Results from a preliminary study that investigated the potential of using drinking water treatment waste sludge as an internal curing agent for concrete are presented. The concept consists of using the high water content, primarily calcium carbonate material, as a concrete admixture. Two other commonly used internal curing agents—prewetted lightweight fine aggregate and a superabsorbent polymer—were investigated as a comparison. Cement mortars were tested for compressive strength, degree of hydration, and shrinkage. Micrographs of mortars containing the three different internal curing agents were compared visually to evaluate the distribution of internal curing agents and relative hydration. Results show that drinking water treatment waste is an effective internal curing agent, improving cement hydration, compressive strength, and mitigating autogenous shrinkage.

Keywords: compressive strength; curing agent; degree of hydration; internal curing; scanning electron microscopy; shrinkage.

INTRODUCTION

Concrete can be a highly durable construction material when permeability and cracking are low. Durability cracking, alkali-silica reaction, freezing-and-thawing deterioration, carbonation, reinforcement corrosion, and many other premature distresses are directly affected and exacerbated by high cement paste permeability and cracking.1,2 Hydrating cement paste shrinks through several mechanisms, broadly grouped into autogenous and drying shrinkage.3 These mechanisms cause cracks that become high-permeability routes for water and aggressive ion movement, such as chlorides to reinforcing steel. Drying shrinkage can be controlled by appropriate curing methods; however, proper curing does little to affect autogenous shrinkage, especially in low water-cementitious material ratio (w/cm) systems.4 Internally supplying additional water, not part of the original mixing water, on an as-needed basis to hydrating cement, reduces autogenous shrinkage and allows for more complete cement hydration. Reduced autogenous shrinkage minimizes total shrinkage and cracking and helps reduce reinforcement corrosion. More complete hydration creates a denser cement paste, reducing permeability and improving durability and longevity. The National Institute for Standards and Technology (NIST) has stated that “it appears that internal curing has the potential to make a substantial impact on the durability and lifecycle costs of concrete structures.”5

Background on internal curing agents

The two most common materials used for internal curing of concrete include prewetted lightweight aggregates (LWs) and superabsorbent polymers (SAPs).5,8 Lightweight aggregates are high-absorption, high-porosity materials and commonly include expanded shale, clay, and slate. For internal curing purposes, prewetted lightweight fine aggregates have shown more benefit than coarser materials due to a better distribution of moisture throughout the hydrating cement paste. Moisture in the lightweight aggregate is physically held by capillary force and released when hydrating paste falls below critical saturation. However, the degree of saturation in lightweight aggregate and moisture management can be problematic.5 Dry or undersaturated lightweight aggregate may take up water from the mixture and impact workability. Superabsorbent polymers are typically crystalline salts, which can absorb significant amounts of water without dissolving.9 For commercially available SAP, the absorbency is generally below 2000%,10 SAPs absorb water and then act as bulk water reservoirs during hydration, releasing the stored water once the internal humidity fall below a critical level.11 The high pH of the fresh concrete paste can significantly reduce SAP absorption compared to values observed for pure water. Whereas the water stored in the internal pores of LW does not impact the mixture, SAP absorption and swelling will impact workability.6 The swelling of the SAP can act as a viscosity modifier and may result in slight water reduction.11,12 Because the current internal curing agents must be manufactured and have special handling considerations, the cost of concrete with these agents will be greater than conventionally cured mixtures.

Background on drinking water treatment waste

A majority of the U.S. population uses surface waters as a drinking water source. Surface water treatment produces large amounts of waste sludge from flocculation and filtration processes. The average American uses 80 to 100 gal. (0.3 to 0.37 m³) of treated water each day and water treatment processes result in approximately 4% sludge generation as a total of water treated.13,14 Sludge handling is responsible for 30 to 40% of the capital cost of a treatment plant, and around 50% of the operating costs.14 Settled sludge particles are dewatered into a semi-dry cake (~50% solids) before disposal and, in 2010, the United States produced 7 million metric tons of lime sludge from drinking water treatment (on a dry solid basis).15 The significant cost occurs because

ACI Materials Journal/January-February 2015

69
natural gas drying is required before disposal, typically as agricultural lime. In many locations, disposal consists of open evaporating pits and there is an ever-increasing need for sludge management, disposal, or reuse.

Through the water treatment process, the particles in the solid sludge are seldom dispersed and instead form into agglomerations called flocs. The water contained in sludge is divided into two categories: bulk water and bond water. Bulk water can be drained and relatively easily removed compared to the bond water. Bond water includes interstitial water, vicinal water, and water of hydration. Interstitial water is water trapped in the interstitial spaces of the flocs, which can become free water when the flocs structure is destroyed. Vicinal water consists of multiple layers of water molecules held to the particle surface through hydrogen bonding. Water of hydration is the water chemically bond to the particles and can only be removed by thermal drying. Of the characteristic water contained in drinking water treatment waste (DWTW), bond water is easily accessible and may be beneficial for concrete internal curing.

RESEARCH SIGNIFICANCE

This paper presents preliminary research to investigate the potential of using waste material from drinking water treatment operations as an internal curing agent in concrete. Low water-cement ratio (w/c) concrete mixtures are highly susceptible to early-age cracking from autogenous shrinkage. Internal curing is beneficial for concrete and mitigates early-age cracking and increases the overall degree of cement hydration. Water treatment operations produce large amounts of waste sludge from flocculation and filtration. The flocculation process produces a material containing large amounts of water, which is difficult for industry to remove, causing high transportation and disposal costs. However, the high moisture content makes DWTW a good candidate for internal curing of concrete.

EXPERIMENTAL INVESTIGATION

The experimental plan was designed to determine: 1) if DWTW behaves as an internal curing agent in concrete; and 2) if the internal curing benefits provided by DWTW are similar to commonly used materials. The investigated experimental plan included three different internal curing agents: prewetted lightweight fine aggregate (LW); a superabsorbent polymer (SAP); and DWTW. Experimental factors included internal curing dosage and impacts of relative humidity (RH) on curing.

Materials

The cement used in this study was ordinary portland cement (OPC) conforming to ASTM C150/C150M Type I. The OPC had a Blaine fineness of 373 m²/kg and a Bogue composition of 55% C₃S, 17% C₂S, 8% C₃A, 10% C₄AF. The DWTW used in the study was light gray in color and had the consistency of damp soil. The material had been dewatered to the as-tested condition and landfilled. The as-received moisture content was 54% on a dry weight basis and specific gravity was 2.41 tested with a helium pycnometer. Chemical composition using X-ray florescence (XRF) showed high calcium content and low contents of silicon, magnesium, and aluminum, which are shown in Table 1. X-ray diffraction (XRD) showed calcite, quartz, and magnetite as the main crystalline components and are shown in Fig. 1. Scanning electron microscopy (SEM) showed conglomerations of calcium carbonate platelets ranging from 10 to 100 μm (Fig. 2). Graded standard sand was used as fine aggregate in the mortars and met requirement for ASTM C109/C109M and C778. The LW was expanded shale from New Market, MO, had a dry specific gravity of 0.84, and a density of 47 lb/ft³ (753 kg/m³). The material was vacuum saturated to the tested moisture content of 15%. The SAP used was partial sodium salt of cross-linked polypropomonic acid and had absorption rated at 2000× in pure water. This SAP has been previously shown effective as an internal curing agent. A polycarboxylate high-range water reducer was used that met ASTM C494/C494M specifications for Type A and Type F admixtures.

Specimen preparation and testing methods

Standard 2 in. (50 mm) mortar cubes were tested for compressive strength according to ASTM C109/C109M, and for degree-of-hydration testing. Cement mortar prisms with dimensions of 1 x 1 x 11-1/4 in. (25 x 25 x 285 mm)
were used for drying shrinkage (ASTM C596) and autogenous shrinkage.

After placement, samples were sealed and cured at standard conditions of 75°F (23°C). Specimens were demolded after 24 hours and cured at one of three relative humidities (RHs), which were 25%, 50%, and 100%. Degree-of-hydration and compressive strength testing was determined at 7 and 28 days.

Degree of hydration (DOH) was determined by measuring the weight of non-evaporable water lost between 212 and 1742°F (100 and 950°C). A general expression for DOH is shown in Eq. (1). Loss on ignition (LOI) was first measured on the unhydrated cement, standard sand, DWTW, and LW. The individual LOIs were first subtracted from the tested value before determining DOH, as shown in Eq. (2).

\[
\alpha(t) = \frac{w_{n,\text{sample}}}{c} 
\]

\[
w_{n,\text{sample}} = \text{LOI}_{\text{sample}} - \text{LOI}_{\text{cement}} - \text{LOI}_{\text{DWTW}} 
\]

where \( \alpha(t) \) is DOH at time \( t \), \( w_{n,\text{sample}} \) is non-evaporable water loss of only the hydrated cement or hydrated cement and DWTW; \( c_{\text{sample}} \) is the cement content by mass of the ground specimen determined from the volumetric mixture proportions, and \( w_{n,0}/c \) is the theoretical amount of water, in g/g, to fully hydrate the cement. For the purpose of degree-of-hydration calculations presented herein, 0.25 g water/g cement was used throughout. Type I cement was used in this study, which contained less than 5% limestone interground with the cement clinker. The LOI of the cement was measured as 0.022 g/g cement. The LOI of the DWTW was measured as 0.406 g/g DWTW, which was expected due to the high carbonate content. Neither the standard sand nor lightweight sand had appreciable LOI. At the desired testing age, a profile grinder was used to powderize material from a representative cross section of the cube specimens. Mass of the samples was recorded to the nearest 0.001 g. Samples were first placed in an oven for 24 hours at 212°F (100°C). Mass was recorded before igniting at 1742°F (950°C) for 4 hours. Samples were cooled in a desicator to room temperature prior to final LOI determination.

Autogenous shrinkage was measured according to ASTM C596 with the exception that samples were sealed with wax after demolding at 1 day. Mass change of the autogenous shrinkage prism was less than 0.097%.

All data represent an average of three samples for cubes for compressive strength and four prisms for total shrinkage and autogenous shrinkage. Drying shrinkage was calculated by subtracting the average of autogenous shrinkage from the average of total shrinkage at each age for each group. All the error bars in the figures present the standard error of each group of data. The coefficient of variation (COV) in the measured compressive strength and DOH was determined to be less than 15% for all groups of data. Data was compared using student’s t-tests, with \( p < 0.005 \) used for significant effects.

**Mixture proportioning**

The mixture designs are shown in Table 2 with the mixture proportions shown in Table 3. A polycarboxylate high-range water reducer was used to achieve the desired consistency for the control mortar, which was a flow of 110 ± 5% from 25 drops of the flow table. Nomenclature used is as follows: portland cement control mortar (PC), portland cement mortar containing superabsorbent polymer (SP), portland cement mortar containing pre-wetted lightweight aggregate substituted for a portion of the standard sand (LW), and portland cement mortar containing DWTW substituted for a portion of the standard sand (WT). The numbers following
The amount of additional internal curing water selected for comparison across treatments was fixed at 0.054 g water/g cement. The value of 0.054 has been recommended by RILEM as the optimum amount for internal curing with SAP. The optimum dosage of LW for internal curing is based on the amount of water contained in the aggregate to satisfy chemical shrinkage. Bentz et al. presented an equation for determining the required amount of lightweight aggregate as a function of cement content, expected DOH, chemical shrinkage, and amount of moisture contained in the lightweight aggregates. While all materials used in this study were dosed to achieve the additional 0.054 g water/g cement, an optimum dosage of LW and presumably DWTW using the Bentz et al. equation would require 0.076 g water/g cement. Based on this optimum dosage, 30% more internal curing water would be required for the best performance of the DWTW and LW used in this study.

EXPERIMENTAL RESULTS AND DISCUSSION

Compressive strength

Figure 3 shows the compressive strength results for the samples cured in lime water (100% RH). Mixtures containing SAP without any additional internal curing water (SP-0) had similar strength to the control at all ages. Both the SAP mixture with additional water (SP-0.054) and the lightweight aggregate mixture (LW-0.054) had lower strength than the control. There were no differences between SP-0.054 and LW-0.054 at either age. The decreases in strength were expected because the lightweight aggregate is weaker than the standard sand it replaced, and the extra water provided for the SAP resulted in a correspondingly larger number of voids. What was not expected for the saturated conditions was the increase observed for the DWTW mixture. The mixture WT-0.054 had 8% and 7% increases in compressive strength compared with control mixture at 7 and 28 days, respectively. Figure 4 shows the compressive strength results of the samples cured under sealed conditions. At 7 days, the sealed specimens had roughly half of the compressive strength of the 100% RH specimens. All of the internally-cured specimens had higher average strength than the control at both 7 and 28 days. The mixtures containing extra internal curing water (SP-0.054, LW-0.054, and WT-0.054) all had similar strength gains. At 28 days, mortar containing SAP without IC water (SP-0) had the highest compressive strength. Assuming that the SAP absorbed some of the original mixing, SP-0 had effectively the lowest w/c. Overall, using DWTW as alternative internal curing agent showed a positive effective on mortar compressive strength, in both curing conditions, with similar performance to SAP and LW.

Table 2—Mortar mixture designs

<table>
<thead>
<tr>
<th>Designation</th>
<th>w/c</th>
<th>SAP, %</th>
<th>LW, %</th>
<th>DWTW, %</th>
<th>Internal curing water, water (g)/cement (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-0</td>
<td>0.3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>SP-0</td>
<td>0.3</td>
<td>0.125</td>
<td>—</td>
<td>—</td>
<td>0.054</td>
</tr>
<tr>
<td>SP-0.054</td>
<td>0.354</td>
<td>0.125</td>
<td>—</td>
<td>—</td>
<td>0.054</td>
</tr>
<tr>
<td>LW-0.054</td>
<td>0.3</td>
<td>—</td>
<td>2.38</td>
<td>—</td>
<td>0.054</td>
</tr>
<tr>
<td>WT-0.054</td>
<td>0.3</td>
<td>—</td>
<td>—</td>
<td>0.98</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Note: Percent is percent by weight.

Table 3—Mortar mixture proportion, lb/yd$^3$ (kg/m$^3$)

<table>
<thead>
<tr>
<th>Materials</th>
<th>OPC</th>
<th>SP-0</th>
<th>SP-0.054</th>
<th>LW-0.054</th>
<th>WT-0.054</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>1375 (638)</td>
<td>1375 (638)</td>
<td>1375 (638)</td>
<td>1375 (638)</td>
<td>1375 (638)</td>
</tr>
<tr>
<td>Sand</td>
<td>2682 (1591)</td>
<td>2682 (1591)</td>
<td>2682 (1591)</td>
<td>2618 (1553)</td>
<td>2656 (1576)</td>
</tr>
<tr>
<td>PLWA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>64 (38)</td>
<td>—</td>
</tr>
<tr>
<td>DWTW</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>27 (16)</td>
</tr>
<tr>
<td>SAP oz/cwt (g/100 kg)</td>
<td>—</td>
<td>2 (127)</td>
<td>2 (127)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Water</td>
<td>322 (191)</td>
<td>322 (191)</td>
<td>381 (226)</td>
<td>322 (191)</td>
<td>322 (191)</td>
</tr>
</tbody>
</table>

Fig. 3—Measured compressive strength for mortars cured under 100% RH condition. (Note: 1 psi = 6.89 × 10$^{-3}$ MPa. Error bars represent standard error.)

Fig. 4—Measured compressive strength for mortars cured under sealed condition. (Note: 1 psi = 6.89 × 10$^{-3}$ MPa. Error bars represent standard error.)
Degree of hydration

Degree of hydration (DOH) was evaluated for samples cured under three relative humidities at 3, 7, and 28 days. The statistical analysis of results across all mixtures and humidities are shown in Table 4. Figure 5 compares DOH of mortars cured under 50% RH. As expected, mortars at later ages had higher degrees of hydration. The rate of DOH gain slowed from 7 days to 28 days due to cement hydration process changing into a diffusion-controlled reaction. At 3 days, mortar containing SAP and with additional IC water (SP-0.054) showed a significantly higher DOH than all other mortars, potentially indicating that the water held by the SAP is more readily drawn into hydrating paste than the water held within the pore spaces of the LW and DWTW. There was no statistical difference between any of the other mixtures with the average DOH around 20% at 3 days. At 7 days, mortars with additional internal curing water (SP-0.054, LW-0.054, WT-0.054) and mortar containing SAP without IC water (SP-0) showed over a 13% DOH increase compared to the control mortar (PC-0). There was no significant difference between SP-0.054 and LW-0.054. At 7 days, however, mortar containing DWTW showed the highest DOH of all groups, which resulted in a 24% DOH increase compared to the control and a 7% DOH increase compared to the other internal curing agents. At 28 days, the DOH of all groups reached over 45%. Mortars containing SAP with and without IC water (SP-0, SP-0.054) showed the highest DOH with no difference between the two. Mortar containing LW lightweight fine aggregate (LW-0.054) had second-highest DOH and had 4% DOH increase above mortar containing DWTW (WT-0.054). LW-0.054 had greatest DOH increase between 7 and 28 days, followed by WT-0.054.

Figure 6 shows the difference on DOH between curing conditions at 28 days. As expected, the higher relative humidities (RHs) resulted in higher degrees of hydration. Generally, at 100% RH under saturated conditions, the internal curing agents had little effect, which would be expected. At the lower RH of 25%, the aggregate-based materials (LW, DWTW) performed better than at 50% RH. The SAP mixtures performed well at all humidities, which would be expected because the internal curing dosage rate was fixed at recommendations for SAP. Specifically, at 25% RH curing condition, mortar containing SAP and IC water (SP-0.054) and mortar containing DWTW (WT-0.054) showed a significant 12% increase compared to the control mortar (PC-0). There was no difference in DOH between SP-0.054 and WT-0.054; however, there was a difference in DOH between SP-0.054 and LW-0.054, even though both LW-0.054 and WT-0.054 were not dosed at the optimum

Table 4—Statistical comparison of degree of hydration cured for different groups for all curing conditions at 28 days

<table>
<thead>
<tr>
<th>Mixture</th>
<th>RH</th>
<th>PC-0</th>
<th>SP-0</th>
<th>SP-0.054</th>
<th>LW-0.054</th>
<th>WT-0.054</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-0</td>
<td>25%, 50%, 100%</td>
<td>—</td>
<td>&lt;0.001, &lt;0.001, 0.015</td>
<td>&lt;0.001, &lt;0.001, &lt;0.001</td>
<td>0.002, 0.001, 0.019</td>
<td></td>
</tr>
<tr>
<td>SP-0</td>
<td>25%, 50%, 100%</td>
<td>—</td>
<td>&lt;0.001, &lt;0.001, 0.015</td>
<td>0.020, 0.878, 0.003</td>
<td>0.281, 0.017, 0.655</td>
<td>0.0016, &lt;0.001, 0.095</td>
</tr>
<tr>
<td>SP-0.054</td>
<td>25%, 50%, 100%</td>
<td>—</td>
<td>0.020, 0.878, 0.003</td>
<td>0.022, 0.002</td>
<td>0.002, 0.003</td>
<td></td>
</tr>
<tr>
<td>LW-0.054</td>
<td>25%, 50%, 100%</td>
<td>0.002, 0.010, 0.034</td>
<td>0.281, 0.017, 0.655</td>
<td>0.022, 0.002</td>
<td>—</td>
<td>0.002, 0.088, 0.743</td>
</tr>
<tr>
<td>WT-0.054</td>
<td>25%, 50%, 100%</td>
<td>0.019</td>
<td>0.016, &lt;0.001, 0.905</td>
<td>0.920, &lt;0.001, 0.003</td>
<td>0.002, 0.088, 0.743</td>
<td></td>
</tr>
</tbody>
</table>

Note: Critical level is 0.005; bold and underlined are statistically significant.
internal curing dosage for lightweight aggregate. Mortar containing SAP without IC water (SP-0) and mortar containing LW (LW-0.054) showed similar DOH increases for all curing conditions. Mortars cured under 100% RH all achieved over 55% DOH. Mortar containing SAP and IC water (SAP-0.054) showed the highest DOH—around 60%. Mortar containing SAP without IC water (SP-0) and mortars containing internal curing by LW and DWTW (LW-0.054, WT-0.054) showed similar DOH, which had around a 3% increase over the control.

Observing the effects of curing time and RH on DOH of all groups, DWTW showed a positive effect on early-age DOH, and also had significant effect on improving DOH under low RH curing condition, especially when RH dropped under 50%.

**Shrinkage results**

Typically, internally cured concrete has higher moisture loss, with water lost both internally through hydration and externally through drying.\(^5,31,32\) In Fig. 7, mass change and total shrinkage of all groups is shown to 28 days. Results of the statistical analysis for shrinkage at 28 days are shown in Table 5. Mortar containing LW (LW-0.054) had the greatest total shrinkage and correspondingly the greatest mass loss. There was no difference in total shrinkage or mass loss between control group (PC-0) and mortar containing SAP without IC water (SP-0) at 28 days. The mass loss for DWTW-0.054 was less than other two internal curing groups with the same IC water (SP-0.054, LW-0.054), which indicates internal curing water from DWTW primarily involves the more easily released bond water.

Internal curing water provides compensation for emptying the capillary pores in cement paste and also lowers the tensile stresses that develop in the capillary space, reducing self-desiccation shrinkage.\(^8\) LWs and SAPs have been shown to reduce autogenous shrinkage.\(^31,33,34\) Figure 8(a) shows the comparison of autogenous shrinkage of the mortars. Overall, all of the internally-cured mortars had less autogenous shrinkage than the control group (PC-0). The IC efficiency factor for reducing autogenous shrinkage (\(\eta\)) was defined by Zhutovshy\(^34\) as the ratio of the difference of autogenous shrinkage between the reference concrete and the internal cured concrete over the autogenous shrinkage of reference concrete (\(\Delta e_{as}/e_{as}\)) at a certain age. At 28 days, among all the groups containing the same internal curing water, mortar containing SAP (SP-0.054) had an IC efficiency factor of 0.51, mortar containing DWTW (WT-0.054) had an IC efficiency factor of 0.31, and mortar containing LW (LW-0.054) had an IC efficiency factor of 0.26. The lower IC efficiency factor of DWTW and LW may be due to the amounts of DWTW and LW included that were less-than-optimally recommended for the realization of full internal curing benefits. There was no statistical difference in autogenous shrinkage between mortar containing SAP with additional water provided for internal curing (SAP-0.054) and mortar containing SAP

<table>
<thead>
<tr>
<th>Autogenous shrinkage (total shrinkage)</th>
<th>PC-0</th>
<th>SP-0</th>
<th>SP-0.054</th>
<th>LW-0.054</th>
<th>WT-0.054</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-0</td>
<td>—</td>
<td>&lt;0.001 (0.587)</td>
<td>0.002 (0.265)</td>
<td>0.053 (0.005)</td>
<td>0.172 (0.249)</td>
</tr>
<tr>
<td>SP-0</td>
<td>&lt;0.001 (0.587)</td>
<td>—</td>
<td>0.675 (0.148)</td>
<td>0.025 (0.005)</td>
<td>0.006 (0.140)</td>
</tr>
<tr>
<td>SP-0.054</td>
<td>0.002 (0.265)</td>
<td>0.675 (0.148)</td>
<td>—</td>
<td>0.053 (0.027)</td>
<td>0.013 (0.964)</td>
</tr>
<tr>
<td>LW-0.054</td>
<td>0.053 (0.005)</td>
<td>0.025 (0.005)</td>
<td>0.053 (0.027)</td>
<td>—</td>
<td>0.452 (0.029)</td>
</tr>
<tr>
<td>WT-0.054</td>
<td>0.172 (0.249)</td>
<td>0.006 (0.140)</td>
<td>0.013 (0.964)</td>
<td>0.452 (0.029)</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: Critical level is 0.005; bold and underlined are statistically significant.
without additional water. The results showed that DWTW behaves similarly to lightweight aggregate for autogenous shrinkage mitigation.

Drying shrinkage was determined as the difference between total shrinkage (Fig. 7(a)) and autogenous shrinkage (Fig. 8(a)). Results of drying shrinkage are shown in Fig. 8(b). The control group (PC-0) had the least drying shrinkage. As expected, the internally-cured samples had higher drying shrinkage. However, drying shrinkage was also greater for the SAP mixture, which did not contain additional curing water (SAP-0). At 28 days, there was no difference in drying shrinkage between any of the internally cured samples.

**Scanning electron microscopy**

Fractured samples from compressive strength testing were examined using the SEM for visual analysis of relative hydration level and incorporation of the IC materials into the hydration matrix. All the samples were dried at 100°F (37°C) for 24 hours prior to imaging. Images shown are from cement mortars cured under sealed conditions and tested at 7 days (Fig. 9). Figure 9(a) shows the SEM image of the control group (PC-0). The control sample contained a number of unhydrated cement particles distributed throughout the hardened cement paste, which appear as bright-colored grains. Comparing the SEM images of mortars containing SAP with and without internal curing water (Fig. 9(b) and (c)), both images showed the similar sizes of SAP voids with no large unhydrated cement particles visible. Figure 9(d) shows mortar containing lightweight aggregate (LW-0.054) with lightweight aggregate particles highlighted. Mortar containing lightweight aggregate showed fewer unhydrated cement particles than the control, especially in close proximity to the lightweight aggregate particles. Although the dosage rate of lightweight aggregate was relatively low, the area of mortar internally cured by LW was difficult to distinguish compared to the general bulk paste. However, comparing unhydrated cement particles between mortars containing the same IC water dosage, LW-0.054 was not as efficiently cured by IC water as SP-0.054. The SEM image (Fig. 9(e)) of mortar containing DWTW (WT-0.054) also shows no unhydrated cement particles near the DWTW particles. Comparing the drinking water treatment particles shown in Fig. 9(e) with individual DWTW particle shown in Fig. 2(b), the DWTW particles in the hardened cement paste have a similar structure and size to the original single particles and did not deteriorate during mixing. Both images (Fig. 9(d) and (e)) containing the DWTW and LW show large calcium hydroxide platelets adjacent to the internal curing particles. Because no localized calcium hydroxide was observed in the SAP images (Fig. 9(b) and (c)), the water most likely leaves the SAP particles earlier in the hydration process than for the water physically held by the LW or DWTW, which corroborates the DOH results shown in Fig. 5 and 6.

**CONCLUSIONS**

The objective of this research was to perform a preliminary investigation into the potential for using high-moisture-content drinking water treatment waste sludge (DWTW) as an internal curing (IC) agent in concrete. For comparative purposes, two other common internal curing agents were investigated and included pre-wetted lightweight fine aggregate and a superabsorbent polymer. Based on the results of this experimental investigation, the following conclusions were drawn:

1. DWTW is a high-calcium waste material generated by drinking water treatment operations. The formation of DWTW flocs in water, combined with minimal dewatering, results in a material with a naturally high in-place moisture content. DWTW flocs individually have a porous microstructure with floc particle sizes ranging from 10 to 100 μm.

2. DWTW provided an increased degree of hydration (DOH) over the control mortar. The improvement on DOH of DWTW was comparable to the other internal curing agents investigated under a range of curing humidities and ages.
3. DWTW used as an internal curing agent in cement mortar mixture resulted in increased compressive strength at 7 and 28 days. Compared with two other common internal curing agents, superabsorbent polymers (SAPs) and pre-wetted lightweight fine aggregate (LW), DWTW showed comparable effect on compressive strength under sealed conditions. When cured at 100% RH, the DWTW samples had the greatest strength of all tested materials.

4. Mortar containing DWTW showed a 25% reduction in autogenous shrinkage versus the control group at 28 days. Shrinkage reduction was similar to mortar containing pre-wetted lightweight fine aggregate. SAP mortars with and without IC water had the greatest autogenous shrinkage reduction.

5. DWTW showed a similar effect on drying shrinkage as the other internal curing agents. Mortars containing internal curing agents showed overall higher drying shrinkage than the control group. Mortars containing DWTW showed greater total shrinkage than the control group, but less total shrinkage than mortars containing pre-wetted lightweight aggregate. Among the mixtures with the same amount of internal curing water, mortar containing DWTW showed less mass loss than mortar containing SAP and mortar containing pre-wetted lightweight aggregate.

6. Scanning electron microscope images of all samples under sealed condition showed all mortars containing internal curing agents had fewer unhydrated cement particles than the control.

7. Drinking water treatment waste is an effective internal curing agent and has similar performance to both the investigated superabsorbent polymer and pre-wetted lightweight fine aggregate. Because drinking water treatment waste is currently a globally available waste product that has a chemical composition similar to cement and contains sufficient moisture for internal curing without additional processing, the use of drinking water treatment waste in concrete has the potential to lower the CO₂ footprint and cost while improving concrete performance.

![Fig. 9—SEM images of mortars with different internal curing agents at 7 days under sealed curing condition.](image-url)
FUTURE RESEARCH

The research presented herein represents a preliminary investigation into the potential of using drinking water treatment waste for internal curing. Although the results were successful, much additional work will be required before wide-spread application is possible. The short-term research needs include an investigation into optimized dosage rates and effects on concrete properties. Long-term research needs include a durability investigation with much of the testing to coincide with performance for high-limestone cements.

AUTHOR BIOS

ACI member Qiwei Cao Nowasell is a Graduate Research Assistant and PhD Student at the University of Missouri-Kansas City, Kansas City, MO. She received her BS from Qingdao Technological University, Qingdao, Shandong, China, in 2009, and her MS from the University of Missouri-Kansas City in 2012. Her research interests include internal curing and concrete durability.

ACI member John T. Kevern is an Assistant Professor of civil engineering at the University of Missouri-Kansas City. He received his BS, MS, and PhD in civil engineering at the University of Wisconsin-Platteville, Platteville, WI, and Iowa State University, Ames, IA, in 2004, 2006, and 2008, respectively. He is a member of ACI Committees 120, History of Concrete; 130, Sustainability of Concrete; and 522, Pervious Concrete. He received the ACI Walter P Moore Jr. Faculty Achievement Award in 2012 and the ACI Young Member Award for Professional Achievement in 2013. His research interests include pervious concrete, sustainable construction using concrete, and green building.

ACKNOWLEDGMENTS

This project was funded by the University of Missouri Fast Track II program. The authors would like to thank WaterOne of Kansas City and Lafarge North America for providing materials. The assistance from Ash Grove Cement Company for assisting with scanning electron microscopy and chemical composition is much appreciated.

REFERENCES
