber, g (lb)	-	15 (0.033)	10 (0.022)	7.5 (0.017)
As-received fiber, g (lb)	-	88.05 (0.194)	62.93 (0.139)	37.58 (0.083)
w/c	0.3	0.3	0.3	0.3
w _c /c	-	0.01	0.01	0.01

Chemical deformation

The chemical deformation of control and fiber-cement pastes was measured by using the volumetric method according to ASTM C1608-07. Approximately 10 g (0.022 lb) of cement paste and fiber-cement paste samples were put into glass vials and then topped with de-aerated water. Then, rubber stoppers with the inserted graded pipettes were placed in the vials, which were then placed in a water bath at $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$ ($77 \pm 1.8^{\circ}\text{F}$). The drop in the water level in the capillary tube is due to the net reduction in volume due to hydration. Thus, as the cement hydrated over time, the water level in a graded pipette decreased, which directly determines the total chemical shrinkage. The normalized volume reduction per g of cement was reported as the chemical shrinkage per unit mass of cement (mL/g of cement) for three replicates per sample type.

RESULTS

Fiber properties

Properties— k , the kappa number, the total residual lignin content, the cellulose-to-hemicellulose ratio, the amount of HR water, fiber width, lumen diameter, and cell wall thickness—of each fiber are shown in Table 3. The k of USF determined by using calorimetry was 1 while that of SCF and UKF were 1.5 and 2, respectively. This suggests, preliminarily, that UKF and SCF should be more advantageous for internal curing, based upon this parameter alone. However, further data regarding composition and morphology, as well as measurements of early age deformation are necessary for a more comprehensive assessment of the potential of these fibers as internal curing agents.

Table 3—Fiber properties

Fiber Properties	Fiber Type		
	USF	SCF	UKF
Absorption capacity, k	1	1.5	2
Kappa number	20-22	150-160	25
Lignin content, %	3-3.3	23-24.5	3.82
Cellulose-to-hemicellulose ratio	3.99	1.05	3.01
HR water, mass water/mass of dry fiber	1.44±0.11	1.76±0.06	1.30±0.02
Fiber width, μm (μin)	12.914 (508)	14.124 (556)	12.602 (496)
Lumen diameter, μm (μin)	5.067 (200)	5.536 (218)	5.340 (210)
Cell wall thickness, μm (μin)	3.924 (154)	4.294 (169)	3.631 (143)

With regard to chemical composition, the lignin and hemicellulose contents in the fiber were found to decrease with increasing degree of chemical treatment, as expected. Both full-chemical treated fibers (USF, UKF) had relatively high cellulose and low lignin contents, compared to SCF which had a high amount of lignin and hemicellulose. The kappa number of UKF was approximately 25, indicating that the fiber was soft-cooked (also called ‘bleachable grade pulp’).

The fibers also varied in their proportion of HR water. It was found that SCF had a highest amount of HR water, whereas UKF had the lowest amount of HR water. If all other parameters (e.g., chemical composition, morphology, etc) remained the same, it could be perceived that the fiber with the highest amount of HR water would be the more effective internal curing agent. However, with these fibers, it is interesting to note that there is no clear relationship between the measured k and the HR water content.

Since water can be held in the lumen as free water and in the cell wall as bound water, the fiber parameters that may be significant are the fiber diameter, the lumen diameter, and the cell wall thickness. SCF had the thickest cell wall thickness, whereas UKF had the thinnest cell wall thickness. This finding showed the relationship between the cell wall thickness and the amount of HR water. The thicker the cell wall resulted in the higher amount of HR water.

Shrinkage behavior of fiber-cement paste

The capacities of the fibers to offset autogenous shrinkage by internal curing were compared through measurements of deformation made after final set. The final setting times of the pastes are shown in Fig. 1. Although lignin can retard the hydration reaction of calcium silicate phases and the use of fiber containing a high amount of lignin could delay the setting time, lengthening of setting time of the fiber-cement pastes determined by Vicat apparatus was not observed in these pastes (Fig. 1). This is further confirmed in the calorimetry data (Fig. 2), which also shows no delay in reaction rate when comparing samples with fibers to that without, when the water contents were adjusted to account for the fiber absorption capacities.

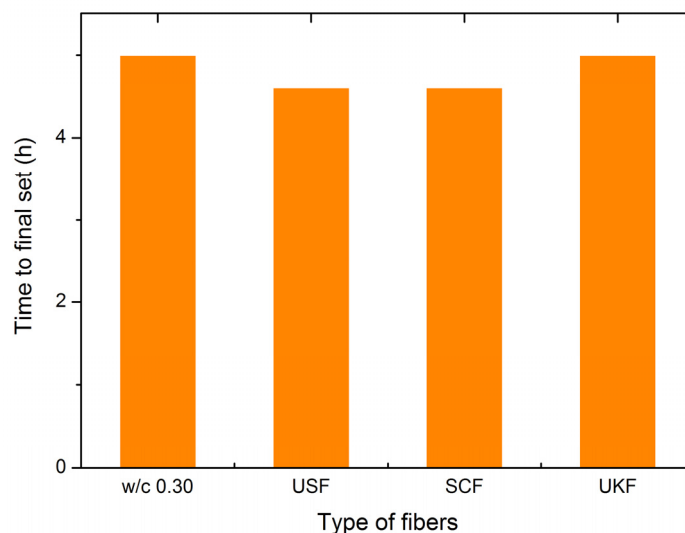


Figure 1—Final setting time of the cement paste compared with that of the fiber-cement pastes at w/c equal to 0.01.

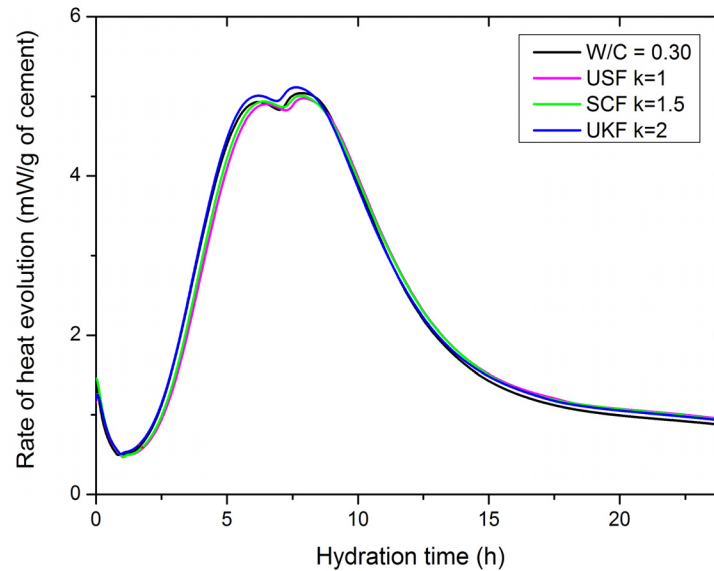


Figure 2—Heat released from the cement paste compared with that of the fiber-cement pastes.

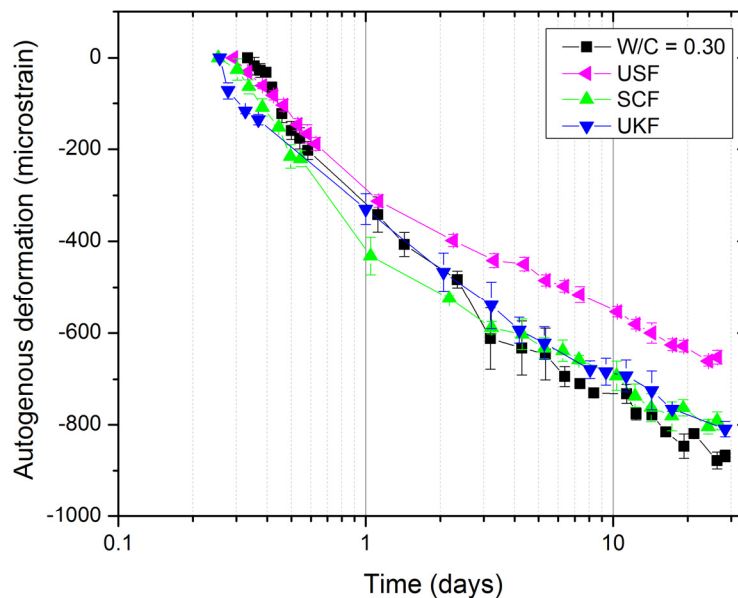


Figure 3—Autogenous deformation of the cement paste compared with that of the fiber-cement pastes at w/c equal to 0.01.

Fig. 3 compares the autogenous shrinkage of the cement paste and internally cured fiber-cement pastes, measured after final set. All of the fiber-cement pastes were prepared to contain 0.01 entrained water per g of cement, based upon each fiber's determined k . Within the first few hours after the final setting, the fiber-cement pastes exhibited a slightly higher (or more negative) autogenous strain than cement paste, indicating greater shrinkage during this period. When the pastes hydrated over time, the *rates* of the length reduction of the fiber-cement paste specimens were lower than that of the cement paste, providing an indication that the fibers released water to the hydrating cement and reduced self-desiccation. However, examining the absolute deformation shows that both UKF and SCF, containing nominally the same amount of entrained water as USF, did not exhibit any effective shrinkage reduction compared to the control sample. This indicates that higher dosage rates of UKF and

SCF may be necessary for effective internal curing. At 28 days, the fiber-cement pastes underwent autogenous strain of $-652.05 \pm 14.73 \mu\epsilon$, $-791.52 \pm 19.84 \mu\epsilon$, and $-809.09 \pm 16.85 \mu\epsilon$ for the USF, and SCF, and UKF, respectively, whereas cement paste underwent autogenous strain at about $-867.77 \pm 12.96 \mu\epsilon$. Overall, these results show that the USF was the most effective at limiting autogenous shrinkage, of the treatments to *Eucalyptus camaldulensis* examined here at a consistent rate of addition based upon entrained water content.

The addition of wood fibers into the cement could affect early hydration behavior of cement. The surface of the fibers might serve as nucleation sites, or the hygroscopicity of the fibers could locally absorb and/or desorb water affecting the amount of available free water of the hydrating cement nearby. Since the addition of fibers could alter the hydration reaction with the interaction between fibers and cement (e.g. nucleation, local absorption or desorption), chemical shrinkage in companion pastes was also measured to better understand the early age deformation in the presence of fibers. Fig. 4 shows the chemical shrinkage measured for fiber-cement pastes at 0.01 of entrained water per g of cement. All fiber-cement pastes show greater chemical shrinkage than the ordinary paste. The, albeit slightly, greater chemical shrinkage in the presence of fibers might suggest some complexities in early hydration behavior, due to their addition, which are not captured in the isothermal calorimetry (where the mix proportions were adjusted to account for moisture present in the fibers). The greater higher chemical shrinkage of fiber-cement pastes could also result from some surface nucleation occurring at the same time that fibers release water or an osmotic effect related to differences in solution concentration in the capillary pores and the fiber lumen. In addition, until the paste densifies sufficiently, it is also possible that the water ponding on the surface could be absorbed through interconnected fibers and porosity, making the external water available for further hydration. This would result in higher chemical shrinkage of fiber-cement pastes compared to cement paste, and would not be apparent in calorimetry or autogenous shrinkage testing, where there is no access to externally ponded water. While further research is needed to better understand the mechanism(s) by which pulp fiber addition might affect chemical shrinkage in cement pastes, these results do raise concerns about the efficiency of these fibers to mitigate early age shrinkage. The experiments provided evidence that the early shrinkage behavior of fiber-cement pastes is complex and that further studies to correlate hydration reactions with early shrinkage behaviors should be performed.

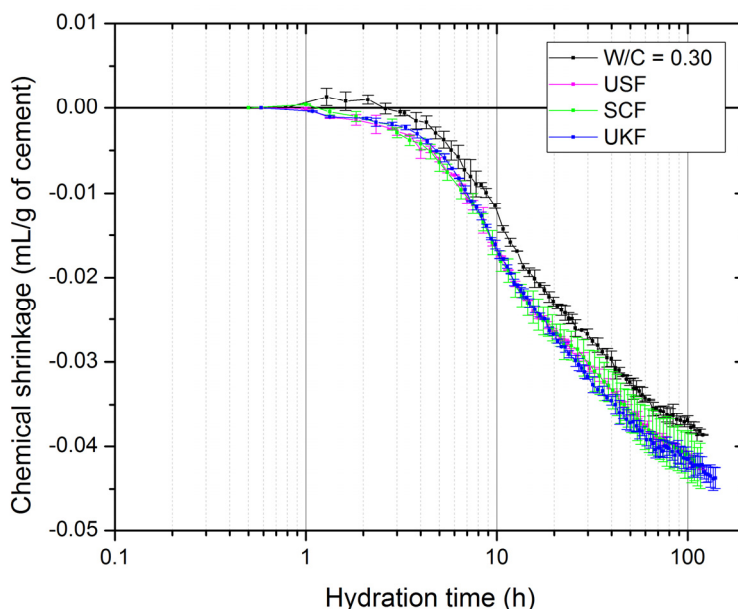


Figure 4—Chemical deformation of the cement pastes compared with that of fiber-cement pastes at w/c equal to 0.01. (Note: 1 mL/g = 0.845 fl oz/oz.)

DISCUSSION

The autogenous deformation measurements show that at the same nominal amount of entrained water ($w/c = 0.01$), USF produced more shrinkage reduction than both UKF and the SCF. Before discussing these results in light of the data regarding composition and morphology of the different fibers, it is worth examining the SCF case specifically.

Among three types of fibers examined, SCF was not effective at the dosage rate examined in mitigating autogenous deformation, producing just an 8% reduction in shrinkage at 28 days. This behavior was not expected, given that the SCF had the highest HR water content and a higher k than USF (which was effective as an internal curing agent, as noted previously). It could be perceived that the relative ineffectiveness of the SCF can be attributed to fiber bundling (or poor dispersion) which is related to this method of fiber processing. Since semi-chemical pulp fiber processing is limited to partial delignification and defiberization, numerous fiber bundles are apparent when examining the morphology of the SCF (Fig. 5). In contrast, individual fibers are associated with the USF and UKF, as shown in Fig. 6. Therefore, it is likely that adequate dispersion was not achieved. As a result, it is suggested that the SCF did not provide a sufficient amount of water because it was not uniformly dispersed throughout the cement. The correlation between dispersion and internal curing performance was also found in prior studies (Akçay and Tasdemir 2010; Kawashima and Shah 2011).

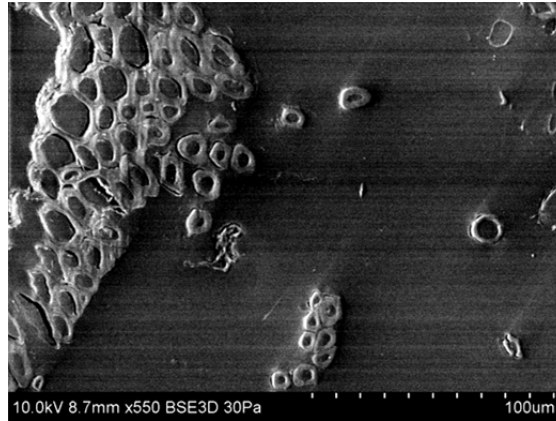
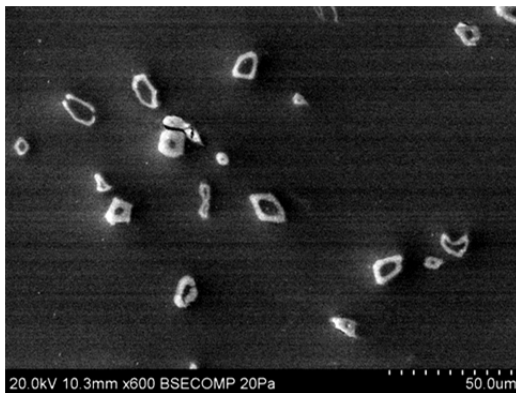
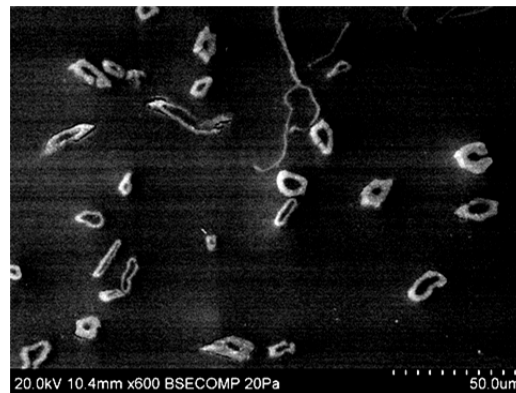


Figure 5—Fiber bundles observed in the SEM cross-sectional image of semi-chemical fiber.
(Note: 100 μm = 3.94 mil)



(a)



(b)

Figure 6—SEM cross-sectional images of (a) unbleached soda fiber and (b) unbleached kraft fiber.
(Note: 50 μm = 1.96 mil)

Considering now in more detail the relative effectiveness of the USF and UKF for internal curing, where the USF produced a nearly 25% and the UKF a 7% reduction in autogenous shrinkage compared to ordinary paste at 28 days, examination of the fiber composition and morphology provides some insights. First, although both of these fibers had similar ratios of cellulose-to-hemicellulose, their autogenous shrinkage behaviors and absorption capacities were dissimilar suggesting that cellulose-to-hemicellulose ratio did not significantly affect the internal curing capacity of the fibers and others fiber properties should be further examined. Pulkkinen (2008) also stated that the amount of hemicellulose did not correlate with fiber properties and water retention value of the fiber. It could be perceived that the relatively better performance of the USF may result from its higher HR water content than UKF, suggesting that the entrained water was more slowly released by the USF to the hydrating cement during the hydration period. This mechanism differs from that found in LWA and SAPs in which the higher water desorption

rates is favor. However, since fibers are smaller than LWA and they are added at higher dosages than SAPs, based on these characteristics, if adequate dispersion of a fiber is achieved, entrained water is easier to release into hydrating cement. Therefore, the rates of water release from a fiber with lower HR water content might be too fast to mitigate self-desiccation that occurs during the hydration period. It is possible that the amount of HR water and the apparently beneficial slower rate of moisture release may be related to increasing cell wall thickness, but further studies are needed on a wider range of fibers to confirm this. If so, this would suggest that thicker cell walled pulp fibers, and especially those with greater HR water contents, are preferred for internal curing applications.

CONCLUSION

This effect of three industrial methods for hardwood fiber pulping on the internal curing efficiency of the eucalyptus (*E. camaldulensis*) fibers was examined. In the first few hours after the final setting, the fiber-cement pastes exhibited more autogenous shrinkage than the cement paste. These results agreed with data showing greater early chemical shrinkage. Together, these results indicate that the interactions between pulp fibers and cement are complex and that further studies should be performed during very early hydration.

Confirming observations in other research, dispersability of the internal curing agent was found to affect the fiber's capacity for mitigating autogenous shrinkage. Here, the partial delignification and partial defiberization of SCF adversely affected its internal curing performance of fiber, because it is proposed that the fiber was poorly dispersed in the cement paste.

Finally, by evaluating the fiber properties and comparing with the autogenous shrinkage experimental results, a correlation was found between the composition and morphology of fibers and their internal curing capacity. Although k was lower than UKF, USF with higher HR water content, exhibited better autogenous mitigating efficiency. It proposed that the higher HR water content suggests a slower rate of moisture release to the hydrating cement, making HR water content a meaningful parameter for the assessment of internal curing agents. These limited data do suggest, also, that HR water content is related to increasing cell wall thickness, suggesting that thicker walled fibers could be more suitable for internal curing.

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Reduction of Autogenous Shrinkage in Cement Paste by IC Using Jute Fiber

by: Mitsuo Ozawa and Hiroaki Morimoto

Synopsis: Internal curing is an effective method of preventing autogenous shrinkage in early-age concrete. In this approach, water-retentive particles act as internal reservoirs to supply water to the surrounding cement paste matrix. The objective of this study was to determine how the early-age shrinkage behavior of cement-based materials is affected by the addition of saturated jute fiber under sealed conditions. The four cement-paste specimens with water-cement ratio of 0.25, and the individual jute fibers of 6 mm length. The fiber contents by volume were 0, 0.5, 1.0 and 2.0%, respectively. The straw-like structures of the jute fiber were observed in a scanning electron microscope photograph. Additions of 0.5% and 1.0% of jute fiber by volume of cement paste resulted in 12% and 36% reductions in autogenous shrinkage strain at a material age of 8 days, respectively.

Additions of 0.5% and 1.0% of jute fiber by volume of cement paste resulted in 3% and 22% reductions in compressive strength at a material age of 8 days, respectively. The material segregation was observed in the cement paste with 2.0% of jute fiber by volume. These results indicate the suitability of jute fiber for an internal curing material.

Keywords: Autogenous shrinkage strain, cement paste, internal curing, jute fiber

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INTRODUCTION

Recent years have seen increased application of high-performance concrete (HPC) in elements of infrastructure thanks to superior properties such as high strength and low permeability, which are owed to its characteristically dense microstructure. This type of concrete has a very low water-binder (w/b) ratio, and contains insufficient water to maintain the state of capillary pore saturation needed to sustain both continuous cement hydration and pozzolanic reaction.

Since autogenous shrinkage is the dominant influence in HPC volume change, it is widely recognized that the high risk of early-age cracking in such concrete is attributable to significant early-age autogenous shrinkage caused by internal drying of the concrete during binder hydration reactions. Internal curing is an effective method of preventing autogenous shrinkage in early-age concrete. In this approach, water-retentive particles act as internal reservoirs to supply water to the surrounding cement paste matrix. Although absorbent particles such as those of lightweight aggregate¹⁻³, super-absorbent polymer (SAP)⁴ and recycled aggregate⁵ are considered as promising materials to create an internal source of water, some reports⁶⁻⁸ have addressed the reduction of autogenous shrinkage for cement materials based on the addition of natural fiber. Kawashima⁶ reported cellulose fibers were not found to affect drying shrinkage but they are effective in mitigating drying shrinkage-induced cracking when adequate dispersion is achieved. The fiber-reinforced samples experienced significant reduction in crack width and continued to carry stress after cracking. Qi⁹ also reported that with increased fiber volumes, plastic shrinkage cracks have smaller widths. Multiple secondary cracks are introduced at sufficient fiber contents. The total (cumulative) crack width is significantly decreased.

The objective of this study was to determine how the early-age shrinkage behavior of cement-based materials is affected by the addition of saturated jute fiber under sealed conditions.

METHODS

Mixture proportions

Ordinary portland cement (density: 3.15 g/cm³(0.114lb/in³)) and tap water were used for all mixtures. Table 1 shows the chemical composition of ordinary portland cement, while tables 2 and 3 show the mixture proportions and materials. All paste mixtures had a water-cement (w/c) ratio of 0.25 and a 2% addition of super-plasticizer by cement mass.

Jute fiber

Table 3 shows the properties of jute fiber, which was used as a natural fiber with addition ratios of 0, 0.5, 1.0 and 2.0% by volume and a density of 1.30 g/cm³(0.0470lb/in³), a length of 6 mm(1/4in.) and an average diameter of 0.02 mm(0.00078in.). The average tensile strength and elastic modulus of the individual fibers were 320 MPa(46,400psi) and 20 GPa(2,900,000psi), respectively¹⁰. For jute fibers saturated in water for 24 h, the absorption rate was found to be 0.75 (mass of water absorbed/mass of dry fiber). A fiber addition ratio of 0% by volume was defined for the control specimen. Figure 1 and 2 show the jute fiber by itself and in the concrete, respectively. The straw-like structure of the jute fiber seen in the scanning electron microscope (SEM) photograph allows it to retain water internally for curing.

Mixing and flow test

The jute fiber was placed in a plastic bag with water for 24 hours. A two-liter Hobart mixer was used for mixing as follows: First, the cement, the water with jute fiber and the super-plasticizer were combined and mixed for 1 minute at low speed. Then, the bowl was scraped, and the combination was mixed for a further 3 minutes at high speed. The flowability of the mortar was evaluated in a flow test. The cone mold used for the test had a top diameter of 70 mm(2.73in.), a bottom diameter of 100 mm(3.9in.) and a height of 60 mm(2.34in.).

Measurement of autogenous shrinkage

Autogenous shrinkage was measured using the corrugated tube approach proposed by Jensen and Hansen⁴, the setup for which is shown in Figure 3. In this method, changes in the length of corrugated polyethylene tubes

measuring approximately 400 mm(15.6in.) in length and 30 mm(1.17in.) in diameter cast with fresh paste and sealed with two end caps are monitored. As the tubes are corrugated, they are much stiffer in the radial direction than in the longitudinal direction, thus effectively translating any volumetric deformation of the paste into linear deformation. The sensitivity of the dial-gauge used was 3/1,000 mm(0.000117in.), and three measurement systems were adopted. The base stands of these systems were made of Invar steel (thermal expansion coefficient: $0.1 \mu\text{°C}(0.00294\mu\text{°F})$; number of pieces: one) and stainless steel (thermal expansion coefficient: $17.3 \mu\text{°C}(0.509\mu\text{°F})$, number of pieces: two).

Paste types with and without the addition of saturated jute fiber were compared. All mixes had a w/c ratio of 0.25 and a 2% addition of super-plasticizer by cement mass. The autogenous deformation of samples with jute fiber additions of 0%, 0.5, 1% and 2% by volume were measured for the paste, and the deformation of two samples for each mix was monitored. Fresh paste was consolidated by running a vibrating rod along the length of the tube. Each test was run for 8 days in a condition-controlled room set at $20 \pm 2^\circ\text{C}(68 \pm 36^\circ\text{F})$, and readings were taken every 10 minutes for the entire duration of the test. The internal temperatures of the specimens were measured using corrugated polyethylene tubes of approximately 200 mm(7.8in.) in length and 30 mm(1.17in.) in diameter. The zero time of measurement was defined as the point at which the temperature started to increase (PTSI). Because it was difficult to determine the setting time via a Vicat needle test.

The level of autogenous shrinkage strain was calculated for each sample size so that consistent sets of results could be used in the calculations. Autogenous shrinkage strain was calculated by following equation (1). This equation is for the temperature correction.

$$\epsilon_{\text{auto}} = (\delta_{\text{total}} - \alpha_{\text{base}} \times L_{\text{base}} \times \Delta T_{\text{am}}) / L_{\text{sp}} - \alpha_{\text{cp}} \times \Delta T_{\text{cp}} \quad (1)$$

Where:

ϵ_{auto} =autogenous shrinkage strain;

δ_{total} =dial gauge value (mm) (1mm=0.039 in.);

α_{base} =thermal expansion coefficient of base stand($\mu\text{°C}$) (°F=9/5°C+32);

Case1 : Invar steel $0.1 \mu\text{°C}(0.00294\mu\text{°F})$;

Case2 : Stainless steel $17.3 \mu\text{°C}(0.509\mu\text{°F})$;

L_{base} =base stand length (mm) (1mm=0.039 in.);

ΔT_{am} =ambient temperature increment (°C) (°F=9/5°C+32);

α_{cp} =thermal expansion coefficient of cement paste: $20\mu\text{°C}(0.588\mu\text{°F})$ (°F=9/5°C+32);

ΔT_{cp} =specimen temperature increment (°C) (°F=9/5°C+32);

L_{sp} =specimen length (mm) (1mm=0.039 in.);

RESULTS AND DISCUSSION

Flow test

Figure 4 and 5 show the flow test results. The flow value of the control paste without fiber was 300 mm(11.7in.), while that for the cement paste with 0.5% of jute fiber by volume was actually higher at 377 mm(14.7in.). The value for cement paste with 1.0% of jute fiber by volume showed a slight decrease in comparison to the 0.5% specimen was 317 mm(12.4in.). The value for cement paste with 2.0% of jute fiber by volume showed a drastic decrease to just 163 mm(6.36in.). It was observed that a cluster of jute fiber remained at the center of the flow spread after the removal of flow cone. It was difficult to make shrinkage measurement specimen with 2.0% of jute fiber by volume. It can be considered that the flow value is higher with the addition of jute fiber up to 1.0% by volume because the water in its straw-like structure discharges into the cement paste during the mixing process.

Mechanical properties

Figure 6 shows the relationship between compressive strength of the cement paste specimen and fiber content ratio. The compressive strength of the control specimen and the 0.5%-volume specimen were very similar at 133 MPa(19,300psi) and 129 MPa(18,700psi), respectively. However, the values for the 1.0%- and 2.0%-volume specimens were 103 MPa(14,900psi) and 90 MPa(13,100psi), respectively, corresponding to reductions of 22% and 33%. Soroushian¹¹ reported that fibers generally have negative effects on the compressive strength of cement-based matrixes.

Length change and internal temperature

Figure 7 shows the length change and internal temperature of a cement paste specimen. It can be seen that the length change began to increase drastically after half a day, and that the internal temperature also started to increase after this time, reaching a maximum value of $24.4^\circ\text{C}(76^\circ\text{F})$ at 1.2 days. It was considered that the

internal temperature started to increase when cement hydration became active. Accordingly, the zero time for autogenous shrinkage was defined as the point at which the temperature started to increase (PTSI). Table 4 shows the PTSI values for each specimen.

Autogenous shrinkage strain of cement paste

Figures 8 and 9 show the autogenous shrinkage strain values of the cement paste samples with and without added jute fiber, the control specimen, the 0.5%-volume specimen and the 1.0%-volume specimen (with the PTSI as the zero time). The 2.0%-volume specimen was omitted because material segregation occurred (See: flow tests results). It can be seen that with addition in sufficient amounts jute fiber up to 1.0% by volume had a mitigating effect on autogenous shrinkage.

Figure 10 shows autogenous shrinkage at a material age of 1 day and 8 days. Shrinkage values at 1 day for the control specimen, the 0.5%-volume specimen and the 1.0%-volume specimen were 1,691 μ , 1,550 μ and 999 μ , respectively. Shrinkage values at 8 days for the control specimen, the 0.5%-volume specimen and the 1.0%-volume specimen were 2,240 μ , 1,950 μ and 1,420 μ , respectively.

Figure 11 shows relationship between Autogenous shrinkage reduction ratio and fiber content ratio. Shrinkage reduction ratio at 1 day, for the 0.5%-volume specimen and the 1.0%-volume specimen were, 8% and 41%, respectively. Shrinkage reduction ratio at 8 days, for the 0.5%-volume specimen and the 1.0%-volume specimen were 12% and 36%, respectively.

This behavior may primarily be attributed to the difference in the amount of internal curing water provided by each dosage of jute fiber to the hydrating paste. The results of the autogenous shrinkage tests demonstrate that jute fiber can contribute to the success of internal curing.

CONCLUSIONS

The following conclusions were drawn:

Additions of 0.5% and 1.0% of jute fiber by volume of cement paste led to 12% and 36% reductions in autogenous shrinkage strain at 8 days, respectively. Additions of 0.5% and 1.0% of jute fiber by volume of cement paste resulted in 3% and 22% reductions in compressive strength at a material age of 8 days, respectively. The material segregation was observed for the cement paste with 2.0% of jute fiber by volume. The results of the autogenous shrinkage tests showed that jute fibers help to support internal curing.

ACKNOWLEDGEMENTS

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Table 1– Chemical composition of ordinary portland cement

Chemical composition (%)						
SiO ₂	Al ₂ O ₃	Fe ₃ O ₃	CaO	MgO	SO ₃	Ig.loss
20.3	4.9	2.7	64.6	1.5	3.2	1.06

Table 2 –Mixture proportion

(1 kg/m³ = 1.6858 lb/yd³)

Jute fiber content (vol%)	Unit weight (kg/m ³)				
	W/C	C	W	SP	Jute fiber
0	0.25	1762	405	35	0.0
0.5					6.5
1.0					13.0
2.0					26.0

Table 3– Materials

(1 g/cm³=0.0361 lb/in³, 1mm=0.039 in.)

Material	Properties
Cement (C)	Ordinary portland cement Density: 3.15 g/cm ³
Water (W)	Tap water density: 1g/cm ³
Super-plasticizer (SP)	Density 1.04-1.11g/cm ³ Total alkali content 1.1%
Jute fiber (J)	Density 1.30g/cm ³ , Length 6mm Diameter: approx. 0.05mm Water absorption ratio 0.75 (Condition: Absorption 24hr, 5min. desorption)

Table 4 –Point at which the temperature started to increase (PTSI)

fiber content ratio	PTSI
Vol%	Age (day)
0	0.66
0.5	0.53
1.0	0.72
2.0	0.55

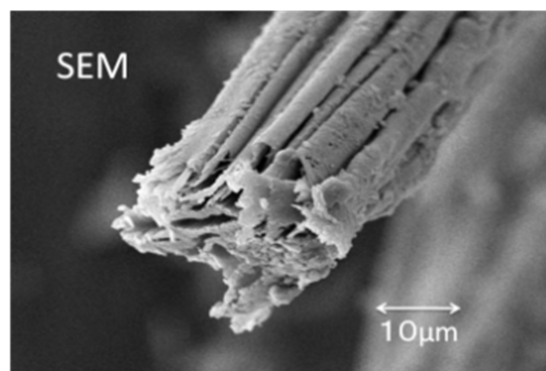


Figure 1– Shape of jute fiber(SEM)
(1μm=0.0000394in.)

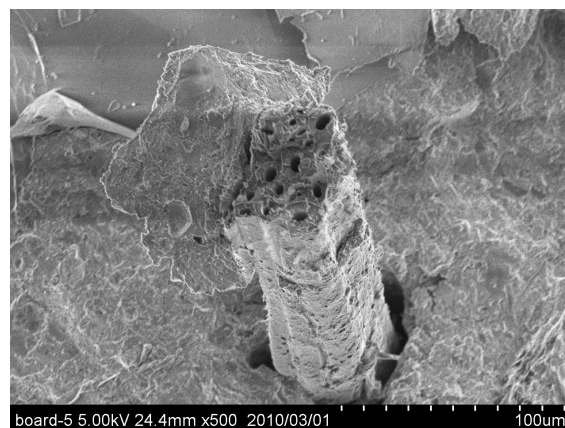
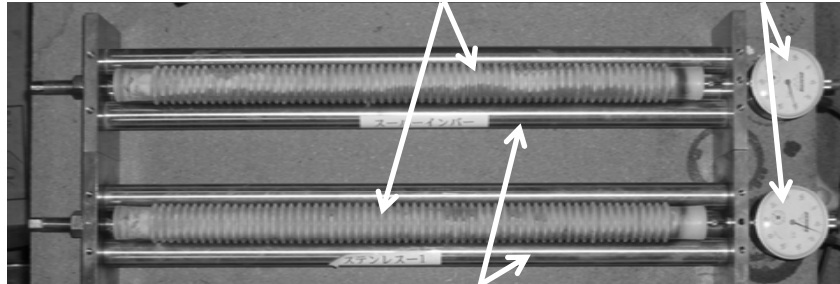


Figure 2– Jute fiber in concrete (SEM)
(1μm=0.0000394in.)



Measurement of Temperature

Cement paste in Corrugated tube Dial gauge(3/1000mm)



Measurement basement
(Made of Invar steel or stainless steel)

Figure 3– Autogenous shrinkage strain measurement system (1mm=0.039 in.)

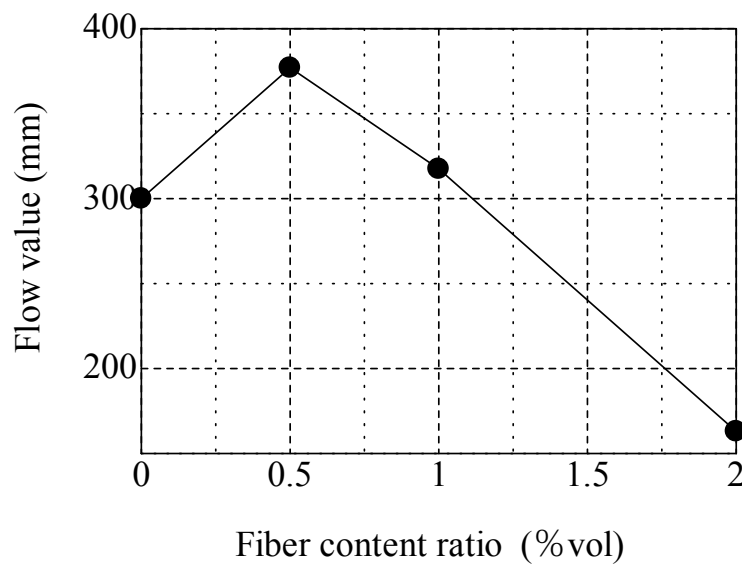


Figure 4– Relation between flow value and fiber content ratio (1mm=0.039 in.)

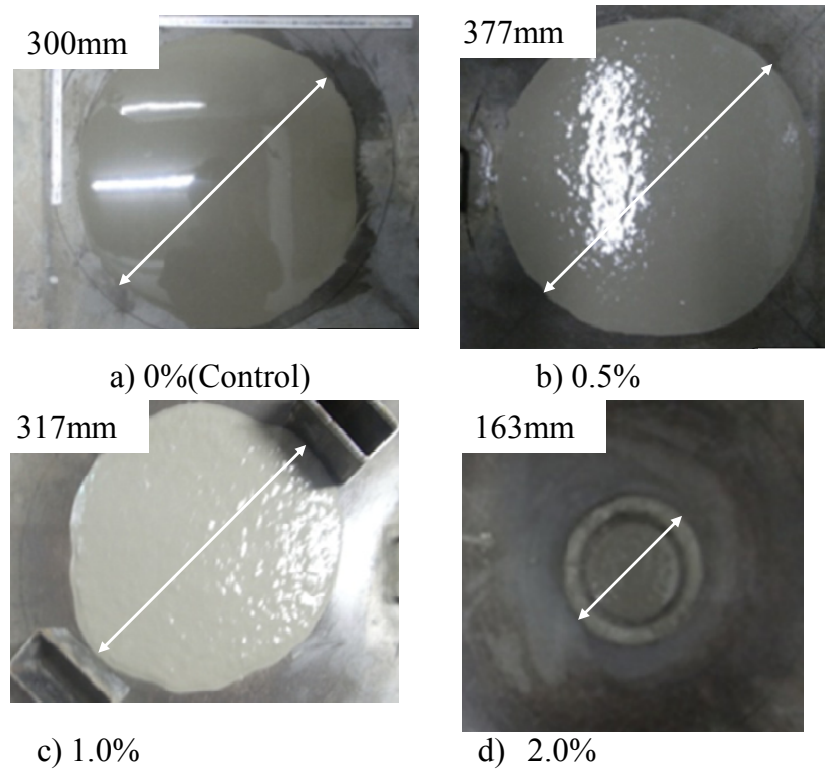


Figure 5– Results of flow test(1mm=0.039 in.)

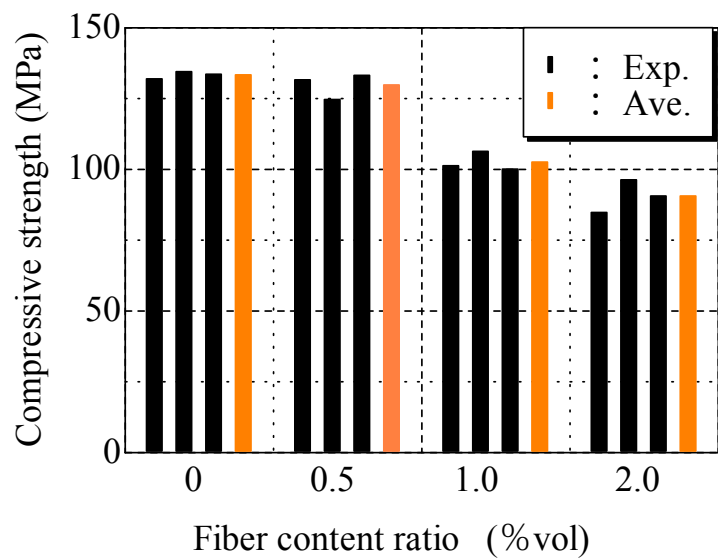


Figure 6– Relationship between cement paste of compressive strength and fiber content ratio (1MPa=145psi)

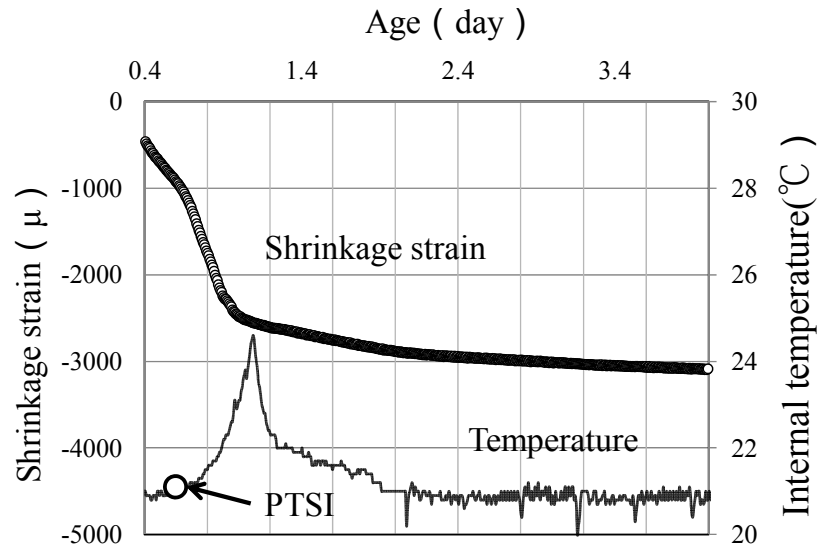


Figure 7– Shrinkage strain/internal temperature vs. age (e.g., control specimen)
(PTSI: the point at which the temperature started to increase)($^{\circ}\text{F}=9/5^{\circ}\text{C}+32$);

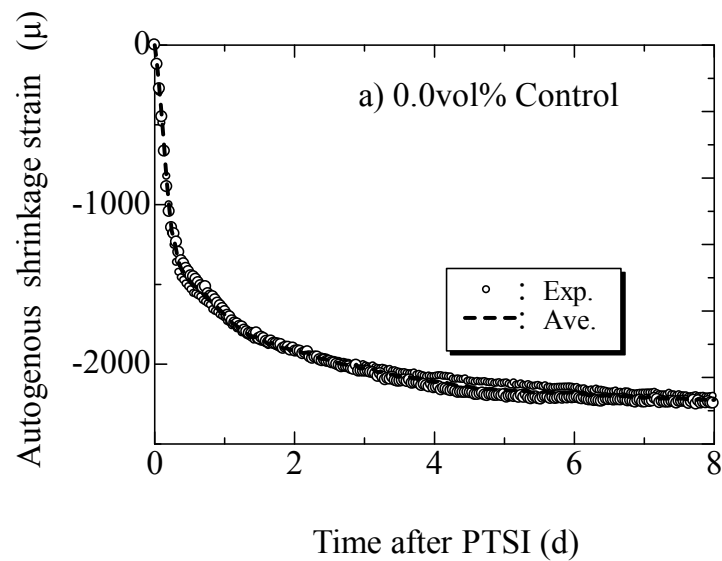


Figure 8 a) –Autogenous shrinkage strain (Control specimen)

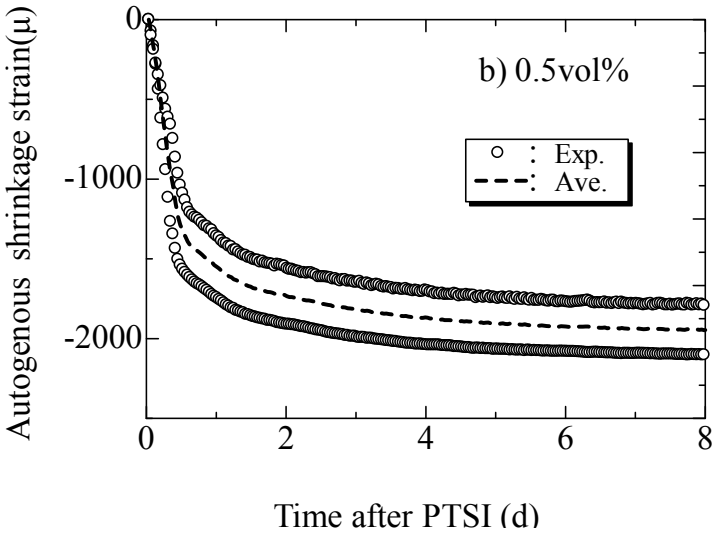


Figure 8 b) –Autogenous shrinkage strain (0.5%vol)

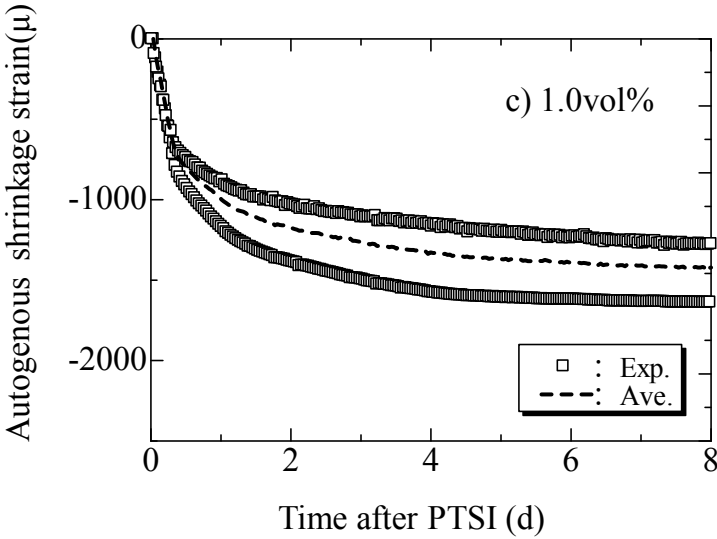


Figure 8 c) –Autogenous shrinkage strain (1.0%vol)

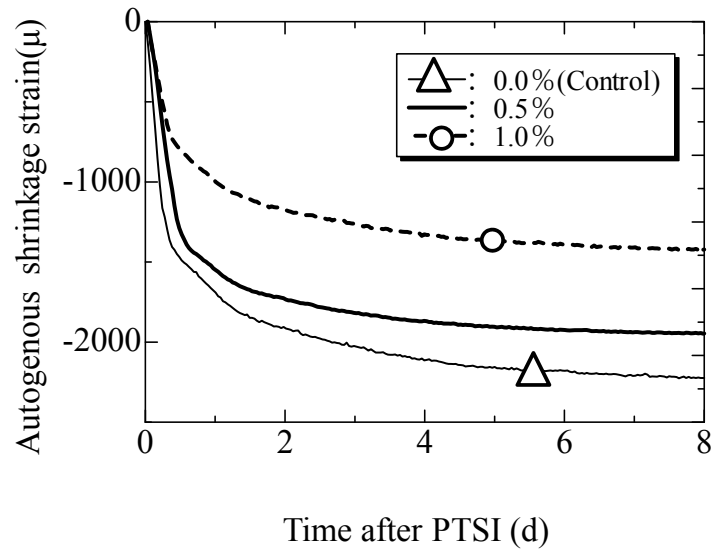


Figure 9– Comparison of autogenous shrinkage strain

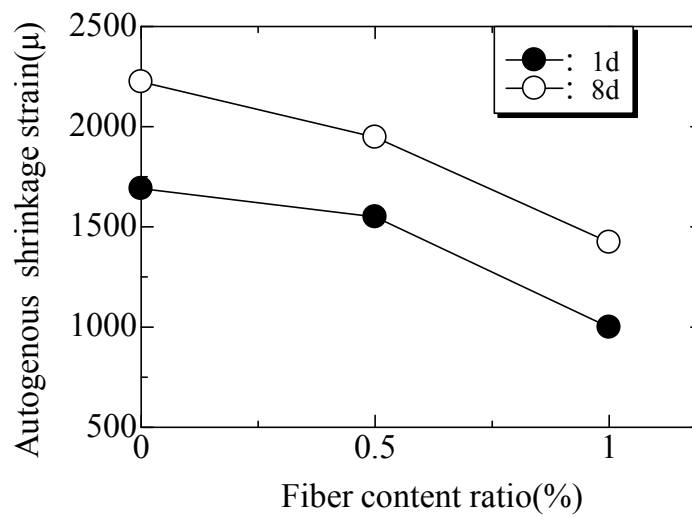


Figure 10– Relationship between autogenous shrinkage strain and fiber content ratio

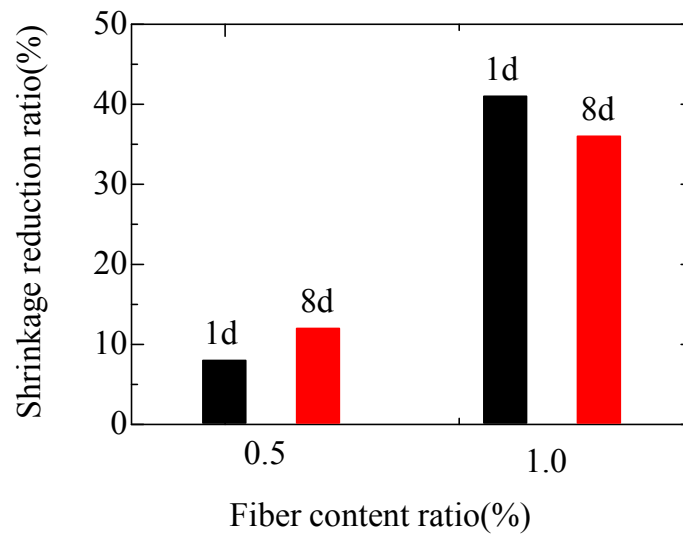


Figure 11– Relationship between shrinkage reduction ratio and fiber content ratio

Design and Construction of an Internally Cured Slab
by: Robert T. Bates, Erik Holck, Miles Dee, Michael King

Synopsis: Constructing large capacity, monolithically placed water storage tank slabs is a complex proposition. Previously, specifying low-shrinkage concrete mixes and monolithic placement of the slab within a specified time period was the prescribed method, yet shrinkage cracking still occurred. We felt more could be done to improve concrete placing and finishing, reducing shrinkage cracking and enhance durability. An investigation on the use of an Internally Cured Concrete mix on the floor and roof slabs of the Denver Water 10-Million Gallon [MG] (38-Million Liter [ML]) Lone Tree Tank No. 2 that Bates Engineering Inc. was designing was pursued. The tank floor and roof slab are each about 61,000 ft² (5,700 m²) and would be monolithically placed. Laboratory trial batches performed determined plastic and hardened characteristics of the ICC as compared to traditionally proportioned mix designs. Tests performed in the laboratory included: compressive strength and drying shrinkage (ASTM C 157⁽¹⁾, modified 7-day saturation). An ICC mix was selected based on durability expectations. Results of the floor slab placement were successful and only two shrinkage cracks were observed, 7-day and 28-day compressive strength tests, workability and consistency surpassed expectations. As a result, it was decided to use ICC concrete on the remaining structural components.

Keywords: Concrete water tank, internal curing, post-tensioned slab, shrinkage cracking

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INTRODUCTION

Denver Water's Lone Tree Facility includes an existing pump station and 10-MG (38-ML) Tank No. 1 designed by Diana Horner, PE, Vice-President of Bates Engineering, and constructed in 1984. The proposed tank, also 10-MG (38-ML) capacity, is needed due to the growth of residential, health care and commercial developments served by the Lone Tree Facility. The proposed tank will be the 7th tank designed by Bates Engineering staff for Denver Water including the 386 ft. (120 m) diameter, 32 ft. (9.8 m) high, 30-MG (114-ML) Foothills Treatment Plant Tank No. 3 constructed in 2001. Thus Bates Engineering had significant prior experience working for Denver Water and in particular Erik Holck, MSCE, P.E., Materials Lab Manager.

At the pre-design meeting Denver Water and Bates Engineering agreed to investigate emerging technologies to further reduce the probability of concrete shrinkage. The proposed tank's design consisted of a 61,000 ft² (5,700 m²) monolithically placed 5 in. (125 mm) thick post-tensioned membrane floor slab and an 8 in. (200 mm) thick structural roof slab. Denver Water was particularly interested in internally cured concrete slabs (ICC) and it was agreed to focus on the concrete mixture design. Other team members included Aggregate Industries (AI), Brundage-Bone Concrete Pumping and TXI ES&C, manufacturer of expanded shale and clay products.

The design team understood that constructing large capacity water storage tank slabs without construction joints is a complex proposition in Colorado's low humidity and often windy climate. One solution that has been successful on previous tank projects was to specify low-shrinkage concrete mixtures and monolithic placement of the slab within a prescribed time period, to reduce the probability of shrinkage cracking. Previously, the focus has been to commence placement of the concrete at a given days peak temperature in the summer months or at 32°F [0°C] and rising in the winter months with daytime temperatures forecasted to be well above freezing. This allowed for optimum concrete/ambient temperature conditions to reduce the potential of early age cracking. However, even under the best of circumstances and planning, shrinkage cracking still occurred. It was felt that more could be done to improve concrete curing, further reducing shrinkage cracking and enhancing durability.

Based on research reviewed by the team it was decided to investigate the use of an ICC mix on the floor and roof slabs of the Denver Water 10-MG (38-ML) Lone Tree Tank No. 2 that Bates Engineering was currently designing. The Lone Tree tank floor and roof slabs are each about 61,000 ft² (5,700 m²) and would be monolithically placed. The slabs could be compared to other 10-MG (38-ML) floor and roof slabs designed by Bates Engineering and were constructed within a few miles of the Lone Tree Project.

CONCRETE MIX DESIGN DEVELOPMENT

The use of prewetted fine lightweight aggregate for internal curing

To accomplish the desired result of an internally cured concrete, prewetted expanded shale lightweight aggregate fines were chosen. The prewetted expanded shale fines were used to replace a portion of the normalweight concrete sand. In order to ensure that the proposed internally cured concrete contained the minimum quantity of moisture available for internal curing, we followed the recommendations of the National Institute for Standards and Technologies' Engineering Lab's web based tool for calculating purposes. That tool is based on the calculation developed by Bentz & Snyder.⁽²⁾

Data was unavailable for the actual chemical shrinkage of the cement. As a result, a default value of 0.07 lb. water per lb. of cement was chosen (0.07 kg water per kg cement when designing metrically). Since the time of this pilot study the industry has settled on this value to ensure minimum internal moisture is available for internal curing.

To determine the desorption characteristics of the prewetted fine lightweight aggregate we relied on moisture content testing of the material in accordance with ASTM D 2216.⁽³⁾ One key component for successfully providing sufficient moisture to internally cure concrete is to determine the desorption characteristics of the material to be utilized. The desorption characteristics as tested for the expanded shale fine lightweight aggregate utilized was 19.6% after 21 days based on a measured absorbed moisture of 24.8%. With this data we were able provide the necessary moisture following the Bentz formula nothing that we had to ensure sufficient absorbed moisture to meet the IC moisture required by the concrete mixture based on the desorption abilities of the prewetted lightweight fines.

Laboratory trial of proposed mix design proportions

Trial mix laboratory testing for proposed concrete mix proportions consisted of a 3-point curve, where w/cm [water/cement ratio] ratio was targeted at 0.38, 0.40, and 0.42. Water content was fixed in each trial based on real world practicalities i.e. workability and finishability. Therefore, cementitious content and admixture dosages were adjusted to compare drying shrinkage potential (ASTM C 157⁽¹⁾) and relative workability of mixtures with the same unit water content. All points contained Type F Water-Reducing Admixture. It should also be noted that the 0.40 and 0.38 w/cm points were trialed with additional 1.0 oz/cwt Type F Water-Reducing Admixture in order to achieve the desired workability > 4 in. slump (100 mm). This was a direct result of the 0.42 w/cm point. The amount of fine lightweight aggregate used in each trial was proportioned such that the water desorption content per unit of cement remained constant. For trial purposes, no supplementary cementitious materials were used. The mixes contained only ASTM C 150⁽⁴⁾ Type I/II Portland cement. Results of lab trials are shown in Table 1.

Table 1 – Lab Trial Plastic & Hardened Properties

Lab Trial Mix	Slump, in. (mm)	Air Content, %	Fresh Bulk Density, lb./ft ³ (kg/m ³)	3-day Comp. Strength, psi (MPa)	7-day Comp. Strength, psi (MPa)	28-day Comp. Strength, psi (MPa)	28-day Drying Shrinkage, %*
w/cm 0.42	3.75 (95)	6.5	136.8 (2190)	5,090 (35)	6,250 (43)	7,010 (48)	0.040
w/cm 0.40	4.50 (115)	5.9	138.2 (2210)	6,290 (43)	6,990 (48)	8,050 (55)	NA**
w/cm 0.38	4.75 (120)	6.2	137.8 (2210)	6,270 (43)	7,240 (50)	8,020 (55)	0.038

* Per ASTM C 157 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete (Modified Method: Drying Shrinkage 7-Day Water Cure)

**Point not tested, rather interpolated between w/cm 0.42 & 0.38 points.

CONCRETE BATCHING AND PLACEMENT – PILOT STUDY FIELD PLACEMENT

Following the trial mix laboratory testing, the design team chose to use the ICC mix with a w/cm ratio of 0.40. This decision was based on previous field experience where typical concrete mixtures were proportioned at a 0.42 w/cm ratio. We felt the workability of the 0.40 w/cm ratio ICC concrete mixture would allow for sufficient place-ability at the lower w/cm ratio value. The team decided to place two slabs side by side at the project site for a field trial. One of the slabs was the ICC mix, and the other was a traditional mix. This test was conducted to determine the

differences if any between the two mixes as far as pumping, finishing, and shrinkage cracking. The slabs were each 10 ft. x 40 ft. x 4 in. thick (3 m x 12 m x 100 mm thick) and unreinforced.

Lightweight fines testing and preparation

In order to ensure adequate moisture content remained in the saturated fine lightweight aggregate during production and batch plant storage, we initiated a field test to replicate real world conditions and the potential for moisture loss over time and temperature in ambient conditions. On August 4th, 2010, three stock piles of approximately 20 yd³ (15 m³) each of expanded shale fine lightweight aggregate were produced and tested at the ES&C production facility for ambient moisture loss analysis. The material had been prepped through a pug mill where water was added to ensure thorough distribution. Targeted initial moisture percentages of the three separate piles were 15%, 20% and 25%. Actual percentages upon placement were 15.1%, 22.0% and 27.6%. After placement, the piles were retested at intervals of 1, 3, 5 and 7 days. The results of these tests, along with the sieve analysis are contained in Tables 2 & 3. Ambient conditions during the test period showed temperatures ranges from 57 °F (14 °C) to 88 °F (31 °C) over the 7 days. Additionally, an accumulation of 0.5 in. (13 mm) of precipitation was recorded, most of which occurred on the 4th day of testing. We targeted minimum retained moisture of 19.6% per Raba-Kistner Consultants Inc. desorption testing report⁽⁵⁾ dated June 10th 2008. Actual delivered moisture to the pilot study and the project were no less than 22%.

The data developed from this test allowed for proper planning and material preparation to meet both the Pilot Study field placements and the actual project placements as well. Field testing of the fine lightweight aggregate continued prior to the pilot study placement at both the ES&C production facility and the concrete batch plant. These tests demonstrated a near match to our field replication study.

Table 2 – Bulk Density and Moisture Content of Stockpiles of Fine Lightweight Aggregate

Stockpile Location	As Placed Loose Bulk Density lb./ft ³ (kg/m ³)*	Initial Moisture Content %**	Moisture Content % 1 Day	Moisture Content % 3 Day	Moisture Content % 5 Day	Moisture Content % 7 Day	Moisture Content % 14 Day
West	58.5 (940)	15.1	14.4	14.4	15.5	14.5	14.4
Middle	60.3 (970)	22.0	22.6	21.0	21.3	21.6	21.5
East	62.4 (1000)	27.6	21.8	18.9	19.0	21.3	18.4

* Per ASTM C 29⁽⁶⁾ Standard Test Method for Bulk Density & Voids in Aggregate – Loose Shovel Method

**Per ASTM C 566⁽⁷⁾ Standard Test method for Total Evaporable Moisture Content of Aggregate by Drying

Table 3 – Gradation Results for Stockpiles of Fine Lightweight Aggregate

ASTM C 330	Limits Passing %	West Stockpile %	Middle Stockpile %	East Stockpile %	Average %
3/8" (9.5 mm)	100	100	100	100	100
#4 (4.75 mm)	85 – 100	99.1	98.9	99.1	99
#16 (1.18 mm)	40 – 80	50.2	50.3	51.9	50.8
#50 (300 µm)	10 – 35	24.9	24.3	26.8	25.3
#100 (150 µm)	5 – 25	18.4	19.3	20.8	19.5

The fine Aggregate utilized for this test and the project met the standards as prescribed in ASTM C 330⁽⁸⁾ Standard Specification for Lightweight Aggregates for Structural Concrete.

Pilot study field placement observations

The contractor did not report any differences in pumping the material, and thought that the ICC slab was somewhat easier to finish. Both slabs were finished with a screed, bull float, and broom finish. After 35-days with no applied or water curing, both slabs were inspected and it was observed that the ICC slab had minimal shrinkage cracking compared to the reference slab. In fact, water had to be applied to the surface for any of the cracks to be visible.