Can Soy Methyl Esters Improve Concrete Pavement Joint Durability?

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ABSTRACT

While many concrete pavements provide excellent long-term performance, some pavements (primarily in the Midwest) have shown premature deterioration at the joints. This premature deterioration is a concern since it can shorten the life of a pavement that is functioning well otherwise. Previous work has hypothesized that these joints may be susceptible to preferential fluid saturation which can lead to freeze-thaw damage or chemical degradation. This work examines the use of soy methyl ester polystyrene blends (SME-PS) as a method to reduce the rate of fluid ingress into the pore system of the concrete, thereby making the concrete more resistant to deterioration. SME-PS are derived from soy beans and have demonstrated an ability to reduce fluid absorption in concrete when SME-PS is used as a topical treatment. A series of experiments were developed to evaluate the effectiveness of various dosage rates of SME-PS for increasing concrete durability at pavement joints. Experiments show that SME-PS reduces fluid ingress, reduces salt ingress and reduces the potential for freeze-thaw damage. As a result of the positive experimental results, the INDOT is currently conducting field trials that use SME-PS on concrete pavements that are beginning to show signs of premature deterioration with the expectation that SME-PS will extend the life of the joint, thereby reducing maintenance costs and extending the life of the concrete pavement.

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1.0 BACKGROUND ON JOINTS IN CONCRETE PAVEMENTS

The premature deterioration of concrete pavement joints is a concern since it compromises the performance and potential service life of an otherwise healthy pavement. This damage manifests itself as either the development of cracking parallel to the joint or cracking from a softened region that develops along one side of the bottom of the saw cut to the surface of pavement approximately 4 to 6 inches (100 to 150 mm) from the joint. During field inspections it has been observed that where the joints have shown signs of damage the joint sealant is also damaged and the joint contained standing fluid (the fluid contains water and deicing salts).

Figure 1 illustrates a typical D-1 pavement construction joint that is used in the state of Indiana. A three step process is used to create the joint. First, shortly after the pavement is cast, a saw-cut is placed in the pavement to 1/3 of the pavement depth to control random cracking (1, 2). This joint typically causes a crack to form directly below the saw cut. After the first saw-cut is placed, a second cut is placed (approximately 1 inch (25 mm) deep and 1/2 inch (12 mm) wide) to widen the saw-cut near the surface. By allowing the pavement to crack and open before the second cut is placed the joint width can be made more uniform from panel to panel creating a more stable geometry for the joint sealant. The third step involves placing a backer rod in the joint to keep the sealant at the top of the joint. A joint sealant is placed on top of the backer rod and the joint sealant adheres to both sides of the widened saw cut. The sealant is thought to be necessary by some DOT's to keep water and incompressible materials out of the joint; however other DOT's have used unsealed joints (3-8). Silicon is a typical material for sealing joints.

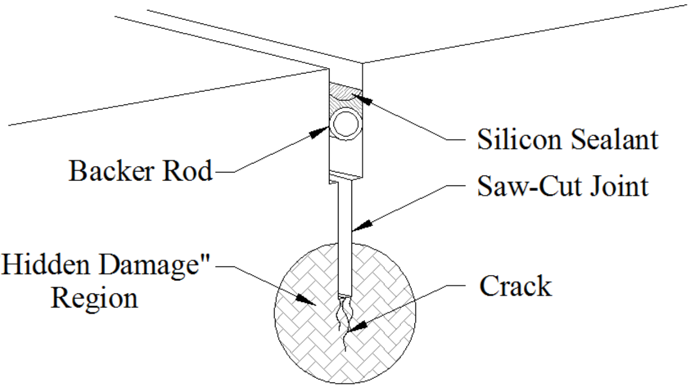


FIGURE 1 Typical D-1 contraction joint (9).

If the joint sealant remains intact, it will keep water and solutions containing deicing salts out of the joint. However, this sealant frequently becomes damaged and the geometry of pavement joints provides a place for fluid to collect. This fluid will be absorbed by the concrete and can lead to saturation which can result in freeze thaw damage (10). Ironically, while the damaged joint sealant may not prevent fluid from getting into the crack, it will reduce the potential for water evaporation from the joint thereby increasing the potential for saturation.

2.0 JOINT SEALENT VS CONCRETE SEALANT

While the previous section describes the conventional concrete joint and sealer used in Indiana, this work also considers the potential for using topical application with a fluid (concrete sealer) that penetrate the pores of the concrete. In this work a distinction will be made between the joint sealant (like a silicon shown in Figure 1) which forms a physical barrier on the surface of the concrete, with concrete sealants (referred to as topical applications) where a fluid is absorbed into the pore system creates a hydrophobic or blocking layer which inhibits the ingress of water. It should be noted that unlike the joint sealants, the penetrating topical applications do not have the ability to keep incompressible objects out of the joints.

3.0 EXPERIMENTAL PROGRAM OVERVIEW

Recent research has shown the potential for using plant-oil based products as concrete topical applications (11-13). One of these products is Soy Methyl Ester (SME). SME also has the potential to be both an effective and environmentally friendly topical treatment for concrete. Previous research has shown that when concrete is treated with SME or Soy Methyl Ester-Polystyrene Blends (SME-PS) the water absorption is reduced (14). The focus of this research is evaluating the effectiveness of SME-PS at increasing the durability of concrete, especially in a freeze-thaw environment. This work examines the influence of SME-PS for reducing water absorption, freeze-thaw durability, and the ingress of chlorides ions. To provide a point of reference the SME-PS is compared with other topical applications for concrete that may be used in this type of application. An overview of the testing program can be seen in Table 1 along with the relevant ASTM standards.

TABLE 1 Testing Program Overview

Test Description	Test Methods	Mixtures*	Topical Application (Concrete Sealant)
Influence of PS on SME Penetration	Volumetric and Visual Observation	C40 & M42	SME SME-PS (M_W 2,400) SME-PS (M_W 44,000) SME-PS (M_W 382,100)
Water Absorption	ASTM C1585	M42	SME – PS (2 doses**) Solvent Based Silane Water Based Silane
Concrete Freeze-Thaw Durability	ASTM C666 (Procedure A)	M45	SME – PS (2 doses**) Solvent Based Silane
Durability of Sealers under Freezing and Thawing Conditions	ASTM C1585 after ASTM C666	C40	SME – PS (2 doses**) Solvent Based Silane Water Based Silane
Chloride Ingress	Visual Observation using $AgNO_3$	M42	SME – PS (2 doses**) Solvent Based Silane Water Based Silane

* Mixture proportions defined in Table 2

** Varying dosages of SME-PS were applied utilizing different SME-PS exposure times

3.1 Mixture Proportions

One concrete mixture and two mortar mixtures were used in this study. The concrete was prepared with a *w/c=0.40* with 28 % fine aggregate and 38 % coarse aggregate by volume). The mortars were prepared with 55 % fine aggregate by volume and with water-to-cement ratios (*w/c*) of 0.42 and 0.45. A complete list of mixture proportions can be found in Table 2 details on the constituent materials are available in (13).

TABLE 2 Mixture Proportions in SSD Condition

Material	C40	M42	M45
Cement (kg/m^3)	316	609	586
Fly Ash – Class C (kg/m^3)	60	-	-
Water (kg/m^3)	150	256	264
Fine Aggregate (kg/m^3)	736	1444	1444
Coarse Aggregate (kg/m^3)	1049	-	-
Air Entraining Admix. (ml/100 kg cem.)	20	-	-
Retarder Admix. (ml/100 kg cem.)	98	-	-
HRWRA (g/100g cem)	0.5	-	-

3.2 Topical Treatments for Concrete (Penetrating Sealers)

During this testing program, samples were tested both with and without topical treatments. Three different topical treatments were tested. The first is Soy Methyl Ester (SME) blended with 5 % polystyrene (PS) by mass. The results from the SME-PS treated samples were compared to two commercially available silane sealants. The first is a solvent-based alkyalkoxysilane sealer (SBS) with greater than 50 % active ingredients. This sealant is a solution of silane dissolved in an isopropanol solvent. The second commercially available sealer is a water-based alkyalkoxysilane penetrating sealer (WBS) that consists of 40 % silane. This sealant is an emulsion of silane in water. The goal of evaluating the SME-PS along with other topical treatments is to provide a point of reference as this research is early in the understanding of how SME-PS performs. It should be noted that no attempt was made to optimize any of the topical treatment applications in this study and more work is likely needed in this area to test additional topic treatments and additional application approaches to provide the DOTs with a variety of approaches that can improve pavement joint performance if this concept is successful.

4.0 PENETRATION OF SME-PS INTO CONCRETE

It is important to understand how SME-PS behaves when it is applied to the concrete. The first step in this study was determining the influence of various factors on the penetrability of SME. Specifically being studied are the influence of concrete moisture, size of the polystyrene molecules, and time the SME is allowed to penetrate into the concrete.

4.1 Influence of Concrete Moisture on SME Penetration

The influence of concrete moisture on SME penetration was tested on concrete samples. A series of 100 mm × 200 mm cylinders were cast of mixture C40. After 24 hours the cylinders were demolded and sealed in double plastic bags at 23 ± 0.5 °C until the samples reached an age of 28 d. After 28 d of curing the cylinders were removed from bags and three 50 mm ± 2 mm thick samples were cut from the central portion of each cylinder with a wet saw. After cutting, samples were placed in environmental chambers at 23 ± 0.5 °C and at three different relative humidities (50 ± 1 %, 65 ± 1 % and 80 ± 1 %) for 18 months before testing.

After the 18 months, the sides of the sample were sealed with epoxy. A plastic mold was placed around the top of the sample to prepare a dam. The edge between the plastic mold and the concrete sample was sealed using silicone, which was allowed to dry for 24 h. The mass of the samples was then recorded. Approximately 20 g of SME sealant were placed in the dam. After 48 h, the additional sealant was removed from the dam and the mass of the sample was recorded. Figure 2 shows both the absorption of sealant or water after 48 h. Three samples were used for each condition. The samples were then cut vertically using a wet saw, for a direct visual measurement of the sealant penetration. It can be observed that the moisture content of the samples has a high influence in the penetration of the sealant. Samples conditioned to a lower relative humidity have more open pore space where water was lost during drying.

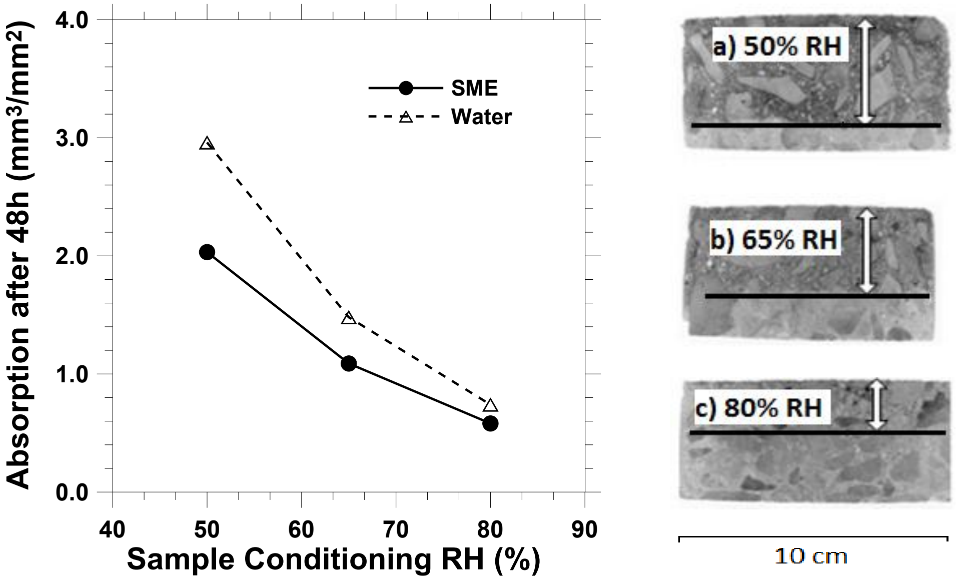


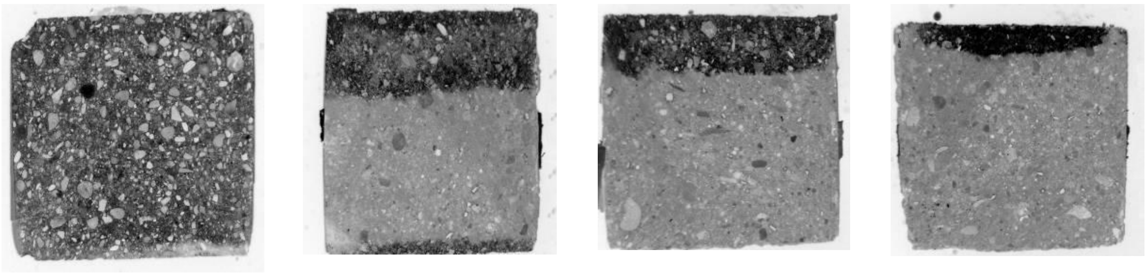
FIGURE 2 Volumetric and Visual observation after 48 h of SME penetration (from top) into concretes with different levels of saturation. SME penetration is highlighted in black. Sample cross-section is 5 cm by 10 cm.

4.2 Influence of Polystyrene Chain Length on SME Penetration

Although SME appears to have positive performance by itself, its high solvent capacity enables it to be blended with polymers such as polystyrene (11). By blending the SME with PS (or other materials), it may be possible to tailor the properties of the solution for a specific need (14). Another benefit of using a SME-PS blend is that the waste polystyrene, which otherwise would be put in a landfill, can be used to extend the material and may remain in the pores as a 'blocking material'. If waste PS is to be used, it is important to understand how different sources of polymer would affect the final product. In this study, the impact of the polystyrene (PS) chain length on sealant penetration was tested by varying the molecular weight of the polystyrene.

Penetration of SME sealants blended with PS of different size polymer chains was tested on mixture M42, which were cast on 35 mm x 300 mm cylinder molds, where they were kept until the age of 28 d. Then, samples were demolded and 50 mm ± 2 mm thick samples were cut from the central portion of each cylinder with a wet saw. After cutting, samples were conditioned by placing them in environmental chambers at 23 ± 0.5 °C and 65 ± 1 % relative humidity for 8 months to allow them to equilibrate before testing.

After the 8 months, the sides of the sample were sealed with epoxy. After the epoxy had hardened, aluminum tape was placed around the sample to prepare a dam. The edge between the aluminum tape and the mortar samples was sealed using silicone, which was allowed to dry for 24 h. The mass of the samples was then recorded. 5 g of sealant was placed on the dam and allowed to absorb. In this experiment four SME-PS blends were tested: No PS (pure SME), M_W 2,400 PS, M_W 44,000 PS, and M_W 382,100 PS. Each of these molecular weights corresponds to the chain length of the polystyrene molecules. Each of the SME-PS blends was prepared with 5 % PS by mass. After 48 h, the sealant was carefully removed and samples were cut vertically using a wet saw, for a direct visual measurement of the sealant penetration (Figure 3). Results show that the presence of PS influenced the ability of the sealer to penetrate the samples. As the molecular weight of the PS increases the penetration depth of the sealer decreases.

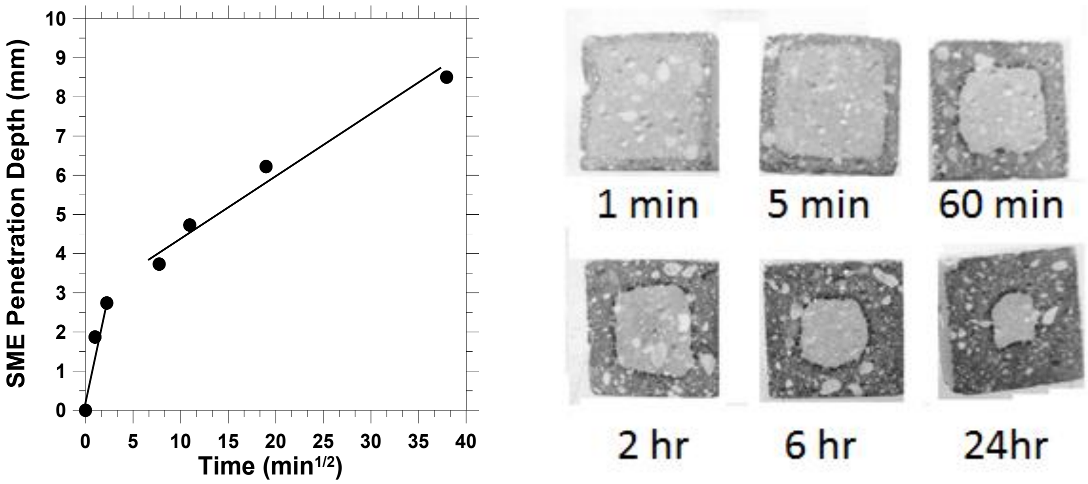


a) SME Only b) M_W 2,400 c) M_W 44,000 d) M_W 382,100

FIGURE 3 Penetration depth of SME-PS blends highlighted in black (penetrating from top surface only). Each sample was treated with a SME-PS blend prepared with polystyrene of various chain lengths. Samples are 35 mm by 50 mm in cross-section.

4.3 Influence of Time on SME Penetration

This test investigated the effect of role of time on the penetration depth of SME-PS. To perform this study, six 2.5 cm x 2.5 cm x 10 cm prisms of mixture M42 were prepared. These samples were demolded at 24 h and allowed to dry at 23 ± 1°C and 50 ± 2 % RH for seven days prior to being submerged in SME-PS containing a fluorescent dye (0.5% by mass). At certain time intervals the samples were removed from the solution. These samples were cut with a small wet saw and photographed under an ultraviolet light to determine the penetration depth of the SME-PS. Both images of the SME-PS penetration and a graphical display of penetration depth over time can be seen in Figure 4. The penetration depth shows a square root of time dependence with two rates, an initial faster absorption rate which appears to slow over time.

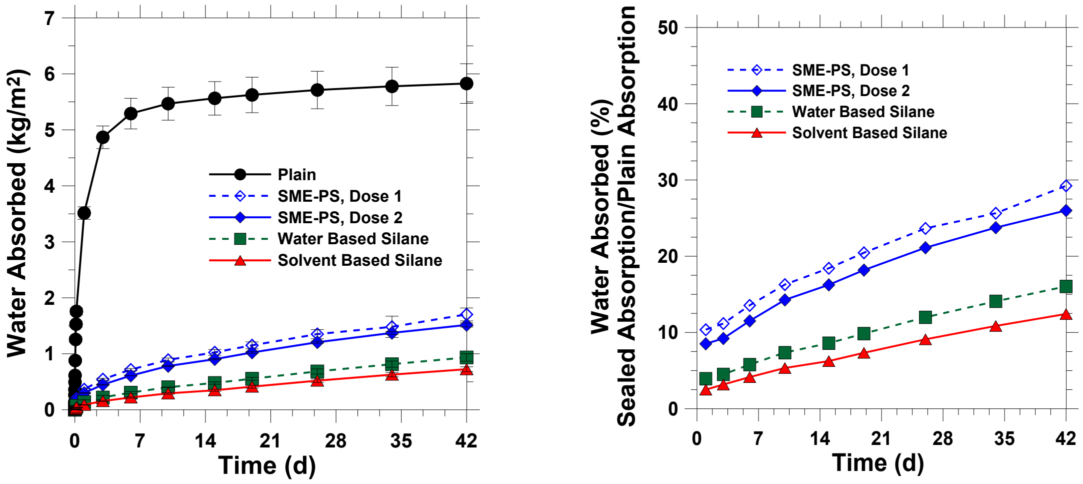


a) b)

FIGURE 4 Penetration of SME into 2.5 cm square samples: a) penetration depth vs. time, b) SME-PS highlighted in black as a function of time.

5.0 WATER ABSORPTION

The ability of the topical treatment to minimize water absorption into concrete was measured using ASTM C1585 (15). The topical treatments being tested are SME-PS (2 dosages), SBS, and WBS. Samples were prepared as 100 mm x 200 mm cylinders of mixture M42. Samples were demolded at 24 h and sealed in a double plastic bag for 14 d. At this time each cylinder was cut into three 5 cm tall discs. The top and bottom 2.5 cm of the cylinder was discarded. The cylinders were allowed to condition at 23 ± 1°C and 50 ± 2 % RH for 6 month prior to the application of the sealants. SME-PS was applied to cylinders by submerging the exposed face in the SME-PS for 6h (dose 1) and 24 h (dose 2). The SBS and WBS were applied evenly with a paint brush on the exposed surface. Results of the water sorption test can be found in Figure 5.



a) b)

FIGURE 5 Water absorption experimental results: a) water absorbed (Error bars represent +/-1 standard deviation), b) reduction in water absorption. (Average of three samples)

The application of each of the topical treatments tested resulted in a substantial reduction in the amount of water absorbed into the samples. Both silane sealants were more effective at reducing water absorption than the SME-PS.

6.0 FREEZE-THAW DURABILITY

When concrete contains water the concrete can be susceptible to reaching a critical level of saturation which can lead to freeze-thaw damage (10, 16). This potential for degradation may be increased when the water contains aggressive ions such as chlorides (17). A common method for improving the freeze-thaw durability of concrete is through the use of air entraining admixtures (AEA) (16). One alternative method for improving freeze/thaw durability of concrete may be to use topical treatments which would help to reduce the potential for saturation by reducing the rate of water penetration (Figure 5). It should be noted that a sealer only protects the concrete from fluid ingress from the surface, however it does not prevent possible water coming from under the slab.

6.1 Cold Weather Behavior of SME-PS

SME is a solution of different fatty acid methyl esters (FAME) which begin to lose their solubility and come out of solution at a critical temperature. This results in a second solid phase forming in the solution. For SME these solids are conglomerations of waxy crystals that will give the solution a cloudy appearance. The temperature at which this first occurs is known as the cloud point. For SME, this value is typically accepted as 0 °C (18, 19). The cloud point of SME-PS with 5 % and 10 % PS was measured to be 5 °C according to ASTM D2500 (20). As the temperature continues to drop below the cloud point, more of the FAMEs will come out of solution and precipitate into waxy solids. Eventually there will be enough solidification that the solution will lose its ability to flow like a liquid. At this point, known as the pour point, SME becomes a gel-like substance. This temperature is typically accepted as -4°C (19). These cold flow properties of SME are a major limitation for using these materials as an alternative fuel source (18) since the waxy solidifications in the SME will clog filters within the fuel system. In terms of concrete, the solidified SME would clog the pores of the concrete, presumably further reducing fluid ingress.

6.2 Concrete Freeze-Thaw Durability

The freeze-thaw of the topical treatments was tested using ASTM C666A (freezing and thawing in water) (21). Samples were prepared from mixture M45. The samples were demolded after 24 h and sealed in double plastic bags for 60 d. After this time the samples were opened and allowed to dry at 23 °C and 50 % RH for 10 d. At this time sealants were applied. The SME-PS was applied by submerging the samples in the sealant for 6 h (dose 1) and 24 h (dose 2). The solvent based silane was applied in an even coating with a paint brush. Prior to starting testing, sealants were allowed to cure for 7 d and then samples were submerged in saturated lime water for 48 h. The relative elastic modulus can be seen in Figure 6.

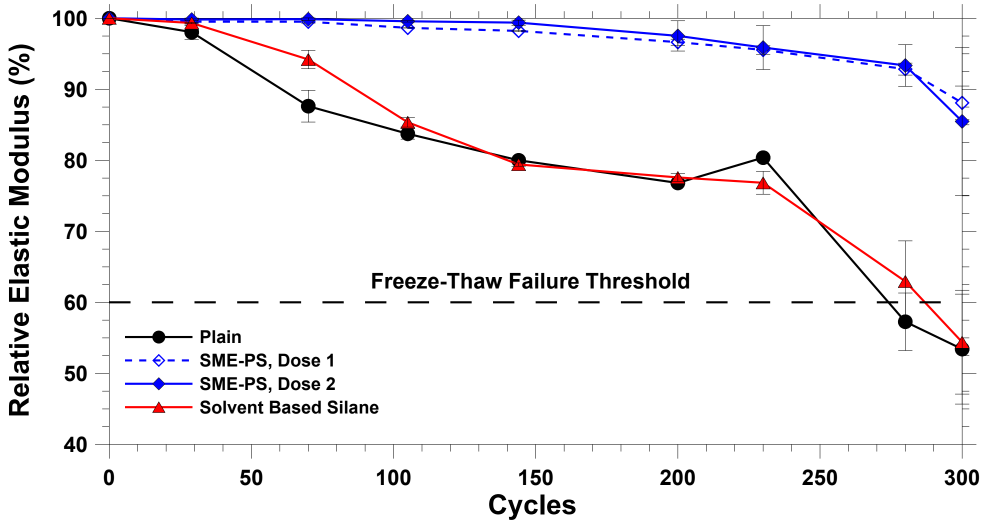


FIGURE 6 Freeze-Thaw experimental results, relative elastic modulus.

Use of the solvent based silane sealant slowed the effects of freeze-thaw damage during the first 100 cycles. Prior to 100 cycles, samples treated with the SBS received 50 % less damage than untreated samples. After 100 cycles the both the SBS treated and untreated samples were at the same level of damage. After 75 cycles the cover of the untreated and SBS began to spall and its mass was reduced (Figure 7). The use of SME-PS sealant was less susceptible to damage from freezing and thawing. After 300 cycles of freezing and thawing the untreated and SBS treated samples had a relative modulus of approximately 55 % (below the ASTM C666 limit of 60 %) while the SME-PS samples had a relative modulus of 85 %.

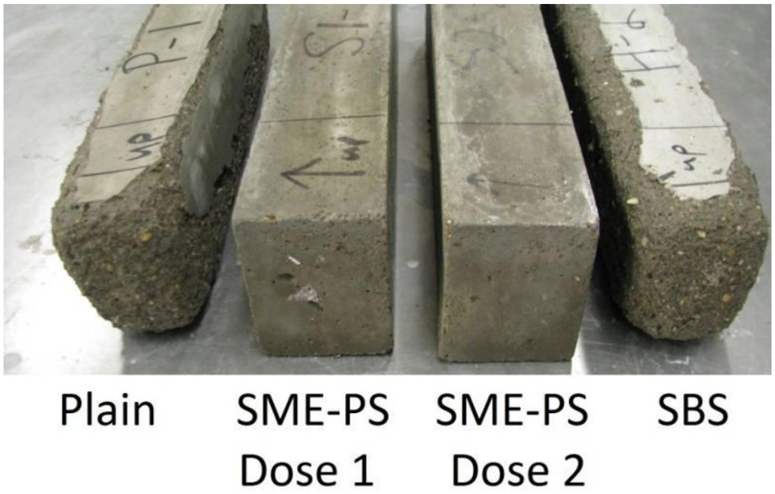


FIGURE 7 Freeze-Thaw samples after 280 cycles. Untreated (plain) samples and SBS treated samples show significant cover loss. SME-PS treated samples show no visual damage.

6.3 Sealant Freeze-Thaw Durability

Concrete samples treated with the solvent based silane sealant showed a reduction in water ingress of approximately 95 % (14). However, when these same materials were tested for freeze-thaw durability (21), the solvent based silane sealant did not show the same benefits. This section begins to explore the reasons for this difference in behavior.

To begin it should be noted that the silane sealants used in this study are not 100 % active ingredients. The silane was transported by an inactive carrier. The silane in SBS was dissolved in isopropanol. The WBS was an emulsion of silane and water. As the sealant cures, the carrier fluid evaporates leaving behind the silane forming a protective membrane on the surface of the concrete. As the membrane is exposed to freezing temperatures it is susceptible to thermal contraction. If the forces become large enough, the membrane could begin to crack and loss effectiveness. In contrast the SME never “cures” or hardens. When SME is applied to concrete, it is absorbed into the pores and remains fluid. Any thermal contraction would not result in the development of tensile stresses in the sealant.

In order to test this hypothesis, mixture C40 was treated with the sealants and exposed to freezing and thawing cycles. After freeze-thaw testing water absorption was evaluated using ASTM C1585 (15). For this series of experiments the samples were conditioned at 23 ± 1 °C and 50 ± 2% RH for 12 months prior to the application of the sealants. The sealants were applied in the same manner as described in the water absorption. Prior to testing, the samples labeled "Freeze/Thaw" were exposed to 7 freezing-thawing cycles between 5 °C and -18 °C. After 3 days of testing these samples are exposed to a daily freezing cycle (without being removed from the water). The efficiency of the sealants, reduction in water absorption compared to untreated samples, can be seen in Figure 8.

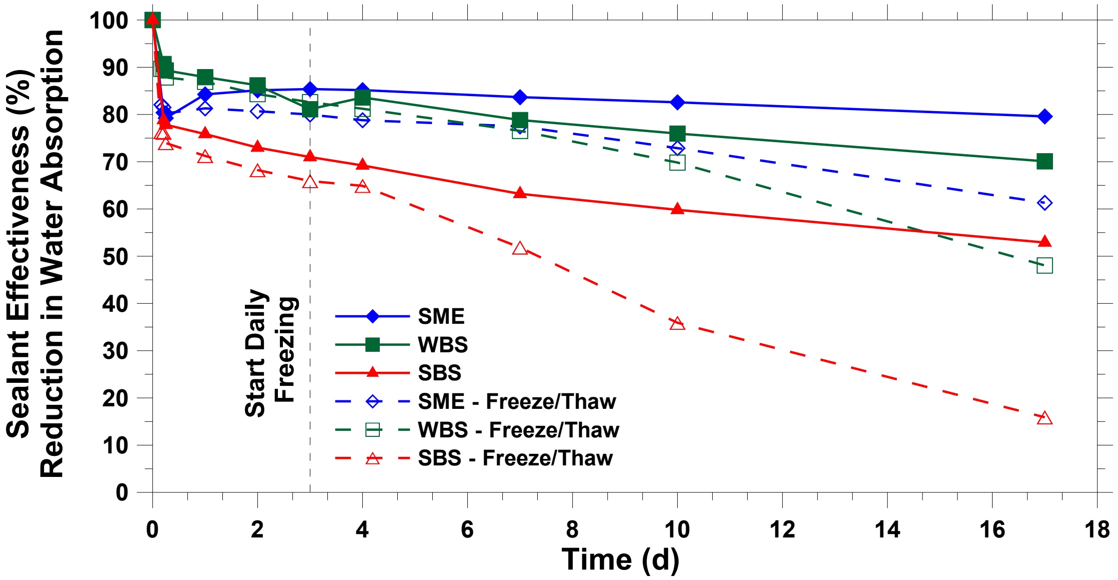


FIGURE 8 Sealant effectiveness after freezing and thawing.

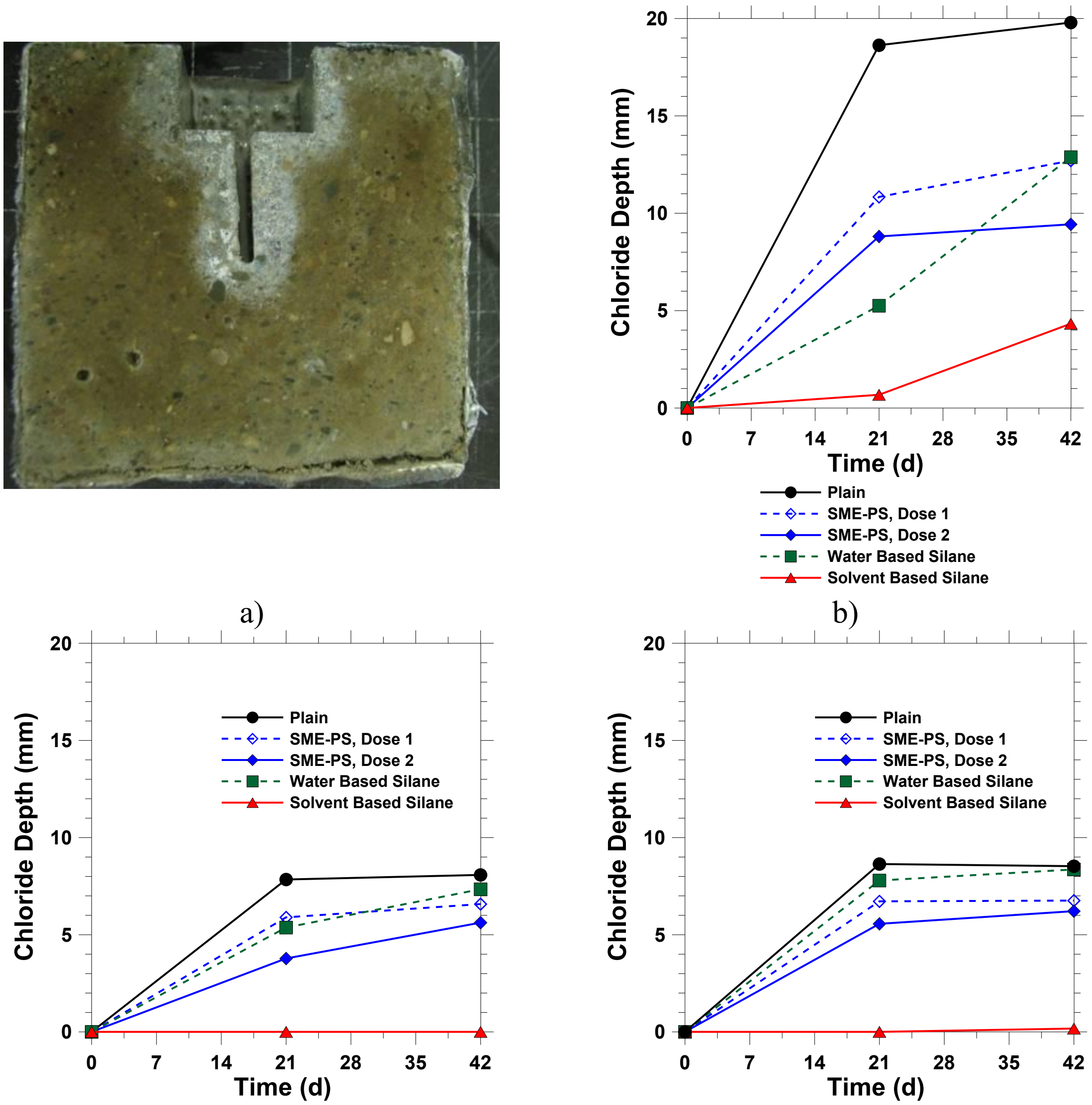
Slight differences (up to 5 %) were observed in the absorption behavior between the samples that underwent freezing and those that were kept at 23 °C within the first three days of testing. From this it can be implied that none of the sealants tested were vulnerable to freeze-thaw damage when the concrete was dry. After three days of testing, samples were exposed to daily freeze-thaw cycles (12 hours at -18 °C and 12 hours at 5 °C) while in water. Following the additional 7 freeze-thaw cycles all of the sealants tested lost some of their efficiency. The most vulnerable sealant type was the SBS, which absorbed 85% of the volume of water absorbed by untreated samples following freezing. The least vulnerable sealant was the SME-PS. It only lost about 20 % efficiency after freezing and thawing. Please note that the WBS only lost 23 % of its effectiveness during this testing. It is believed that the emulsifying agents left in the concrete allowed for some movement of silane as the concrete was being damaged. This will lead initial effectiveness of the sealant under these conditions.

7.0 CHLORIDE INGRESS

In addition to studying water penetration, this research evaluated the potential ingress of chloride ions that may come from deicing salts. Saw-cut joint specimens of mixture M42 were created. These specimens, shown in 10, were 10 cm x 10 cm x 10 cm mortar cubes. On the top face of this cube a 2.5 cm x 2.5 cm well was cast in place (Figure 9a). 24 hour after casting, the specimens were demolded and a 25 mm deep saw cut was cut into the middle of the well. At this time the specimens were sealed for 14 days and then allowed to dry in a 50 % RH chamber for an additional 90 days. The sides of the specimen were sealed to form a reservoir to hold the salt solutions. This specimen geometry was selected as it attempts to mimic the behavior of a saw cut joint in the field (11).

After the construction of the epoxy damns, the samples were treated with the topical sealants. The topical treatments being tested are SME-PS (2 dosages), Solvent Based Silane, and Water Based Silane. For SME-PS dose 1, SBS, and WBS the sealant was pooled in the reservoir for 6 h. For SME-PS dose 2, the material was pooled for 24 h. The sealants were allowed to cure for 7 d prior to the addition of the salt solutions.

For this series of tests three salt solutions were used. The three solutions are all commercially available de-icing solutions of 23 % Sodium chloride ($NaCl$), 30 % Magnesium chloride ($MgCl_2$), and 32 % Calcium chloride ($CaCl_2$). These salts solutions were pooled in the reservoir for 21 d and 42 d. At this time the samples were saw cut and 0.1M Silver nitrate ($AgNO_3$) was applied to samples. A white precipitate ($AgCl$) forms on the sample in the presence of chloride ions. This reaction will occur when the chloride ion concentration is over 165 ppm (22). These samples were photographed and the images were analyzed to determine the chloride penetration depth using image analysis (13). The depth of chloride ingress for this experiment can be seen in Figure 9 b) to d).



a) b)

b) c)

FIGURE 9 Chloride ingress depth: a) typical chloride ingress sample (100 mm x 100 mm) sprayed with silver nitrate, b) sodium chloride (23% by mass), c) magnesium chloride (30% by mass) , and d) calcium chloride (32% by mass).

The SBS sealant was the most effective of the topical treatments at reducing chloride ingress completely eliminating any ingress of chlorides for the $MgCl_2$ and $CaCl_2$ solutions and reduced the penetration depth by 80 % at 42 d for the NaCl solution. When using SME-PS, the dosage rate of sealant was directly related to its effectiveness. The samples were treated with a larger dosage of SME-PS resulted in a reduction of chloride depth about 10 % greater than that of the smaller dosage. The least effective sealant for preventing chloride ingress was the WBS. After 42 d of ponding, the chloride penetration depth was reduced by 35 %, 10 %, and 0 % for the NaCl, $MgCl_2$ and $CaCl_2$ solutions respectively.

8.0 CONCLUSIONS

This paper has reported results of experiments to evaluate the use of Soy Methyl Ester Polystyrene (SME-PS) as a topical treatment for concrete pavement. Based in the results of these experiments it is hypothesized that SME-PS may increase the durability of concrete pavement joints. It was observed that the penetration depth of SME-PS is dependent on concrete moisture level, size of PS molecules, and time. As the concrete moisture level increases, the amount of SME-PS that can be absorbed will decrease. As the chain length of PS increases, the amount of SME-PS absorbed will decrease. SME-PS reduced damage from freezing and thawing. After 300 cycles, the untreated samples had a relative elastic modulus of 55 % compared to the 85 % of the SME-PS treated samples. Field trials have begun to evaluate the performance of using SME-PS in pavement joints during new construction as well as in areas where the concrete has begun to show signs of premature deterioration.

9.0 ACKNOWLEDGEMENTS

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