Reducing Curing Requirements for Pervious Concrete with a Superabsorbent Polymer for Internal Curing

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This paper presents the results of a research project to investigate reducing the need for curing pervious concrete under plastic by incorporating a superabsorbent polymer (SAP) normally intended for internal curing. Pervious concrete samples were produced with and without the SAP along with additional curing water. Compressive strength, unit weight, voids, and permeability testing was performed on hardened cylinders. Shrinkage was determined on beams for total and autogenous deformation with restrained ring testing. Moisture loss was determined with a modified version of the standard used to evaluate curing compounds, followed by rotary cutter surface abrasion. Field test sections were placed and cured under plastic or left open. The results show that mixtures containing the SAP had better workability and were stronger at equal void contents. The mixture containing the SAP had reduced shrinkage, moisture loss, and abrasion. After one winter, the uncured SAP field mixture had performance equal to the control mixture cured under plastic. Although preliminary, the results show that SAP has good potential to reduce curing requirements for pervious concrete under many environmental conditions.

Pervious concrete pavements are gaining more widespread use in the United States as stormwater best management tools for the quantity and quality improvements required by the National Pollutant Discharge Elimination System permits (*1*). The drawbacks for more widespread pervious concrete usage are the perceived lack of freeze–thaw durability, surface durability, concerns over clogging, and inexperience with construction best practices.

PERVIOUS CONCRETE DURABILITY

Freeze–thaw durability has been a primary concern preventing pervious concrete utilization in northern climates. In the early 2000s, many research projects were initiated to examine the freeze–thaw durability of pervious concrete mixtures and for improved mixture proportioning, including a MS thesis and PhD dissertation by the author (*2, 3*). Resulting research has shown that material-related freeze–thaw distress has not been readily observed for in-place pervious concretes and mixtures can be highly freeze–thaw durable in laboratory testing (*4, 5*). For pervious concrete to be freeze–thaw durable, a lower absorption coarse aggregate is desirable (<2.5%) (*6*). A small fraction of sand is needed to increase the paste or mortar thickness surrounding the coarse aggregate, improving load transfer and reducing stress between the aggregate particles (*7*). Sand addition of 5% to 7% of the total aggregate has been the single most important finding for improved freeze–thaw durability of pervious concrete. Although air entrainment is not easily measured on the fresh or hardened pervious concrete, air-entraining admixtures do produce a small amount of entrained air and show improved freeze–thaw durability (*8, 9*). Polypropylene or cellulose fibers or both are often included to reduce raveling and improve permeability (*10*). For pervious concrete, pavement construction practices have the greatest impact on ultimate durability, with distress commonly resulting from poor construction practices rather than incorrect mixture design or proportioning (*11*). Material-related freeze–thaw durability in the field has generally not been a problem even with deicer usage. However, the most common distress for pervious concrete is raveling of individual aggregate pieces from the surface, which can be exasperated by freezing and thawing, deicers, and plowing operations. Surface raveling is caused by poor mixture compaction or inadequate curing, leading to low-density, low-strength cementitious paste.

Durability and strength of pervious concretes are correlated to a designed void content and produced at a given unit weight, typically around 20% voids and 120 lb/ft^3 (1,920 kg/m^3). When a mixture is overcompacted, durability is good but permeability is poor. Likewise, when a mixture is undercompacted, the permeability is good but the durability is poor (*12*). Undercompaction may be caused by overmixing, which decreases water-reducer effectiveness and evaporation during transportation in hot weather. Delayed curing under plastic allows the surface concrete to dry and is also a common cause for poor surface durability (*13*). A variety of specialty admixtures and mixture designs are available to achieve proper density and acceptable durability with numerous examples of high-quality pervious concrete in most markets. Pervious concrete mixture proportioning has advanced to a point so that a pervious concrete wearing course overlay was constructed in Minnesota that is quiet (<95 dB) and has good permeability and durability (*14*).

Compaction is not a value typically associated with traditional concrete placement and lack of proper compaction has resulted in many poorly performing pervious concretes. Compaction is a function of both the mixture workability and the construction method. A highly workable pervious concrete mixture may require little additional compaction and achieve good strength and durability from hand placement, while a stiff mixture may require significant additional force to achieve the design void content (*15*). Typically a stiffer mixture is more difficult to place and slower to discharge from

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the delivery truck, resulting in more evaporation, loss of admixture effectiveness, and poorer durability. Along with appropriate material selection, sufficient workability is a fundamental requirement of durable pervious concrete.

INTERNAL CURING

The process of curing involves maintaining satisfactory moisture content and temperature after concrete is placed in order to hydrate the cement particles and produce the desired hardened concrete properties. Proper curing can improve strength, durability, abrasion resistance, resistance to freeze–thaw cycles, and deicer scaling resistance and reduce concrete shrinkage. Traditionally, concrete has been cured externally either through the use of water curing or sealed curing. Curing either supplies additional moisture from the original mixing water or minimizes moisture loss from the concrete. Water may be ponded directly on the concrete surface or other methods may be used, such as wet burlap bags or fogging near the surface of the concrete, to prevent evaporation of water from the fresh concrete. Sealed curing is accomplished by applying some sort of sealant to the surface of the concrete to prevent moisture loss (*16*). The water-permeable voids in pervious concrete eliminate water ponding as a curing option and prevent membrane sealing of the paste except for the immediate surface.

Internal curing (IC) can be divided into two categories. The first category is internal water curing in which an IC agent stores water during mixing, which is gradually released as hydration processes. The second category is internal sealing, which is similar to external sealed curing in that its goal is to prevent the loss of moisture from the concrete (*16*). The materials used for IC tend to fall into three categories. The first category is presaturated high-absorption aggregates, which slowly release water from the pores of the aggregate into the surrounding concrete. Aggregate saturation must be maintained during storage to realize full water storage potential. Presaturated lightweight fine aggregate is more effective at IC because the extra water is more evenly distributed throughout the paste than water supplied by saturated coarse aggregate. Because pervious concrete has little or no fine aggregate, there may not be enough storage potential to supply the required water for both improved hydration and maintaining elevated relative humidity. The second category is superabsorbent polymers (SAPs). The SAPs are either prehydrated or soak up water during the mixing process and slowly release the absorbed water back to the hydrating concrete. The third category encompasses the other materials not listed above, such as saturated clay and wood pulp. For concrete mixtures with little to no fine aggregate, such as pervious concrete, SAPs are an alternative method to provide IC.

PROJECT SIGNIFICANCE AND OBJECTIVE

The research results presented in this paper include moisture loss and shrinkage characteristics of a SAP applied to pervious concrete mixtures to help reduce curing requirements. The extra water held in pervious concrete by the SAP helps maintain a higher internal relative humidity. Eliminating the required plastic curing and improving surface durability will help transition pervious concrete from a specialty material to a product placed using more common construction techniques.

MIXTURE PROPORTIONS AND TEST METHODS

Concrete Mixture Proportions

The selected pervious concrete mixture is given below:

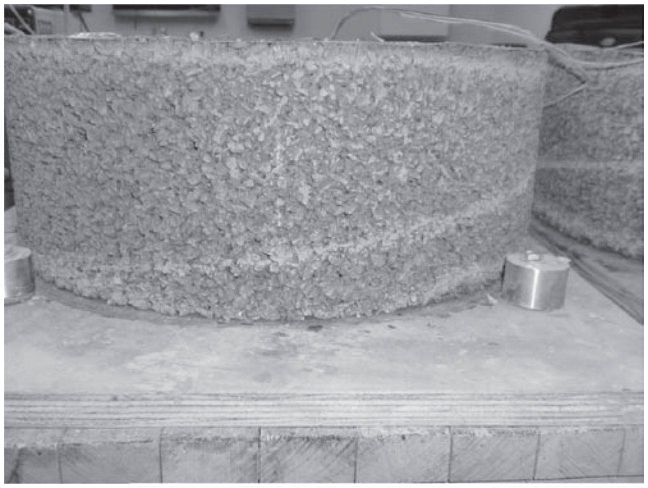
Composition	*lb/yd³ (kg/m³)*
Material	
Cement	255 (150)
Slag	180 (105)
C fly ash	75 (45)
Coarse aggregate	2,330 (1,380)
Fine aggregate	180 (105)
Fibers	1.5 (0.90)
Water	180 (105)
Property	
Design unit weight	118.3 (1,900)

Proportions are shown for correct yield at 22.5% design voids. The selected mixture contained crushed limestone with 100% passing the 3/8-in. (9.5-mm) sieve, 19% passing the No. 4 (4.75-mm) sieve, and 0% passing the No. 8 (2.35-mm) sieve. The limestone specific gravity was 2.63 with 1.8% absorption. The coarse aggregate is a commonly used clean Superpave® asphalt gradation. The fine aggregate was washed river sand conforming to ASTM C33 gradation. The binder-to-aggregate (b/a) ratio was 0.20 by mass, which is much lower than the recommended 0.24 for angular coarse aggregate (*2*). The lower cementitious materials content was selected to balance the volume of additional water added for IC with the desired void content. Admixtures included a standard vinsol resin air-entraining agent dosed at 2 oz per 100 lb (oz/cwt) (1 mL/kg) of cement, polycarboxylate water-reducing agent dosed at 4 oz/cwt (3 mL/kg), and a hydration-stabilizing admixture dosed at 8 oz/cwt (5 mL/kg). The SAP was dosed at 0.375% by weight of cementitious materials along with additional curing water following International Union of Testing and Research Laboratories for Materials and Structures recommendations (*16*). The amount of additional curing water was 28 lb/yd³ (15 kg/m³).

Superabsorbent Polymer

SAP is a crushed crystalline partial sodium salt of cross-linked polypromancic acid rated at 2,000 times absorption for pure water. The polymer is coated with blast furnace slag and ground silica to allow handling and prevent clumping of the gel during initial polymer hydration. The unhydrated polymer is angular with particle sizes ranging from 50 to 300 μm. Once the SAP hydrates, swells, and releases the stored water, the SAP becomes inert and is unable to rehydrate. Additional water is provided to the fresh concrete and the SAP is added dry. Absorption occurs during normal mixing.

The SAP used in this study is commercially available and marketed for pervious concrete and high-performance concrete. The effectiveness of the selected SAP as an IC agent has been previously demonstrated and complete testing results can be found in the MS thesis by Farney (*17*). A statistically significant increase in degree of hydration was observed for pervious concrete mortar samples. At 28 days, the degree of hydration for samples cured at 50% relative humidity was 45.8% for the control mixture and 53.0% for the mixture containing SAP and the additional curing water (*17*). Degree of hydration testing was determined by measuring nonevaporable water content at 950°C on straight cement specimens (*18*).



(a)

(b)

FIGURE 1 Pervious concrete ring shrinkage.

Mixing and Testing Methods

The concrete was mixed and cured according to ASTM C192. Concrete cylinders were placed at three compaction levels to define the compaction density relationship. The three levels included no compaction (CL1), two lifts with five drops from a height of 1 in. (25 mm) onto a concrete floor (CL2), and three lifts with 10 drops per lift (CL3). Compressive and splitting tensile strengths were determined on 4- × 8-in. (100- × 200-mm) specimens according to ASTM C39 and C496, respectively. Compressive strength samples were sulfur-capped before testing. Voids and unit weight were determined using the procedure developed by Montes et al. (*19*).

Total shrinkage was determined according to ASTM C596 on 3- × 4- × 16-in. (75- × 100- × 400-mm) concrete beams. Autogenous shrinkage measurement was performed with the same measurement procedure as ASTM C596. Pervious concrete autogenous shrinkage beams were wrapped in plastic film at 1 day and coated with paraffin wax. Testing began at 1 day. Beam weights were measured at all ages to ensure that no unattended moisture loss occurred. Restrained ring shrinkage was performed according to ASTM C1581. The void content of all shrinkage samples was fixed at 20% by preweighing a fixed amount of fresh concrete for each specimen. The restrained ring testing setup is shown in Figure 1.

Concrete moisture loss was determined according to the ASTM C156 test procedure used for membrane-forming curing compounds. Moisture loss samples were 9 × 13 × 2 in. (230 × 330 × 50 mm). Because evaporation of bleed water is not measurable on pervious concrete, fresh unit weight was determined and the samples were immediately placed in an environmental chamber at 100°F (38°C) and 32% relative humidity. Mass loss was measured at 24-h intervals for 3 days. Surface abrasion was determined on samples after moisture loss testing according to ASTM C944 (Figure 2). Abraded material was vacuumed from the surface between tests to determine mass loss per test.

All tests for significance were analyzed using paired *t*-tests with $\alpha = 0.05$. All data tested were normally distributed.

RESULTS AND DISCUSSION

The cylinder testing results are shown in Table 1. All values represent the average of three specimens with coefficient of variation less than 15% for all tests. A linear compaction density relationship was developed with the three compaction levels for the mixtures with and without the SAP, as shown in Figure 3. The reported unit weight represents oven-dry specimens tested after curing for 7 days. The low paste content resulted in high aggregate-to-aggregate contact and generally poorer workability than would be desirable in the field. The SAP mixtures were noticeably more workable from the additional water absorbed in the polymer. The increased workability resulted in denser samples at the same level of compaction.

The compressive strength relationship for the different compaction levels is shown in Figure 4. The linear best-fit lines are shown for the mixture with SAP (dashed) and without SAP (solid). The R^2 relationships for the best-fit lines were greater than .94. For a given void content, the mixture containing the SAP was stronger than the mixture without. Although the void content was not fixed for the compaction density samples, the relatively low unit weight and

FIGURE 2 Abrasion testing on pervious concrete beam.

TABLE 1 Hardened Concrete Testing Results

Sample	Void (%)	Unit Weight, lb/ft^3 (kg/m^3)	Compressive Strength, psi (MPa) 7 days	Compressive Strength, psi (MPa) 28 days	Splitting Tensile Strength, psi (MPa) 28 days
Control CL1	41.7	100 (1,560)	630 (4.3)	870 (6.0)	120 (0.9)
Control CL2	40.0	100 (1,610)	960 (6.6)	1,170 (8.0)	140 (1.0)
Control CL3	36.4	105 (1,700)	1,240 (8.5)	1,370 (9.4)	190 (1.3)
SAP CL1	41.6	95 (1,560)	8,230 (5.7)	1,160 (8.0)	150 (1.0)
SAP CL2	34.0	110 (1,715)	1,330 (9.2)	1,840 (12.7)	200 (1.4)
SAP CL3	31.2	110 (1,790)	1,730 (11.9)	2,060 (14.2)	250 (1.7)

correspondingly high void content suggest that further mixture optimization is needed to increase the paste content and create a denser, more workable mixture.

Shrinkage Behavior

The total and autogenous shrinkage results for the pervious concrete beams are shown in Figure 5. Each point represents the average of three specimens. Coefficient of variation was less than 15% for all shrinkage specimens. As expected, the measured autogenous shrinkage on both samples was very low. The low water–cement mortar in pervious concrete undergoes significant autogenous shrinkage; however, the primarily coarse aggregate-on-coarse aggregate contact in the concrete resists shrinkage. The significant void spaces also allow for the coating paste to shrink without building up stress on the concrete sample. However, total shrinkage was observed and was larger than the measured autogenous shrinkage for both the control and SAP mixtures. The SAP mixture had significantly less shrinkage at all ages except 3 and 28 days.

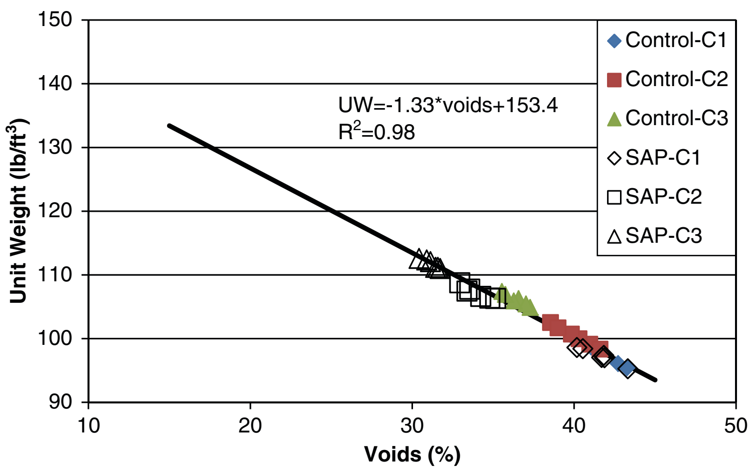


FIGURE 3 Compaction density relationships for mixtures with and without SAP (UW = unit weight).

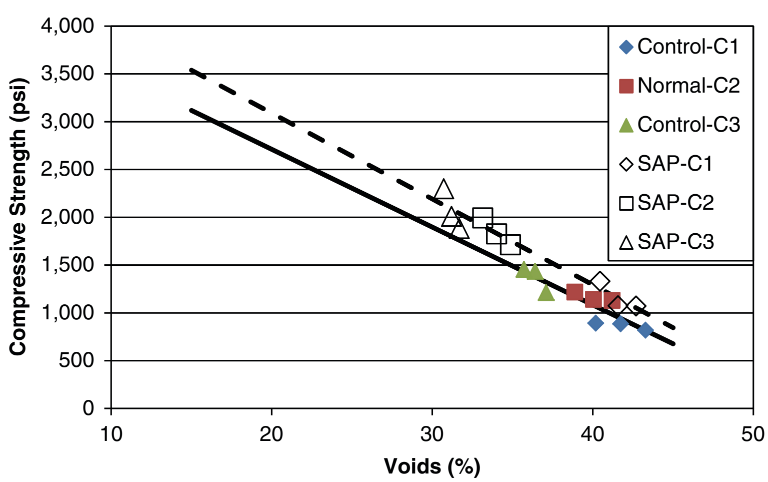


FIGURE 4 Twenty-eight-day compressive strength relationship for both mixtures.

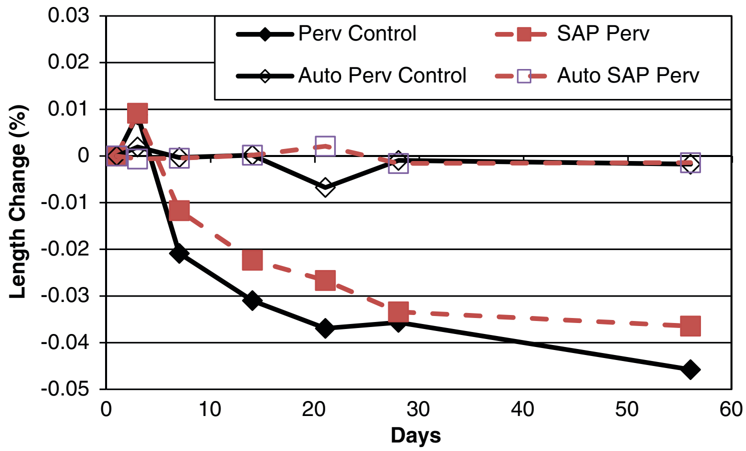


FIGURE 5 Total and autogenous shrinkage results (perv = pervious).

The restrained ring shrinkage results are shown in Figure 6 for the average of two rings for each mixture. All rings of the same concrete mixture achieved maximum strain within 12 h of each other. The average control sample crack occurred at 111 h (4 days 15 h) and 21.9 microstrain, while the SAP samples cracked at 147 h 15 min (6 days 3 h) and 26.9 microstrain. Maximum tensile stress in the concrete on cracking was determined using the equation provided by Hossain and Weiss (*20*). The maximum tensile stress in the control pervious concrete at cracking was 214 psi (1.5 MPa). Residual stress was determined by using the average strain from 240 h until the test was completed. The residual stress for the control mixture was 98 psi (0.7 MPa), a 54% reduction from the peak value. The maximum tensile stress in the SAP pervious concrete at cracking was 263 psi (1.8 MPa). The residual stress for the SAP mixture was 166 psi (1.1 MPa), a 37% reduction from the peak value. All samples retained some residual capacity, which is consistent with traditional fiber-reinforced concretes (*21*).

Moisture Loss and Durability

Moisture loss for the concrete samples was determined in an environmental chamber at 100°F (38°C) and 32% relative humidity. The results for moisture loss testing are shown in the following table:

	Mass Loss (kg/m²)		
Sample	*24 h*	*48 h*	*72 h*
Control	3.63	4.02	4.23
SAP	3.50	3.90	4.16
SAP-IC water	1.49	1.89	2.14

Data represent an average of three samples. The standard deviation varied from 0.22 to 0.28 kg/m² with coefficient of variation around 6% for all samples. The moisture loss results are shown in Figure 7. Moisture loss from the control pervious concrete mixture and the mixture containing the SAP, including mass of the extra water, were statistically the same. The data shown by the dashed line were calculated assuming that the extra water added with the SAP was an evaporable admixture. In the second case, the extra water can be considered sacrificial water for evaporation and elevation of the relative humidity. Because the extra water added with the SAP did not result in additional moisture loss and the rate of moisture loss was similar between the samples with and without SAP, additional hydration may have occurred. Increased degree of hydration is consistent with IC provided by SAP.

After moisture loss testing, the dried samples were subjected to rotary cutter abrasion using ASTM C944 as shown in Figure 2. The following table shows the abrasion mass loss results average data for nine tests, three tests on each of the three moisture loss samples.

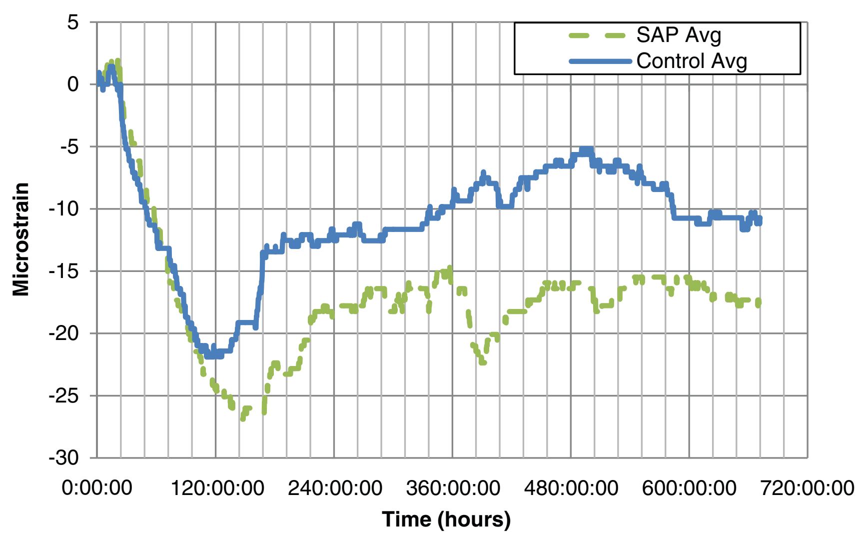


FIGURE 6 Restrained ring shrinkage results (avg = average).

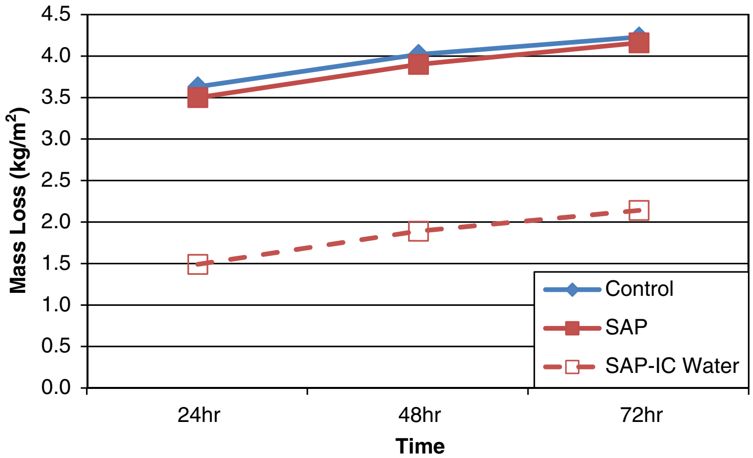


FIGURE 7 Moisture loss results.

The abrasion mass loss results were much higher than reported for normally cured pervious concrete because of the relatively severe conditions used for moisture loss testing (*22*). The SAP samples had significantly better performance with $p < .001$.

Sample	*Average Mass Loss (g)*	*Standard Deviation (g)*	*Coefficient of Variation (%)*
Control	83.5	27.7	33.1
SAP	68.0	24.7	36.4

Field Durability

A pervious concrete test placement was conducted with the use of mixtures with and without SAP on September 22, 2010. Sections were placed by mixtures with and without SAP. Sections of both mixtures were cured with and without plastic sheeting. For the plastic-cured sections, curing materials were left in place for 7 days. Fresh concrete was placed using a skid-steer bucket. The SAP mixture was much more workable than the control mixture. The improved workability of the SAP mixture allowed finishing to be performed with a straight edge for form elevation (Figure 8), with the final surface created with a standard bull float (Figure 9). The control mixture was finished with a hydraulic roller-screed. The hand placement was a relatively slow process, taking about 90 min to discharge the 6 yd^3 of concrete used for each section. It was observed that the workability of the SAP mixtures was much the same at the end of the load as at the beginning of placement, while the control mixture stiffened noticeably throughout the placement. Winter maintenance was typical and included plowing and power-brooming to remove snow along with deicer applications. After one winter, all sections are in good condition; the only observation is that the sections cured under plastic have some remaining surface marking from curing.

CONCLUSIONS

This study investigated the use of an SAP in a pervious concrete mixture to reduce the need for curing under plastic. The results show that the investigated SAP is effective in pervious concrete and has the potential to eliminate plastic curing in many situations. Specific results from the study include the following:

FIGURE 8 SAP mixture: striking off with straight edge.

FIGURE 9 SAP mixture: finishing with bull float.

- The extra water carried by the SAP produced a more workable pervious concrete mixture without the paste clogging the water-permeable pores.
- At equal void contents, the mixture containing the SAP was stronger.
- The SAP mixture had less unrestrained total shrinkage.
- The SAP mixture developed higher strains before cracking in restrained ring shrinkage testing, had delayed time to cracking, and had a higher percentage of residual strength than the control mixture.
- The SAP mixture retained the same amount of water as the control, even though additional water had been included in the mixture.
- During a field placement, the SAP mixture was workable enough for hand placement.
- After one winter, the SAP mixture cured in open air had durability similar to the control mixture cured under plastic for 7 days.

FUTURE RESEARCH

Because both field test sections had good performance after one winter, either cured under plastic or left open, an additional set of lower durability mixtures should be placed. A second field placement is recommended with less cementitious material or in harsher weather conditions to create a range of durability responses. Further investigation is needed into the void cavities left behind when the SAP dries. Laboratory research has shown that pervious concrete can have air entrainment (*8*), but field placements show low levels (*9*). SAP may be an effective method to introduce void space into stiff concretes.

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REFERENCES

1. Tennis, P. D., M. L. Leming, and D. J. Akers. *Pervious Concrete Pavements.* EB302, Portland Cement Association, Skokie, Ill., and National Ready Mixed Concrete Association, Silver Spring, Md., 2004.
2. Kevern, J. T. *Mix Design Determination for Freeze–Thaw Resistant Portland Cement Pervious Concrete.* MS thesis. Iowa State University, Ames, 2006.
3. Kevern, J. T. *Advancements in Pervious Concrete Technology.* PhD dissertation. Iowa State University, Ames, 2008.
4. Delatte, N., D. Miller, and M. Mrkajic. *Portland Cement Pervious Concrete: Field Performance Investigation on Parking Lot and Roadway Pavements.* Final Report of the RMC Research and Education Foundation, Silver Spring, Md., 2007. http://www.rmc-foundation.org/newsite/images/Long%20Term%20Field%20Performance%20of%20Pervious%20Final%20Report.pdf.
5. Kevern, J. T., V. R. Schaefer, K. Wang, and M. T. Suleiman. Pervious Concrete Mixture Proportions for Improved Freeze–Thaw Durability. *Journal of ASTM International,* Vol. 5, No. 2, 2008. DOI:10.1520/JAI101320.
6. Kevern, J. T., K. Wang, and V. R. Schaefer. The Effect of Coarse Aggregate on the Freeze–Thaw Durability of Pervious Concrete. *Journal of Materials in Civil Engineering,* Vol. 22, No. 5, 2010, pp. 469–475.
7. Wang, K., V. R. Schaefer, J. T. Kevern, and M. T. Suleiman. Development of Mix Proportion for Functional and Durable Pervious Concrete. *Proc., 2006 NRMCA Concrete Technology Forum–Focus on Pervious Concrete,* Nashville, Tenn., 2006.
8. Kevern, J. T., K. Wang, and V. R. Schaefer. A Novel Approach to Determine Entrained Air Content in Pervious Concrete. *Journal of ASTM International,* Vol. 5, No. 2, 2008. DOI: 10.1520/JAI101434.
9. Kevern, J. T., K. Wang, and V. R. Schaefer. Test Methods for Characterizing Air Void Systems in Portland Cement Pervious Concrete. *Journal of ASTM International: Selected Technical Papers STP 1511 Recent Advancements in Concrete Freezing and Thawing (FT) Durability,* Vol. 6, No. 9, 2009.
10. Kevern, J. T., V. R. Schaefer, and K. Wang. Mix Design Development and Performance Evaluation of Pervious Concrete for Overlay Applications. *ACI Materials Journal,* Vol. 108, No. 4, 2011, pp. 439–448.
11. Kevern, J. T., and J. Montgomery. Hitting the Targets: A Case Study of a Pervious Concrete Quality Assurance Program. *ACI Concrete International,* March 2010.
12. Kevern, J. T., K. Wang, and V. R. Schaefer. Pervious Concrete in Severe Exposures: Development of Pollution-Reducing Pavement for Northern Cities. *ACI Concrete International,* July 2008, pp. 43–49.
13. Kevern, J. T., K. Wang, M. T. Suleiman, and V. R. Schaefer. Pervious Concrete Construction: Methods and Quality Control. *Proc., 2006 NRMCA Concrete Technology Forum–Focus on Pervious Concrete,* Nashville, Tenn., 2006.
14. Schaefer, V. R., J. T. Kevern, B. Izevbekhai, K. Wang, H. Cutler, and P. Wiegand. Construction and Performance of Pervious Concrete Overlay at Minnesota Road Research Project. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2164,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 82–88.
15. Kevern, J. T., K. Wang, and V. R. Schaefer. Evaluation of Pervious Concrete Workability Using Gyratory Compaction. *American Society of Civil Engineers Journal of Materials in Civil Engineering,* Vol. 21, No. 12, 2009, pp. 764–770.
16. International Union of Testing and Research Laboratories for Materials and Structures (RILEM). *Internal Curing of Concrete.* State-of-the-Art Report of RILEM Technical Committee 196-ICC. RILEM Publications SARL, Paris, 2007.
17. Farney, C. The Use of Superabsorbent Polymer in Standard and Pervious Concrete. MS thesis. University of Missouri–Kansas City, 2011.
18. Bentz, D., X. Feng, C. Haecker, and P. Stutzman. *Analysis of CCRL Proficiency Cements 135 and 136 Using CEMHYD3D.* National Institute of Standards and Technology Internal Report 6545, Aug. 2000.
19. Montes, F., S. Valavala, and L. M. Haselbach. A New Test Method for Porosity Measurements of Portland Cement Pervious Concrete. *Journal of ASTM International,* Vol. 2, No. 1, 2005.
20. Hossain, A. B., and W. J. Weiss. Assessing Residual Stress Development and Stress Relaxation in Restrained Concrete Ring Specimens. *Cement and Concrete Composites,* Vol. 26, No. 5, 2004, pp. 531–540.
21. Tritsch, N., D. Darwin, and J. Browning. *Evaluating Shrinkage and Cracking Behavior of Concrete Using Restrained Ring and Free Shrinkage Tests.* The Transportation Pooled Fund Program, Project TPF-5(051), Structural Engineering and Engineering Materials SM Report 77, The University of Kansas Center for Research, Inc., Lawrence, Kans., Jan. 2005.
22. Kevern, J. T., V. R. Schaefer, and K. Wang. The Effect of Curing Regime on Pervious Concrete Abrasion Resistance. *Journal of Testing and Evaluation,* Vol. 37, No. 4, 2009, pp. 337–342.

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