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Improved Performance of Jointed Plain Concrete Pavements (JPCP) Through a Better Awareness of Drying Shrinkage

FINAL REPORT

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16. Abstract
Long-term drying shrinkage and early-age plastic shrinkage cracking can affect the performance of jointed plain concrete pavements (JPCPs). While plastic shrinkage cracking affects the durability, long-term drying shrinkage affects the fatigue life.

This study evaluates current Pennsylvania Department of Transportation specifications and practices pertaining to the paving mix design and construction, specifically finishing and curing, and their effects on long-term performance. This specification review was supplemented by a laboratory study to evaluate curing and mix design enhancements. Based on the results from the study, it is recommended that PennDOT require a curing compound with a poly alpha methylstyrene resin rather than the currently required wax-based compound. A maximum shelf life of 6 months for the curing compound should also be enforced. The application of the curing compound should be performed exclusively with mechanized equipment for mainline paving to ensure a uniform application. Regarding the finishing of JPCPs, the practice of pulling a wet burlap drag immediately behind the paving equipment but before the finishing should be eliminated. If used, the wet burlap drag should occur after finishing and only to add texture but without adding excessive water to the surface. A denser aggregate gradation should be used for pavement mix designs to reduce the cement demand thereby reducing drying shrinkage and increase durability. The Shilstone methodology can be used for establishing this gradation. Finally, a target 0.40 water-to-cement ratio is recommended for paving mixes to improve durability.

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Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

The goal of this study is to evaluate the effects of the mixture design and construction practices on the plastic and drying shrinkage characteristics for jointed plain concrete pavements constructed in Pennsylvania. A review of current state transportation specifications, as well as the specifications for the Pennsylvania Department of Transportation (PennDOT) was performed. Site visits were then made to five concrete paving projects to evaluate current practices. Areas for suggested improvement were identified and a list of suggested improvements was generated. A laboratory study was then developed and executed to evaluate the effectiveness of these suggested improvements. Based on the findings from these activities a list of recommendations was generated.

Before presenting the results of this study, a discussion is provided on both concrete plastic and drying shrinkage.

2. BACKGROUND

Volumetric changes in concrete occur with changes in moisture content (Page and Page 2007). Concrete pavements are susceptible to undergoing moisture-related volumetric changes due to their large surface area with respect to the total volume of concrete. Drying shrinkage or plastic shrinkage cracking can occur when these volumetric changes are restrained.

Plastic shrinkage is a type of moisture-related volume change that occurs while the concrete is still fresh and can produce cracks even before hardening. Plastic shrinkage cracking occurs in freshly placed concrete when the rate of water evaporation from the surface of the pavement exceeds the amount of surface water produced by bleeding. Small, irregular cracks can be observed on the surface of freshly placed concrete from plastic shrinkage. It has previously been observed to be a prevalent distress in some Pennsylvania roadways (Ramirez et al. 2011). Plastic shrinkage cracking can be prevented through improved curing and construction practices.

Plastic shrinkage cracking has been found to primarily affect the durability of a concrete pavement surface by allowing for the infiltration of moisture, thus increasing susceptibility to freeze-thaw as well as other durability related distresses. These distresses more often affect durability rather than the structural integrity by increasing the surface permeability, because the cracks typically propagate to a depth of 0.75 in. One study has documented that these shallow plastic shrinkage cracks can develop into full-depth fatigue cracks over time. This was observed on I-80 in Clinton County, Pennsylvania (Ramirez et al. 2011). The plastic shrinkage cracks reduce the effective thickness of the pavement and when they developed in the transverse direction and in the middle third of the slab, some eventually developed into full-depth fatigue cracks.

Both reversible and irreversible long-term drying shrinkage occurs in concrete pavements. The irreversible drying shrinkage develops over the first 5 to 7 years after paving in climates similar to Pennsylvania, while the reversible drying shrinkage is dictated by the seasonal wetting/drying patterns (Nassiri et al. 2011). Throughout the life of the pavement, the cyclic volumetric changes with changing moisture content are a function of the initial irreversible, drying shrinkage. Stresses develop when these volumetric changes are restrained. These slabs are restrained due to the friction between the slab and the supporting layer, tie and dowel bars and the self-weight of the slab. The larger the drying shrinkage, the larger the resulting stresses that develop do to these restraints.

As drying shrinkage occurs uniformly across the depth of the slab, contraction of the slab is restrained and stresses develop at the bottom of the slab at mid-slab. It has been shown that the moisture content in the upper 2 in of the slab fluctuates with the ambient relative humidity and rain events. The middle portion of the slab has a relative humidity of approximately 85 percent while the bottom of the pavement is saturated (Janssen 1986). This moisture gradient through the depth of the slab causes upward curvature. This curvature is restrained due to the self-weight of the slab, thereby causing tensile stresses to generate at the top of the slab at midslab. The magnitude of the drying shrinkage that develops is a function of both the concrete mixture design and the curing conditions (Mindess et al. 2003).

2.1.Contributing Factors

2.1.a. Plastic shrinkage cracking

Plastic shrinkage cracking occurs in fresh concrete pavements, most often from excessive surface evaporation when the evaporation rate exceeds the rate of bleed water rising to the pavement surface. This surface evaporation causes the formation of menisci within the paste as previously filled capillaries begin to drain. A capillary pressure arises as a result of the formation of the menisci, which ultimately leads to contraction of the paste. The increasing build-up of pressure reaches a critical point at which the unevenly distributed water rearranges itself to form distinct areas of voids and water (Mindess et al 2003). Typical plastic shrinkage cracking on the surface of the pavement is shown in Figure 1.

Figure 1. Typical plastic shrinkage cracking (Kostmatka 2002).

Plastic shrinkage cracking is frequently associated with hot weather paving due to the accelerated evaporation rate produced by high ambient temperatures. However, there are four primary climatic conditions that increase the rate of evaporation from the surface and thus the potential for plastic shrinkage cracking (Kostmatka 2002):

1) High air temperature
2) High concrete temperature
3) Low relative humidity
4) High air speed

The nomograph provided in Figure 2 is commonly used to estimate the rate of evaporation.

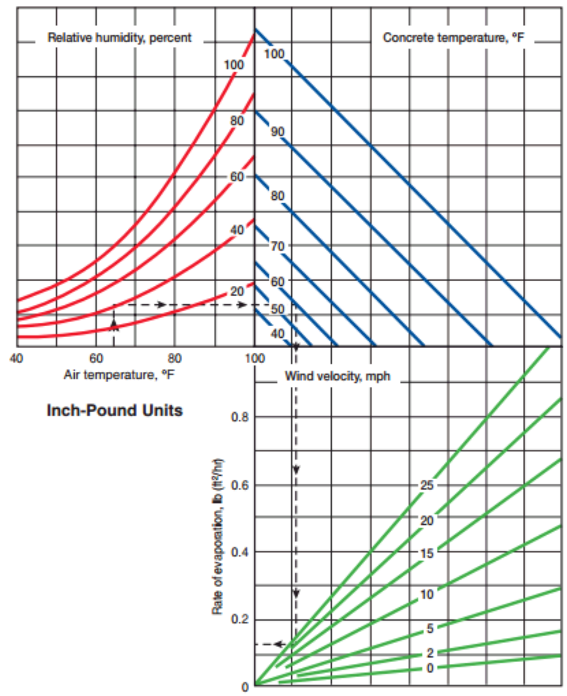


Figure 2. Relationship between air temperature, concrete temperature, wind velocity, and relative humidity to the rate of evaporation from a concrete surface (Kostmatka 2002).

This nomograph is based on the relationship developed by Menzel (1954) and is described by the following equation:

$$E = \left(T_c^{\ 2.5} - rT_a^{\ 2.5}\right)(1 + 0.4V) \times 10^{-6} \qquad \text{Equation 1.}$$

Where,

E= rate of evaporation on concrete surface, lb/ft^2/hr

T_c= concrete temperature, F

r= relative humidity, percent

T_a= ambient air temperature, F

V= wind velocity, mph

This relationship provides insight into the variability of surface evaporation based on external paving conditions, such as climate and environment. Typical weather data for the Pittsburgh area is summarized in Table 1. The climatic data was obtained from http://www.weather.com/weather/wxclimatology/monthly/USPA1290 (accessed November 2013) and the wind speed data from http://www.windpoweringamerica.gov/images/windmaps/pa_80m.jpg (accessed November 2013). This weather data was used along with Equation 1 to estimate the rate of evaporation summarized in Table 2. Table 2 shows the rate of evaporation varies between 0 and 0.5 lb/ft^2/hr during the construction seasons, based on these average value for the climatic conditions. It is recommended that the rate of evaporation not exceed 0.2 lb/ft^2/hr for normal concrete or between 0.1 to 0.05 lb/ft^2/hr when supplementary cementitious materials are used. From the table of evaporation rates, it becomes very clear that typical Pittsburgh-area paving conditions frequently exceed this rate. Therefore, plastic shrinkage cracking can occur if proper curing techniques are not used.

Table 1. Weather conditions for Pittsburgh, PA.

Pittsburgh Weather Data

	Apr		May		June		July		Aug		Sept		Oct	
	am	pm	am	pm	am	pm	am	pm	am	pm	am	pm	am	pm
RH, %	72	50	76	52	79	53	82	54	85	55	86	56	82	55
T_{high}, F	64	64	73	73	81	81	85	85	83	83	76	76	65	65
T_{low}, F	38	38	47	47	56	56	61	61	60	60	52	52	41	41

Assumed windspeed = 10 mph

Table 2. Rate of evaporation estimated for Pittsburgh, PA.

Rate of Evaporation of Surface Moisture, lb/ft^2/hr

T_c, F	Monthly T_{air}, F	Apr		May		June		July		Aug		Sept		Oct	
		am	pm	am	pm	am	pm	am	pm	am	pm	am	pm	am	pm
60	High	0.02	0.06	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
	Low	0.11	0.12	0.08	0.10	0.05	0.08	0.02	0.06	0.02	0.06	0.06	0.08	0.10	0.11
70	High	0.09	0.12	0.03	0.09	0.00	0.05	0.00	0.03	0.00	0.03	0.00	0.06	0.07	0.11
	Low	0.17	0.18	0.15	0.17	0.11	0.14	0.09	0.13	0.09	0.13	0.12	0.15	0.16	0.18
80	High	0.17	0.20	0.11	0.17	0.05	0.13	0.01	0.11	0.02	0.11	0.07	0.15	0.15	0.19
	Low	0.25	0.26	0.23	0.25	0.19	0.22	0.17	0.21	0.17	0.21	0.20	0.23	0.24	0.26
90	High	0.27	0.30	0.21	0.27	0.15	0.23	0.11	0.20	0.12	0.21	0.17	0.24	0.24	0.29
	Low	0.35	0.36	0.33	0.34	0.29	0.32	0.27	0.31	0.27	0.31	0.30	0.33	0.34	0.35
100	High	0.38	0.42	0.33	0.38	0.27	0.34	0.23	0.32	0.23	0.33	0.28	0.36	0.36	0.41
	Low	0.47	0.48	0.44	0.46	0.41	0.44	0.38	0.42	0.38	0.42	0.42	0.45	0.46	0.47

Lightly shaded areas represent times when the rate of evaporation is in the critical range ($\geq$ 0.1 lb/ft^2/hr) when SCMs are used and the darker shaded regions represent critical times for normal concrete ($\geq$ 0.2 lb/ft^2/hr).

Proper construction and curing practices help reduce the effects of the climate on the rate of evaporation of surface moisture. The timely application of a curing compound allows for the retention of moisture while the concrete hardens. It is critical to apply the curing compound just after the sheen evaporates from the surface. The curing operation should be within 100 ft behind the paving operation and it is essential that the curing compound be of high quality so an impermeable membrane is created.

2.1.b. Drying shrinkage

External moisture exposure is a key contributing factor for the development of drying shrinkage. This is largely a function of the climatic factors (ambient air temperature, relative humidity, frequency and duration of rain events and wind speed), which cannot be controlled. However, the largest controllable factor that contributes to drying shrinkage in concrete pavements is the water and paste content. The relationship between drying shrinkage and total water content is shown in Figure 3 below (Kostmatka 2002). Figure 3 shows that a greater amount of drying shrinkage occurs when the water content is higher.

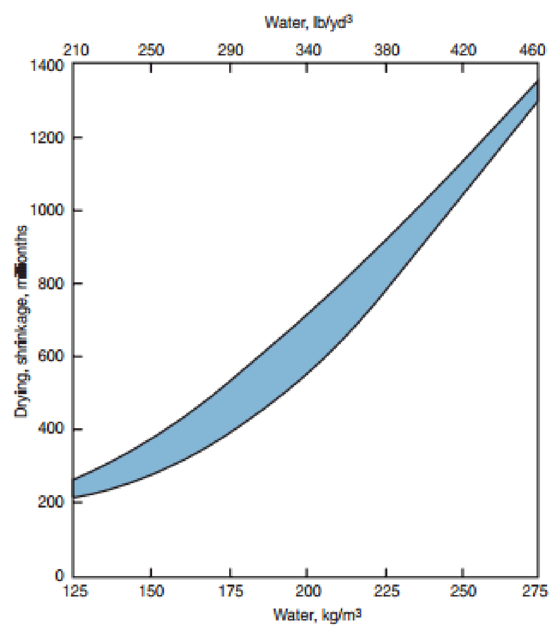
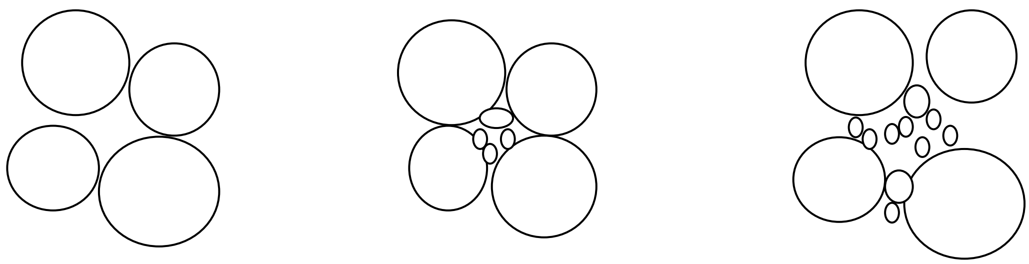


Figure 3. Effect of water content of concrete mix on drying shrinkage.

The aggregate does not experience shrinkage and acts to physically restrain shrinkage. Therefore, the shrinkage of the concrete is a function of the paste content. By decreasing the cement, which also results in an increase in the aggregate content, the drying shrinkage decreases. Drying shrinkage can be further reduced by refining the gradation of the coarse aggregate. More voids between the large aggregate particles can be filled with smaller coarse aggregate particles, if an aggregate blend with a uniform distribution of particle sizes is used. Aggregate gradations can be divided into three categories: a. open graded, b. densely graded and c. excessive fines, as shown in Figure 4, reproduced from Atkins (1997).



a. Open graded b. Dense graded c. Excessive fines

Figure 4. Aggregate gradations.

Full contact exists between the large coarse aggregate particles for both dense and open grading. The excessive fines prohibit full contact between coarse aggregate to coarse aggregate contact and therefore prevents optimal packing. It also requires a higher cement content to coat the particles due to the increase in surface area, which also results in a higher drying shrinkage. The open graded case contains large voids, which will be filled by cement paste and is therefore more susceptible to drying shrinkage. The densely graded case allows for the strength benefit of fully contacting aggregate particles, which reduces the drying shrinkage. The volume of voids between the aggregate particles is also lower so less cement paste is required to fill the voids. This also makes the concrete more durable. Many of the concrete durability issues occur in the paste, so by reducing the paste content, the durability of the concrete can be enhanced.

3. SPECIFICATION REVIEW

Several factors dictated by the state controlled standard construction specifications directly affect the tendency of a concrete pavement structure to experience plastic or drying shrinkage cracking. Plastic shrinkage cracking is affected largely by the finishing and curing practices. This includes the application method, dosage rate and the type of curing compound. Drying shrinkage is affected by many factors, both regarding mix design and construction. The most prominent factors include the water/cement ratio, paste content and the coarse aggregate gradation.

State specifications that dictate mixture design, construction practices and curing have an effect on both plastic shrinkage and drying shrinkage cracking and were reviewed. Trends are discussed and a complete summary table of specification information is given in the Appendix. The mixture design and curing practices will be assessed separately.

3.1 Mixture Design

As previously discussed, the mixture design can also exacerbate the effect of plastic and drying shrinkage. Drying shrinkage occurs as a result of a mechanism occurring in the paste only. Therefore, by reducing the paste content, a reduction in drying shrinkage should logically follow. The water-to-cement (w/c) ratio of a concrete mix, dictated by state specifications, would have a potentially large impact on the development of drying shrinkage. Across states, the water cement ratio ranged from a low of 0.40 to a high of 0.53. At present, the Pennsylvania DOT dictates a maximum w/c ratio of 0.47.

Additional mix design considerations were compared across states including slump, maximum cement content, air entraining, and required 28-day strength. Table 3 below gives average values across the states for these factors along with the values given in PennDOT Publication 408. A full summary of other state specifications included in the specification review is provided in Table A in the Appendix.

Table 3. Specification review of concrete mix design parameters.

Criteria	National Average	Maximum	Minimum	Pennsylvania
Max. w/c ratio	0.47	0.53	0.40	0.47
Slump, in	<2.5	2.5 to 4.5	<1	<5
Air entraining	4% to 7%	5.5% to 8%	2.5% to 5.5%	4.5% to 7.5%
Min.28-day compressive strength	3600 psi	4500 psi	3000 psi	3500 psi
Max. cement content	730 lb/cyd	850 lb/cyd	600 lb/cyd	752 lb/cyd

As can be seen from Table 3, there is significant variability in the criteria used across the country. Despite the fact that PennDOT has a w/c ratio equal to the national average, it is still relatively high, especially considering the many benefits from lowering the w/c ratio with regard to drying and plastic shrinkage cracking and overall durability. A lower w/c ratio is also desired when the concrete will be exposed to freezing and thawing in a moist condition or deicer chemicals. The lowest w/c ratio of less than 0.40 was specified by the Minnesota DOT. Similar benefits are provided by minimizing the cement content. As shown in Table 3, the maximum cement content for PennDOT is slightly above the national average.

The Minnesota DOT sponsors an incentive/disincentive program for concrete pavement construction to ensure quality performance. Following on-site testing, a monetary incentive or disincentive is assigned to the project cost. These w/c ratio payment incentives and disincentives are given in Table 4 below (reproduced from MnDOT Table 2301-8, Standard Specification). It can be seen from this table that adjustments to the price per cubic yard can be between - $3.00 and + $3.00 per cubic yard.

Table 4. Minnesota DOT Incentive/Disincentive program for w/c ratio.

W/c ratio	Pavement incentive or disincentive per cubic yard
≤0.37	+ $3.00
0.38	+ $1.75
0.39	+ $0.50
0.40	$0.00
0.41	- $0.50
0.42	- $1.75
0.43	- $3.00
≥0.44	Determined by the concrete engineer

Another important aspect of the mix design is the cement content. Using an insufficient amount of cement will result in inadequate strengths but using an excessively high cement content increases the shrinkage and decreases the overall durability of the concrete. Typically when developing a mix design, the water content is selected to achieve the desired workability and then the cement content is established such that the maximum allowable w/c ratio is met. Consideration should also be given to limiting the cement content to minimize drying shrinkage and maximize durability so that the cement content is limited to only that necessary to coat the aggregate particles such that sufficient workability is achieved.

In addition to the w/c ratio and the cement content, consideration should be given to the coarse aggregate gradation. Many states simply suggest ranges for a standard aggregate gradation. The required gradations for several states, including Pennsylvania, are provided in Table 5. Pennsylvania, as well as some other states, specify the American Association of State Highway Transportation Officials (AASHTO) No. 57 aggregate gradation. Other states consider this to be too open-graded and prescribe a more densely graded aggregate.

Table 5. Coarse aggregate gradations from selected state construction specifications, given as percent passing.

Sieve	**VA**	**CA**	**WA**	**IL**	**MN**	**PA**
1 ½ in	100	100	99-100	100	100	100
1 ¼ in					95-100	
1 in	95-100	90-100	95-100	90-100		95-100
¾ in		55-100			55-85	
½ in	25-60		25-60	30-60		25-60
3/8 in		45-75			20-45	
No. 4	0-10	35-60	0-10	0-10	0-7	0-10
No. 8	0-5	27-45	0-5			0-5

It can be seen that the use of the AASHTO No 57 gradation can potentially allow for up to 60 percent of very similarly sized aggregates. Allowing the removal of the material between the No. 4 sieve and the fines results in a gap graded mix that will require a higher paste content to achieve the desired workability. It will also be more susceptible to segregation. To eliminate the potential of having a gap graded aggregate, the Minnesota DOT narrowed the ranges of the acceptable aggregate gradations. In addition, incentives are provided for aggregate gradations that are even more densely graded. While the standard coarse aggregate gradation requirement is included in Table 5, gradations defining this incentive are shown in Table 6.

Table 6. Minnesota DOT incentive coarse aggregate gradations.

Sieve Size	Option 1: + $0.50 per cubic yard, %	Option 2: + $2.00 per cubic yard
2 in	0%	0%
1 ½ in	≤9 %	≤9 %
1 in	7-18%	8-18%
¾ in	7-18%	8-18%
½ in	7-18%	8-18%
3/8 in	7-18%	8-18%
No 4.	7-18%	8-18%
No. 8	7-18%	8-18%
No. 16	7-18%	8-18%
No. 30	7-18%	8-18%
No. 50	≤13 %	≤13 %
No. 100	≤8 %	≤8 %
No. 200	≤8 %	≤8 %

From Table 6, it can be seen that upwards of a $2.00 per cubic yard incentive can be paid. No other state was found to have such an incentive program or such an even aggregate gradation recommendation. This kind of incentive and suggested gradation would greatly contribute to achieving a dense aggregate gradation and would help to prevent the occurrence of excessive drying shrinkage and segregation.

3.2 Finishing and Curing

Curing practices for pavements are used to retain as much moisture as possible in the pavement. A curing practice is generally considered effective if it is able to retain the surface moisture above 80 percent relative humidity for seven days following construction to ensure full hydration (Kostmatka 2002). Finishing and curing practices are known to affect both plastic shrinkage cracking. The finishing and curing practices for several states have been collected and are synthesized in Table B of the Appendix. Several of these components of the finishing and curing practices will now be discussed.

Curing is performed after finishing of the concrete pavement surface. The most common texturing among the states consisted of a combination of dragging burlap for providing micro texture followed by tining or grooving for providing macro texture. Some states use an astrotruf drag for providing micro texture. Most generally, curing practices were recommended to begin following texturing and immediately after all free water has left the surface of the pavement. This is often assumed to occur within 30 minutes after finishing but will be a function of the mixture design and the ambient climatic conditions.

The recommendations for types of curing varied by state and acceptable methods of curing include using water, wet burlap, white polyethylene sheeting, wet cotton, waterproof paper, blankets, and a liquid membrane-forming concrete curing compound. The economics, availability and ease of application of liquid membrane forming curing compounds (They can be applied and do not require retrieval, unlike sheeting or blankets.) contributes to the popularity of the liquid membrane-forming concrete curing compound among state specifications. The curing compound application rate also varied between 1 gallon per 100 ft^2 to 1 gallon per 200 ft^2. The most commonly recommended application rate was 1 gallon per 150 ft^2 of concrete pavement. This is the target curing application rate recommended by the Pennsylvania DOT standard specification as well.

The method by which the liquid membrane curing compound was applied was extremely consistent between states. It was important that the sprayers be mechanical, with an atomizing nozzle (to ensure complete and uniform coverage) and that the tank have an agitator. Some states also required an operational pressure gage and the ability to control the application pressure. Almost all states only permitted hand spraying for irregular pavement sections with odd widths and shapes. Pennsylvania's requirements remained consistent here and included requiring mechanical atomizing sprayers and allowing hand-spraying only for irregular sections, although the site visits revealed that hand-spraying was commonly performed on mainline paving as well.

States which specified a type of liquid membrane curing compound required those which fulfilled the requirements outlined by the AASHTO M 148 specification (superseded by ASTM C309). States required at least Type 1-D (clear with fugitive dye) or Type 2 (white pigmented). It was more common for states to require Type 2 (white pigmented) curing compound. Two classes of curing compounds exist within Type 2: Class A (any white pigmented curing compound including wax-base) and Class B (curing compounds with a resin-base). Only California, Idaho, Connecticut, Minnesota, North Dakota, Utah and Wyoming require exclusively Type 2 Class B (resin based) curing compounds. The Pennsylvania DOT requires a Type 1D or Type 2 curing compound. Additionally, several states had additional requirements outside of the listed AASHTO M 148/ASTM C309 requirements, as discussed below.

General requirements are specified such that Type 1-D contains enough fugitive dye such that it can be distinguished from the concrete surface for at least 4 hours following application but no more than 7 days. Type 2, however, requires a uniform white appearance and the formation of a continuous white film when applied. Several properties of the curing compounds are specified by the ASTM C309 specification and include water loss, reflectance, drying time, long-term settling, and nonvolatile content. The specification also dictates that liquid membrane curing compounds should be stored for a maximum of 6 months.

Moisture loss testing indicates the effectiveness of a curing compound to retain moisture within the specimen and can be measured in accordance with ASTM C156 procedure. The ASTM C309 specification requires that water loss should be restricted to less than 2.79 lb/ft^2 in 72 hours. Reflectance indicates the amount of light that is reflected from a surface treated with the curing compound. A higher reflectance indicates less absorbed light (and consequently, heat), which would impact curing. This property is measured through ASTM E1347 and must be greater than 60 percent, according to ASTM C309. Drying time only indicates the duration of time required for a curing compound to dry on the surface of the pavement, and is required to be less than 4 hours. This ensures that the compound is dry before the final set of the concrete occurs when the surface would be exposed to any traffic or contact. Long-term settling is assessed to insure the curing compound can be stored for six months and then be re-agitated into a homogenous solution with minimal settling of the solids. This property is tested in accordance with ASTM D 1309 and all curing compounds must pass this test. Finally, the non-volatile content must be measured because a high concentration of volatile content (VOC) can cause respiratory problems (Kostmatka 2002). The VOC is monitored by the Environmental Protection Agency (EPA), which has established a maximum allowable VOC of 2,620 oz/gal for curing compounds when tested in accordance to ASTM D 2369. These testing requirements and target values are summarized in Table 7.

Table 7. ASTM C309 specifications for liquid membrane forming curing compounds.

Property	Required Test	Required Value
Water Loss	ASTM C156	2.79 lb/ft^2
Reflectance	ASTM E1347	>60%
Drying Time	ASTM C309	< 4 hours
Long-Term Settling	ASTM D1309	Pass
Non-volatile Content	ASTM D2369	< 2,620 oz/gal

Some states have added additional requirements outside of the testing requirements outlined in ASTM C309 for liquid membrane forming curing compounds. These states include Minnesota, New York, North Dakota, and Ohio. Their additional requirements beyond the requirements outlined in ASTM C309 are given in Table 8 below. Some states not only dictate the minimum percent solid but also dictate that the resin must by poly alpha methylstyrene (AMS). This would include California, Minnesota and Utah.

Table 8. Specific curing compound characteristics for select states.

State	Minimum solids	Water Retention	Reflectance	Settling Rate
Minnesota	≥ 42%	0.73 lb/ft^2 at 24 hrs 1.96 lb/ft^2 at 72 hrs	≥ 65%	0.02 oz / 1 oz in 2 hrs
North Dakota	42%	0.73 lb/ft^2 at 24 hrs 1.96 lb/ft^2 at 72 hrs	> 65%	0.02 oz / 1 oz in 2 hrs
Ohio	25%	0.73 lb/ft^2 at 24 hrs 1.96 lb/ft^2 at 72 hrs	> 65%	> 4.9 oz in 2 hours but < 4.23 oz in 24 hours

The Pennsylvania specifications could be improved by including requirements for percent solids, water retention, reflectance, and settling rate. However, as shown by Vandenbossche (1999), several factors can critically affect the application rate of a curing compound including the presence of tining as well as the nozzle spacing and the height above the pavement. Therefore, both the specification and the implementation is critical for obtaining a good cure.

4. SITE VISITS

In order to observe construction practices and procedures, several site visits were conducted throughout western Pennsylvania. Construction practices, and curing procedures were observed and documented for each site visit and a summary of the observations is provide below.

4.1 I-79 South Section 20-H, Washington County, PA

The first site visit took place on June 5, 2013 and was a ramp paving project off of I-79 at the I-70/I-79 interchange in Washington County, Pennsylvania. Paving conditions were sunny and warm and work began at 7:00 AM. The project involved placing 12 in of Portland cement concrete (PCC) over 4 in of concrete stabilized base. The concrete arrived on site with a 1 in slump, which is appropriate for slip-form paving.

The paving procedure was generally smooth and the main paving equipment used a GPS system rather than a stringline for alignment. The paving machine, however, lacked an auger-style placer in the front of the paver and instead had a sliding drum, which caused the concrete to mound at the edges of the pavement. A wet burlap was attached to the back of the paver for texturing. The burlap appeared to be consistently (but not excessively) wet. It is not know why the burlap texture was applied since floats were used behind the burlap, which removed any texture provided by the burlap, as shown in Figure 5. The finishing was followed by hand-tining with a rake.

Figure 5. Wet burlap drag for texturing following finishing.

Curing was performed with a resin-based curing compound and was applied with a hand sprayer (wand), which led to a nonuniform application of the curing compound. See Figure 6 where both regions of pooling of the curing compound and sections of sparse application can be seen. The compound was hand sprayed beginning with edges and then the surface until deemed satisfactory based on visual inspection of the surface. Typically, empty containers are counted and distance is measured to ensure the proper application rate but no empty containers were visible; therefore, it was not possible to verify the correct application rate was being used. There also appeared to be a large distance between the curing application operation and the paving truck. At one point, the curing compound application cart was approximately 240 feet behind the paver.

Figure 6. Application of curing compound. Note nonuniform application.

4.2 Warrington Avenue, Allentown, PA

The second site visit occurred on June 6, 2013 and was a project located on Warrington Avenue in the neighborhood of Allentown in Pittsburgh, Pennsylvania. This project was a cooperative effort between the city of Pittsburgh and the Port Authority. Paving conditions were sunny and warm. This project was unusual as it involved placing 4 in of concrete on a base prepared to support the above-ground portion of the Pittsburgh subway system. The concrete mix contained fibers. The concrete was placed and a roller screed was used to strike off the top of the pavement surface flush with the top of the form, as shown in Figure 7. The finishing was performed using hand trowels, as seen in Figure 7. The concrete pavement was then cured using white polyethylene sheeting, as shown in Figure 8.

Figure 7. Striking off the concrete and hand finishing.

Figure 8. White polyethylene sheet used for curing the roadway section.

4.3 Route 119-South Section 10K, Fayette County, PA

The third site visit occurred on August 1, 2013 on 119-South at Section 10K. The paving was being performed at the County Line Bridge in Fayette County, Pennsylvania. Paving conditions were warm (approximately 75 ^{o}F) and cloudy. This section was to be paved at night; therefore, paving began at 7:00 PM and continued until approximately 6:00 AM the next morning. The project included an 11-in PCC placed over a 4-in bituminous treated base over 6 in of subbase.

The concrete was provided by two different plants to meet the supply demands required to keep the paver moving at a constant rate since both traffic lanes and a shoulder were being placed for a total paving width of 32 ft. The paving was fixed-form and a stringline was used to align the work bridges that ran on top of the forms. A bridge paver with an auger mounted on the front to move the concrete horizontally along the front of the paver was used. It also contained vibrators and a roller screed for finishing the surface of the pavement off flush with the top of the form. A super smoother is mounted on the back of the paver. See Figure 9. Manual hand finishing of the edges was performed before the passing of the first work bridge. This was followed by the passing of two work bridges: the first used for hand finishing and tining and the second work bridge was used for applying the curing compound using a hand wand, as shown in Figure 10.

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Figure 9. Paving placement equipment.

There was approximately 50 feet between the initial paving operations and the final curing work bridge. The curing compound was a white pigmented wax-based curing compound. The curing compound was applied manually with a hand wand and a relatively uniform coverage was achieved. Empty containers were counted per distance to ensure an application rate of approximately 150 square feet per gallon. The second work bridge, used for tining and the application of the curing compound can be seen in Figure 10 and the final surface is shown in Figure 11.

Figure 10. Application of curing compound with hand wand on work bridge.

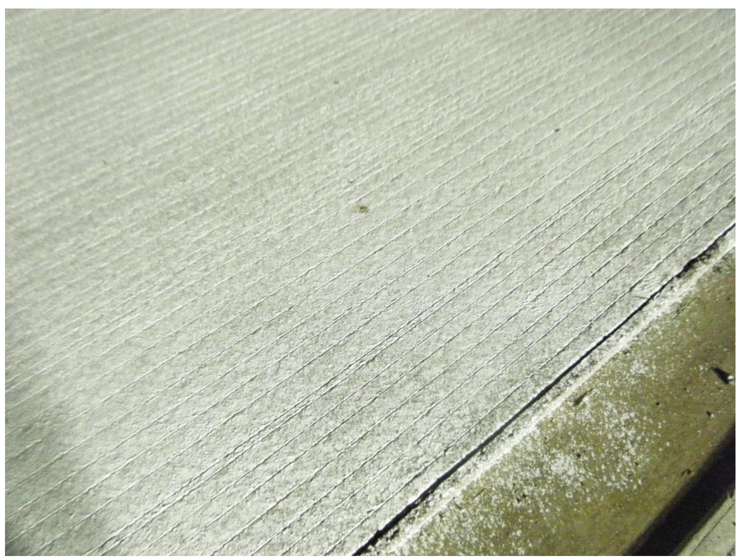


Figure 11. Curing compound on the pavement surface.

4.4 I-80, Reynoldsville, PA

The fourth site visit took place on October 3, 2013 on Interstate 80 at Exit 86, near Reynoldsville, in Jefferson County, Pennsylvania. Paving conditions began under an overcast and warm ambient temperatures (approximately 75 ^{o}F but with high humidity) but it turned rainy by the afternoon. Paving operations were suspended at 1:00 PM since rain clouds were moving into the area. This project consisted of placing 14 in of PCC on a dense cement stabilized base over 2 feet of undercut rock.

The paving went relatively smoothly but progressed slowly. The pavement equipment was aligned using a stringline. The main paver with a soaked burlap drag hanging from the back was followed by hand-finishers. The paver with the soaked burlap drag can be seen in Figure 12. A combination tining/curing compound spraying cart was used for the final operations.

Figure 12. Main paver with burlap drag.

The large amount of moisture added to the surface by the soaked burlap resulted in excess water being worked into the pavement surface, as seen in Figure 13. The excess water is seen collecting between the two finishers in this figure. This excess surface water increases the w/c ratio of the surface of pavement, which increases the potential for plastic shrinkage cracking and a nondurable wearing surface. The reason for the burlap drag is unclear since the intention should be to provide surface texture but any texture provided would be finished out with the floats being used behind the burlap drag.

The tining procedure can be seen in Figure 14. Following tining, the curing compound was applied using the curing cart. The cart spanned the width of the pavement and was equipped with a row of nozzles to spray the curing compound evenly on the surface of the pavement as well as a wind screen. This is shown in Figure 15.

Figure 13. Excess surface water during hand finishing.

Figure 14. Tining the pavement surface.

Figure 15. Spray nozzles and wind screen on the cure cart.

The curing compound used was WR Meadows 1600, which is a white, wax-based compound. A field test was implemented to measure the application rate. Five 8 in × 8 in pads with an absorptive surface and a non-permeable backing were placed on the pavement surface. A plastic sheet was placed between the pad and the pavement surface to prevent the concrete from sticking to the bottom of the pad. The absorbent side of the pad was facing upward, as shown in Figure 16. The specimens were weighed prior to taking them to the field. They were then placed on the pavement surface just prior to the passing of the cure cart. After the cure cart passed over the pads, they were weighed once again to determine the application rate of the curing compound. All five specimens are shown in Figure 17.

Figure 16. Field specimen for measuring the application rate of the curing compound.

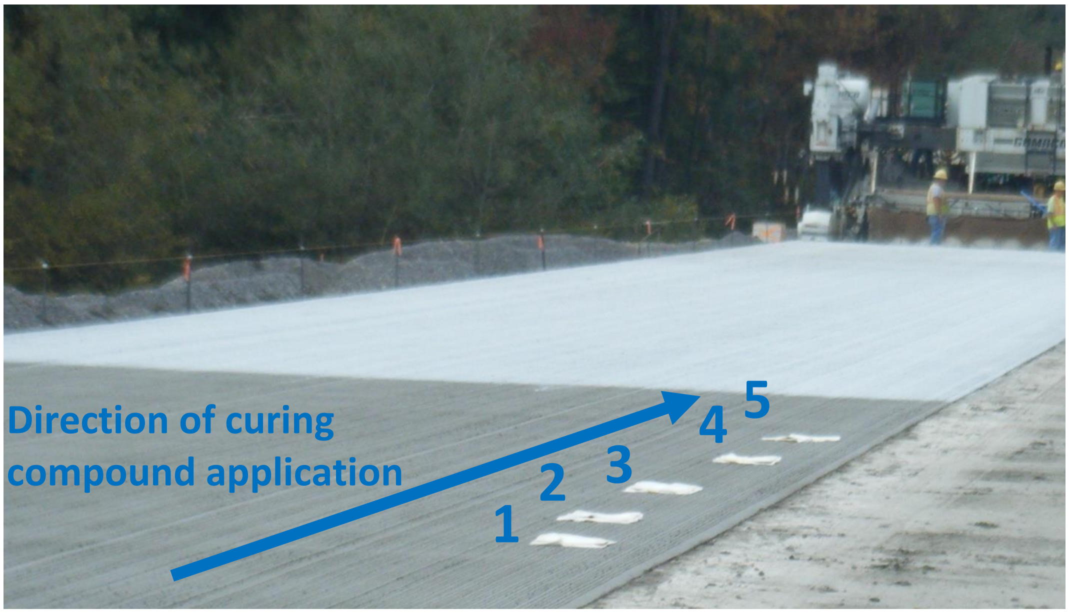


Figure 17. Five specimens for measuring the curing compound application rate.

Using the known area of the absorbent pad, the known density of the curing compound (8.25 lb per gallon), and the weight of the specimens, the application rate was estimated. The application rate was estimated to be approximately 220 ft^2 per gallon of curing compound with a standard deviation of 19 ft^2 per gallon for the 5 samples. This is lower than the recommended target value of 150 ft^2 per gallon of curing compound but more comparable with the manufacturer recommendation of 200 ft^2 per gallon. The final appearance of the curing compound can be seen in Figure 18. It is very clear that the curing cart was able to distribute the curing compound more uniformly than was achievable using the hand wand. Following curing, the project used an additional white plastic sheeting to cover the freshly cured concrete due to the impending rain. This is shown in Figure 19.

Figure 18. Pavement with applied curing compound.

Figure 19. Sheeting used in addition to the curing compound due to impending rain.

5. FINDINGS FROM SPECIFICATION REVIEW AND SITE VISITS

A review of the specifications and the site visits provided an opportunity to assess current practices and identify potential improvements. The two areas of focus were the mix design and construction practices. Construction practices will be discussed first followed by a discussion on mix designs.

5.1 Construction

The focus of this review was on the placement, finishing and curing of the pavement. Consolidation is a component of the placement process that can have an effect on the durability of the concrete. Over-consolidation can knock out the entrained air between the time the fresh concrete is tested and the entrained air is measured in the hardened concrete. It can also contribute to segregation. The placement of the concrete and vibration appeared to be adequate for the projects visited, although the frequency at which the vibrators were operating could not be determined. The paving vibrators should be operating at a frequency between 60 and 100 hertz. Previous projects constructed in Pennsylvania indicate that segregation can be an issue at times as seen by the cores shown in Figure 20. These cores were taken from pavements in Pennsylvania (Ramirez, et al. 2011). The fact that segregation is observed on some projects indicates the ability to monitor the frequency of the vibrators could be beneficial.

a. Core from SR202 (Chester County, PA) | b. Core from SR22 (Murrysville, PA) | c. Core from I-79 (Washington County, PA)

Figure 20. Segregation found in cores pulled from pavements in Pennsylvania.

The finishing process of each slipform paving project consisted of a wet burlap drag behind the paver followed by approximately five or six people finishing the surface with floats. Tining was then performed either in the transverse or longitudinal direction. The tining was performed either manually or with automated equipment. Many times the burlap drag behind the paver was so saturated that an excessive amount of water was being applied to the pavement surface. The hand finishing removes the texture applied by the burlap so the sole purpose of the burlap was to add water to the surface. The water is then worked into the surface by the finishers. This practice creates a high w/c ratio at the surface which increases the potential for plastic shrinkage cracking and reduces the overall durability of the surface by increasing the porosity.

The effects of this practice can be seen in pavements across Pennsylvania. Figure 21a shows a core taken from I-80 in Clinton County, PA as part of a study on the premature deterioration of concrete pavements (Ramirez et al. 2011). Figure 21 also shows several locations where plastic shrinkage cracking was observed on this section of I-80. Five of the six pavements investigated as a part of this study exhibited plastic shrinkage cracking. Photos of two of these pavements can be seen in Figures 22 and 23. These cracks typically propagate to a depth of about 0.75 in. They typically are a greater concern in contributing to material-related distress than fatigue cracking since, although the cracks do not propagate to a significant depth, they make the surface of the pavement more porous. Several of these projects also exhibited paste worn away at the surface, as seen in Figure 24. Although it is not common, plastic shrinkage cracks that developed in the transverse direction and in the central portion of the slab can contribute to the development of full depth fatigue cracks. This was observed on I-80 (Ramirez et al. 2011).

These cracks can be prevented through the adoption of proper curing and finishing practices. Proper curing should include not only avoiding adding water to the pavement surface to aid in finishing but also a uniform application of a curing compound at an appropriate application rate. It is also critical that the curing compound used have sufficient water retention characteristics. Special attention should also be paid to ensure the curing compound is less than 6 months old or it might not be possible to re-suspend the settled solids regardless of the time/energy put into agitation. Based on the site visits, it was not apparent that tracking the age of the cure was part of standard practice. Table 2 shows that pavements constructed in

Pennsylvania are susceptible to plastic shrinkage cracking for a significant portion of the construction season if precautionary measures are not taken.

(a) Surface of core

(b) Plastic shrinkage crack number 27
(*the crack has been digitally enhanced*)

(c) Plastic shrinkage crack number 29
(*the crack has been digitally enhanced*)

Figure 21. Plastic shrinkage cracking on I-80 in Clinton County, PA.

Figure 22. Plastic shrinkage cracking on SR 202 in Chester County, PA.

Figure 23. Plastic shrinkage cracking on US 22 in Murrysville, PA.

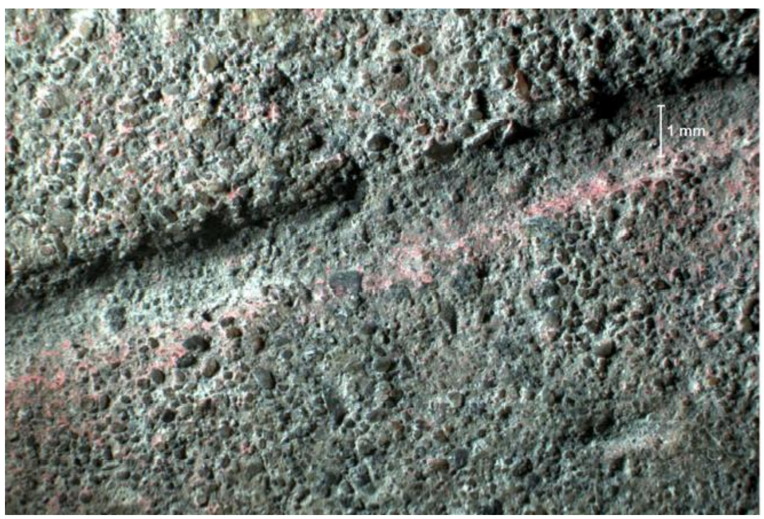


Figure 24. Wear/erosion of the pavement surface on the surface of core form US 22 in Westmoreland County, PA.

5.2 Mixture design

A refinement of the concrete mixture design specification should also be performed. Using a more uniformly graded coarse aggregate along with using a lower w/cm ratio will help reduce the potential for segregation. Using a more densely graded aggregate will reduce the voids present between the aggregate particles and the corresponding volume of paste required to fill those voids. Lowering the paste content then makes the concrete more durable and decreases the long-term drying shrinkage. Reducing the allowable w/cm ratio also reduces the porosity of the paste and therefore increases the durability but also increases the importance of proper curing. The durability can also be increased by decreasing the paste to aggregate ratio as well by limiting the total cement content for a defined w/cm ratio.

To improve the durability of the pavement and decrease the long-term drying shrinkage, it is recommended that the w/cm be reduced to a maximum of 0.42 with possible incentives for lower values down to a minimum of 0.38. The current maximum allowable w/cm ratio for PennDOT is 0.47. A study conducted in 2011 by Nassiri and Vandenbossche included measuring the w/cm ratio in the field using the microwave oven test for four different concrete pavement projects in Pennsylvania. The average w/cm ratio established for Project 1, 2, 3 and 4 were 0.45, 0.47, 0.49 and 0.46, respectively. The corresponding standard deviation for each project was 0.04, 0.01, 0.03 and 0.01. It is recommended that a maximum cement content of 600 lbs/cyd should be established to limit the drying shrinkage and increase the durability of the mix. Finally, it is recommended that a more densely graded aggregate be used to help reduce the cement demand and to reduce the potential for segregation. The following section discusses how the Shilstone method can be used to establish a suitable aggregate gradation.

The Shilstone method incorporates aggregate properties into a methodology for establishing the suitability of an aggregate gradation in a concrete mix (Shilstone, 1990). The Shilstone method divides the total aggregate gradation into three components on a volumetric basis. The three components are the coarse fraction (Q), intermediate fraction (I), and the fine fraction (W). The coarse fraction is the aggregate retained on the 3/8 in sieve, the intermediate fraction is the aggregate that passes the 3/8 in sieve and is retained on the No. 8 sieve, and the fine fraction is the aggregate that passes the No. 8 sieve and is retained on the No. 200 sieve. These three aggregate gradations along with the workability and the coarseness factor are entered into a chart to determine the quality of the aggregate gradation. The coarseness factor (CF) is the percent ratio of the coarse fraction to the sum of the coarse and intermediate fractions, as shown in Equation 2:

$$\mathrm{CF} = \frac{\mathrm{Q}}{\mathrm{Q+I}} * 100 \qquad \text{Equation 2}$$

Therefore, a CF of 100 would correspond to a completely gap graded aggregate with no intermediate fraction (3/8 in to No. 8) and a CF of zero would represent an aggregate in which no material is retained on the 3/8 in sieve.

The workability (W) is defined as the fine fraction or the percent material passing the No. 8 sieve. W is adjusted based upon the cement content of the mix. This parameter assumes that six 94 pound bags of cement (564 lb) will be used in the mix. The adjustment to W that is used is 2.5 percent per bag of cement or fraction of cement bag which deviates from the standard six bags. This adjustment was derived from the fact that one bag of cement is approximately equivalent to 2.5 percent of the absolute aggregate volume.

With the coarseness factor and the workability as defined above, Figure 25 can be used to establish the quality of the aggregate gradation. This version of the CF chart is divided into zones based upon the predicted aggregate properties. The zones are defined as follows:

- Zone I: Coarse and gap graded aggregate which tends to segregate
- Zone II: Well graded and best for every day mixes
- Zone III: ¾ inch and finer for use in pea gravel mixes
- Zone IV: Sandy and sticky mixes
- Zone V: Rocky aggregate, which may be suitable for mass concreting

Zone I is the optimum range, however this should be avoided as a significant amount of control over the quality of the mix is required, which is difficult to achieve. Zone II, which results in the most well graded aggregates, is further divided into 5 subcategories. These zones are defined as follows: II-1 is excellent but caution is required, II-2 is excellent for form paving and slipforming, II-3 is for high quality slabs, II-4 is good for general concrete mixes, and II-5 varies according to material and construction needs. From the figure, it can be observed that these trends extend into Zone III as well.

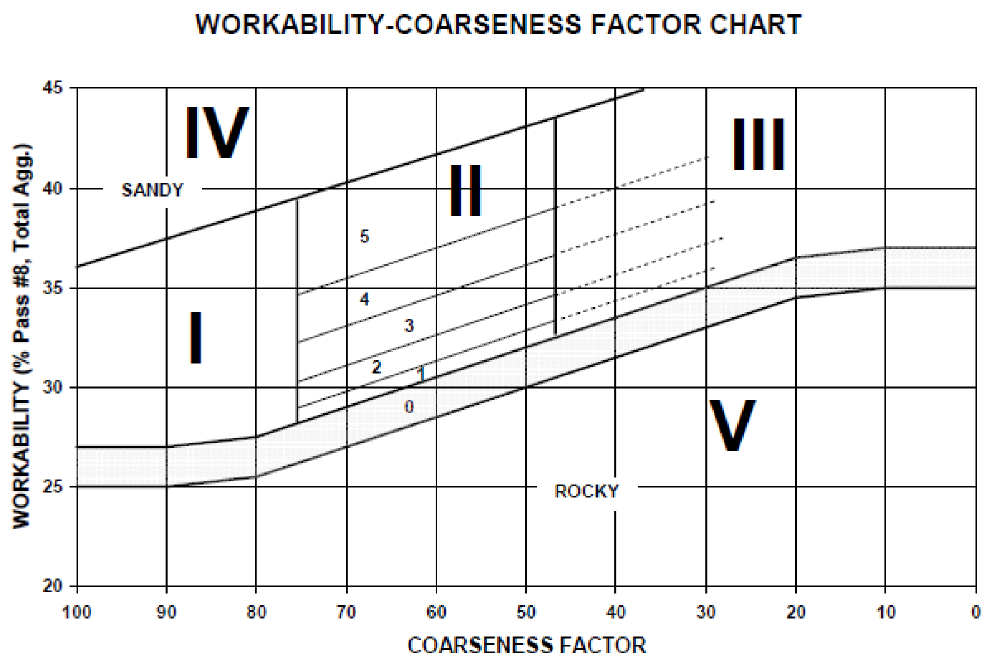


Figure 25. Revised Shilstone coarseness factor chart (Shilstone and Shilstone Jr., 1997).

The use of an optimized gradation can result in a lowering of the cement paste content. A potential reduction in the water content would also result in lower shrinkage and cracking potential for the concrete pavement structure. The potential for increased durability and smoothness can result in both lower initial and life cycle costs for concrete pavements. Therefore, effort should be taken to ensure that the gradation utilized is within the zone for which aggregate properties are wanted. For concrete paving operations, the ideal conditions would be within Zones II-2 and II-3.

The intermediate size aggregate fraction fills the major voids between the large coarse particles and as a result decreases the need for fine material. The intermediate size, as is defined above, can come from either the coarse or fine aggregate, as defined under ASTM C33. ASTM C33 specifies that the division between the coarse and fine fractions is the 3/8 in sieve with no intermediate fraction. As a result, it is possible that a gradation within the limits of ASTM C33 does not contain an adequate portion of the intermediate fraction. The intermediate fraction can fill the voids between the coarse and fine fractions. Without this intermediate fraction, the voids must be filled with mortar (sand, cement, and water). When mortar is required to fill the voids within the aggregates, less is available for finishing the concrete, which decreases workability and can make the concrete hard to finish.

6. LABORATORY INVESTIGATION

Two areas to investigate further were identified after performing the site visits and the specification review; 1. Effectiveness of curing compounds and 2. Mixture design refinements. Two separate laboratory investigations were developed. The focus of the first was to better quantify the effects of curing compound characteristics on water retention. The focus of the second was to evaluate the effects of using a more densely graded aggregate and a lower w/cm ratio on drying shrinkage. Both investigations are described below.

6.1.Curing compound study

The variables considered in the evaluation of curing compound effectiveness included, type of curing compound (wax vs resin), percent resin and type of resin. Five different curing compounds were tested. A wet cure and a dry cure were also included for comparison as control. Both control specimens were placed in the environmental chamber with the curing compound containing specimens: the dry cure had no compound applied and the wet cure was placed in a water bath. The three performance parameters considered include moisture loss, compressive strength and permeability. Moisture loss is generally considered to be the standard measure of effectiveness of a curing compound. However, since pavement performance is also an important consideration, compressive strength of the samples was measured. Likewise, to investigate the potentail durability of the resulting pavement, permeability was also measured.

6.1.a. Description of the curing study

Curing compounds with wax, an unnamed resin and a poly alpha methylstyrene (AMS) resin were considered. In addition to the type of resin or compound, the percent resin was also considered an important factor. For this study, the percent of resin and the percent of total solids is assumed to be the same. Technically, the solid component consists of both the pigment and the resin but the percent pigment is assumed to be relatively consistent between the curing compounds considered and the overall percentage is quite small. Table 9 lists characteristics of each curing compound considered, including percent solids, the VOC and the reflectance. VOC and reflectance are dictated by specification and provide an indication into curing compound performance. The values provided in Table 9 were not measured as part of this effort but are those reported by the manufacturer. As noted above, two additional curing regimes were considered; a wet cure, where the specimen was placed in a water bath, and a dry cure, which had no compound applied. The environmental conditions in this curing chamber are described in a subsequent section.

Table 9. Characteristics of the curing compounds included in this study.

Name	Type of solid	Percent solids	VOC (oz/gal)	Reflectance (%)
Wax 24%	Wax	24	10	67
Wax 38%	Wax	38	13	66
Resin 24%	Unknown resin	24	28	66
AMS 37%	AMS	37	47	73
AMS 44%	AMS	44	35	75

A w/c ratio of 0.42 and fine aggregate to cement ratio of 2.5:1 was used for all mortar samples. The mortar was mixed in a standing concrete mixer and required four batches for all specimens. The mix proportions used per batch are given in Table 10.

Table 10. Batch quantities for the mortar mixes.

Cement, lbs	48.0
Water, lbs	19.2
Fine Aggregate, lbs	120

Mortar was then placed in molds in two lifts and vibrated for 20 seconds between lifts on a vibrating table, as shown in Figure 26.

Figure 26. Mortar specimens placed in lifts on vibration table.

Four samples were cast for each curing method: three 14 in × 2 in round pans and one 8 in × 2 in round pan. After the samples were cast, they were placed in the environmental chamber at a temperature of 100 ^{o}F +/- 2 degrees, with 32 percent relative humidity +/- 2 percent and a windspeed established based on the permeability cup test (ASTM C1653) of 0.07-0.12 oz/hour in accordance with ASTM C 156. The specification requires the samples be removed for finishing once the bleed water has fully evaporated and a moisture sheen is no longer visible on the surface. This took approximately 1.5 hours for each sample. Finishing procedures then followed by brushing the samples with a dry paint brush to create texture and then a small groove was cut into the edge of the mortar, as shown in Figure 27. A silicone sealant was used to seal the gap between the mortar sample and the pan. This ensured that moisture loss would occur only from the surface of the sample and not from drying that may occur between the edge of the specimen and the pan. The finished sample is shown in Figure 28. The initial mass was then measured. Finally, the curing compound was then sprayed on the surface of the samples using a hand wand sprayer and the final mass and time were recorded. Specimens were then immediately returned to the controlled environmental chamber, as shown in Figure 29.

Figure 27. Grooves cut in mortar specimens following dry brush texturing.

Figure 28. Silicone sealed specimens following groove cutting.

Figure 29. Finished specimens placed in environmental chamber.

The mass of the specimens was measured daily for determining moisture loss. At 3, 7 and 28 days following casting, specimens were removed from the controlled environmental chamber, a final mass was taken, and the specimens were demolded and then cut into compression and permeability specimens. Three compression strength cubes (2 in × 2 in × 2 in cubes) were cut from the mortar samples for 3-, 7- and 28-day testing. A typical demolded specimen to be sawed is shown in Figure 30.

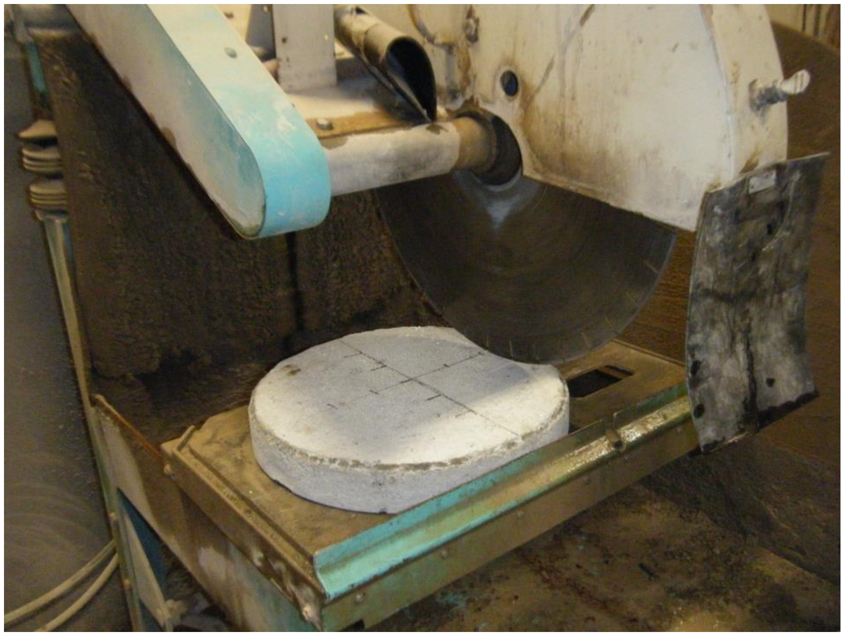


Figure 30. Mortar cubes being cut from the curing specimens.

Following sawing, the cubes were submerged into a water bath for at least an hour, which was determined to be the minimum time required for the cubes to reach saturation. Compressive strength was then tested according to the specification ASTM C109 using the compression machine shown in Figure 31.

Figure 31. Typical 2 in mortar cube tested for compression strength.

At 28-day testing, three 4-in diameter cores were cut from each specimen for permeability testing as well. The permeability testing setup was devised to quantify the amount of water traveling through the cylindrical mortar specimen and is shown in Figure 32.

Once the permeability specimens were cored from the mortar specimens, they were then submerged for one day to ensure complete saturation before being placed in the permeability apparatus. This was to ensure water flow through all specimens would occur in a fully saturated condition. The specimens were then blotted dry to a saturated surface dry condition and the outside was coated with a thin layer of petroleum jelly. The top and bottom funnels of the apparatus were attached and tightly wrapped in plastic to prevent moisture loss from the sides. Water was then pumped into the funnel, until reaching the desired level on the pipette. The drop in the water level within the pipette was then measured over a period of several days.

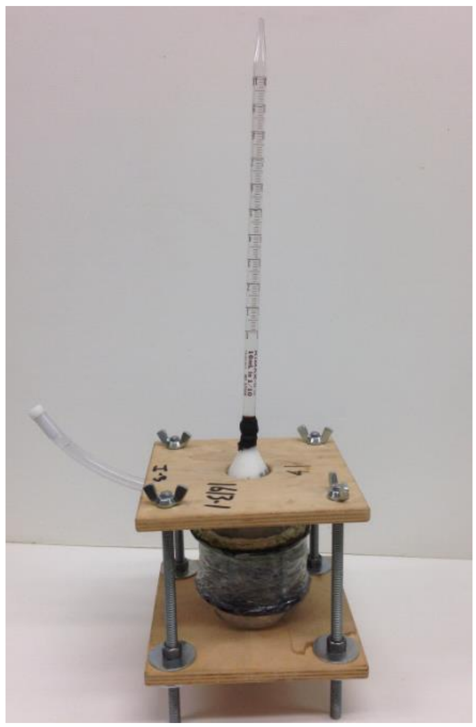


Figure 32. The permeability testing setup.

6.1.b. Results from the curing study

The moisture loss, compressive strengths and permeability measurements and surface observations for each of the curing methods is provided below with a discussion of the results. Figure 33 shows the cumulative moisture loss for the specimens in pounds per square foot of surface area versus time for the first 3 days. This is the required test duration for the ASTM C 156 specification but values extending to 7 days are given in Figure 34. The moisture loss for each of the treatments is consists of the average of the samples treated with each specific curing method. From all three plots, it can be seen that the dry treatment resulted in the greatest moisture loss while the wet treatment resulted in the lowest moisture loss. In fact some increase in moisture was observed. This can be attributed to the additional adsorption of water over time. All five curing compound treatments resulted in a moisture loss between the two extremes of the dry and the wet curing treatment.

From Figures 33 and 34, it can be observed that the moisture loss was significantly lower for the curing compounds with the AMS resin. The curing compounds with the wax did perform slightly better than the non-AMS resin. An increase in the percent solids from 37 to 44 percent did result in a lower moisture loss for the AMS resin. The benefit of the increase in the percent solids was not as apparent for the wax based curing compounds. The moisture loss between the wax based curing compounds was very similar.

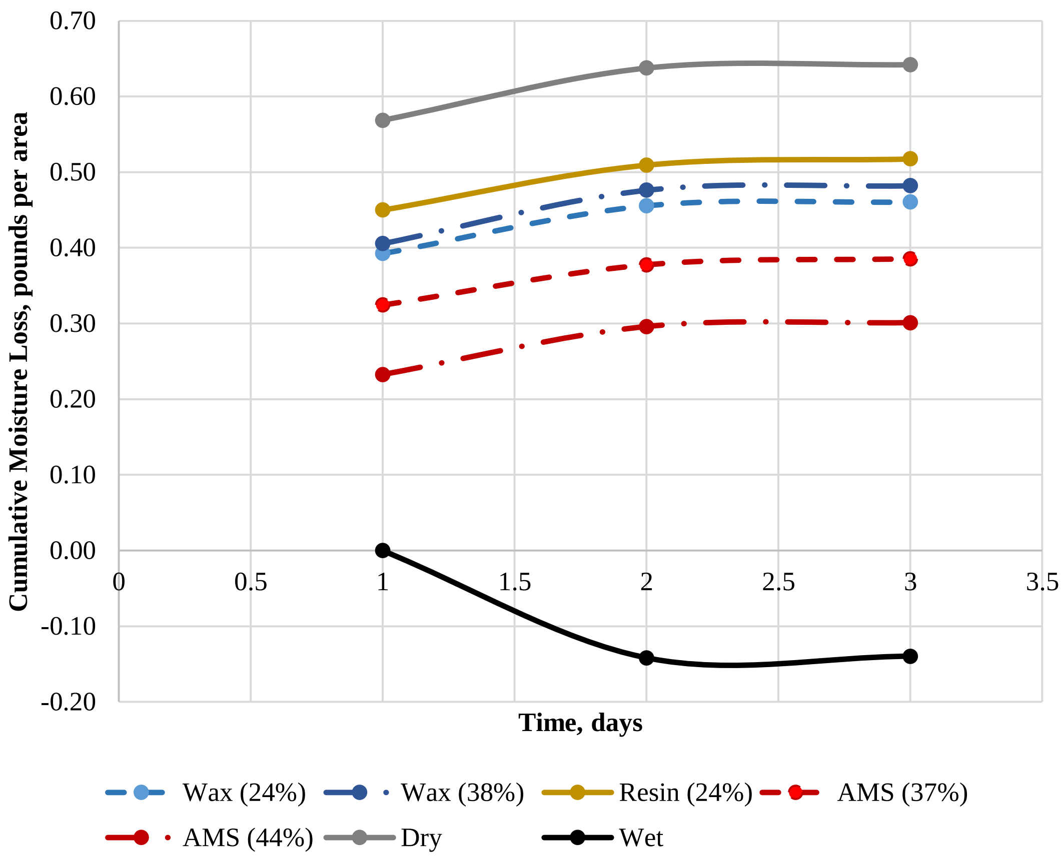


Figure 33. Moisture loss per area vs. time for 3 days.

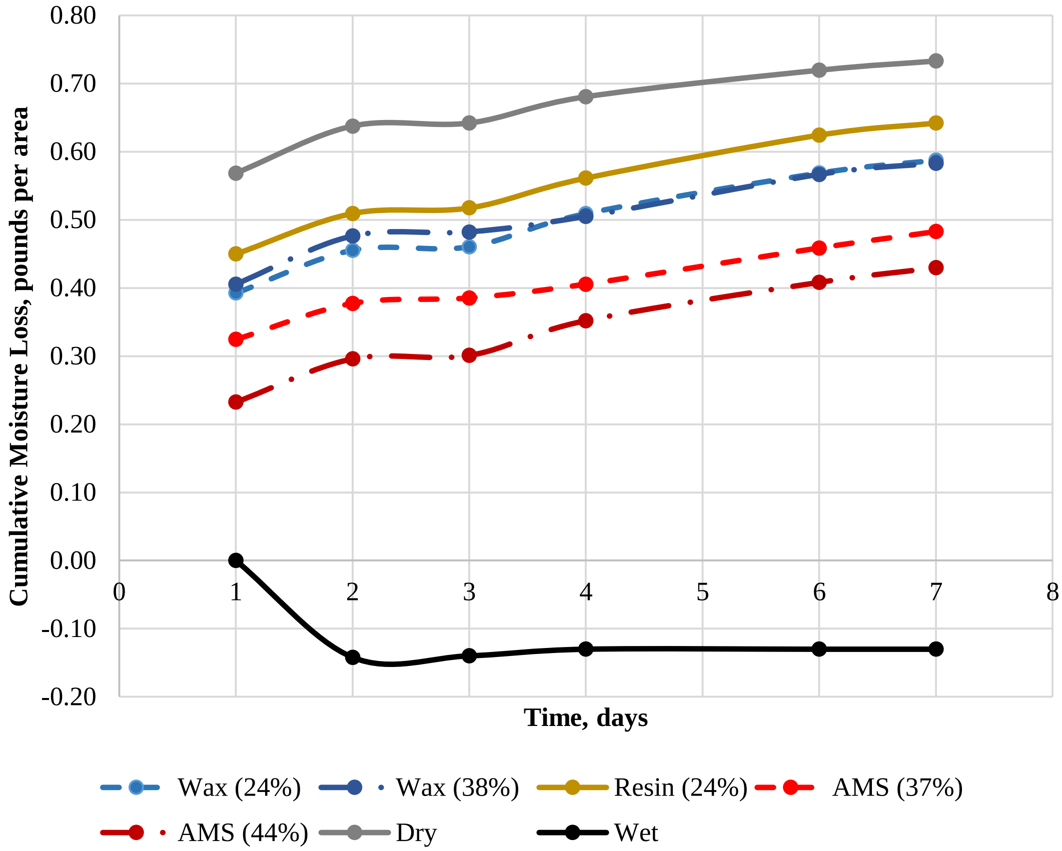


Figure 34. Moisture loss per area vs time for 7 days.

Hypothesis testing was then completed for moisture loss for the cumulative values of moisture loss per unit area for the 3- and 7-day results. As seen in Figures 33 and 34 above, the average values for similar solid type (ie, wax, resin, or specifically, the AMS resin) are quite close. Therefore, the data was initially divided by the resin type in order to observe statistically significant trends. Data from both wax based curing compounds was combined for the "Wax" category and data from both AMS curing compounds was combined for the "AMS" category, while the unnamed resin was averaged by itself and is labeled "Resin." The P-values from significant observations (defined as having a P-value of less than 0.1), which emerged from this one-tailed hypothesis testing analysis will be discussed.

First, significant relationships relative to the two control curing methods will be discussed. The wet cure and the dry cure methods provided control methods for this curing compound study and provided boundaries between which all other moisture loss values fell. The wet cure would be considered an 'ideal' curing method and should optimally have no moisture loss at all. The dry cure would be considered the worst curing method and would experience the greatest level of moisture loss. Table 11 below shows the significant relationships between different curing methods and both control curing methods for both 3-day and 7-day moisture loss.

Table 11. Significant relationships for cumulative moisture loss for control curing methods.

	Compared curing methods			P-value
3-day	Dry cure	>	Wax	0.0040
	Dry cure	>	Resin	0.0162
	Dry cure	>	AMS	0.0003
	Wet cure	<	Wax	0.0000
	Wet cure	<	Resin	0.0000
	Wet cure	<	AMS	0.0000
	Wet cure	<	Dry cure	0.0000
7-day	Dry cure	>	Wax	0.0276
	Dry cure	>	Resin	0.0661
	Dry cure	>	AMS	0.0020
	Wet cure	<	Wax	0.0000
	Wet cure	<	Resin	0.0000
	Wet cure	<	AMS	0.0002
	Wet cure	<	Dry cure	0.0013

From these values, it becomes evident that statistically, the dry cure experiences more moisture loss than all other methods of curing for both the 3-day and the 7-day testing. The wet cure experiences significantly less moisture loss than all curing methods for both 3-day and 7-day moisture measurements. This implies both that any method of curing is better than no curing at all and that wet curing remains the best curing method of any possible curing method. Therefore, the curing compounds behaved as expected in relation to the control curing methods, such that both control curing methods provided statistically significant boundaries for the other curing methods. These significant relationships were all expected. The relationships between the specific types of curing compound are given in Table 12 below.

Table 12. Significant relationships for cumulative moisture loss by solids type.

	Compared compounds			P-value
3-day	Wax	<	Resin	0.0208
	Wax	>	AMS	0.0010
	Resin	>	AMS	0.0010
7-day	Wax	<	Resin	0.0462
	Wax	>	AMS	0.0266
	Resin	>	AMS	0.0087

There are some expected significant relationships from the moisture loss results, which followed ASTM C 156 testing. First of all, it can be seen that all curing compound performance maintained the same trends across 3-day and 7-day moisture loss, albeit with different P-values. It can be seen that the wax experienced more moisture loss than only the AMS resin: the unnamed resin experienced more moisture loss than the wax for both 3-day and 7-day results. Additionally, it can be seen that the AMS type resin always performed better, as in, experienced less moisture loss, than the unnamed resin and finally, that the AMS resin always performed better than the wax-based curing compounds. It is important to note that the AMS based curing compound samples had statistically less moisture loss than the wax-based curing compounds with a P-value of 0.0010 and 0.0266 for 3-day and 7-day results, respectively. All of these relationships were statistically significant.

The data was then further divided by curing compound and specific percentage of solids and hypothesis testing was then completed based on these categories. Again, all curing methods will be first compared against the two control methods and the statistically significant relationships are given in Table 13 below.

Table 13. Significant relationships for cumulative moisture by solids type and percentage against two control methods.

	Compared compounds			P-value
3-day	Dry cure	>	Wax (24%)	0.0032
	Dry cure	>	Wax (38%)	0.0080
	Dry cure	>	Resin (24%)	0.0162
	Dry cure	>	AMS (37%)	0.0244
	Dry cure	>	AMS (44%)	0.0006
	Wet cure	<	Wax (24%)	0.0001
	Wet cure	<	Wax (38%)	0.0023
	Wet cure	<	Resin (24%)	0.0000
	Wet cure	<	AMS (37%)	0.0045
	Wet cure	<	AMS (44%)	0.0010
	Dry cure	>	Wet cure	0.0001
7-day	Dry cure	>	Wax (24%)	0.0173
	Dry cure	>	Wax (38%)	0.0160
	Dry cure	>	Resin (24%)	0.0661
	Dry cure	>	AMS (37%)	0.0840
	Dry cure	>	AMS (44%)	0.0123
	Wet cure	<	Wax (24%)	0.0001
	Wet cure	<	Wax (38%)	0.0023
	Wet cure	<	Resin (24%)	0.0000
	Wet cure	<	AMS (37%)	0.0216
	Wet cure	<	AMS (44%)	0.0078
	Dry cure	>	Wet cure	0.0002

It is clear that the trends discussed from the general results from Table 11 all hold consistently here across both 3-day and 7-day moisture loss values. Again as expected, all curing methods performed statistically better than the dry curing method control and all curing methods performed statistically worse than the wet curing method control. All of the relationships were consistent across 3-day and 7-day moisture loss but with different P-values. The curing compounds were then compared against each other and the statistically significant results are given in Table 14 below.

Table 14. Significant relationships for cumulative moisture by solids type and percentage.

	Compared compounds			P-value
3-day	Resin (24%)	>	Wax (24%)	0.0151
	AMS (44%)	<	Wax (24%)	0.0172
	Resin (24%)	>	Wax (38%)	0.0812
	AMS (44%)	<	Wax (38%)	0.0353
	AMS (44%)	<	Resin (24%)	0.0036
7-day	Resin (24%)	>	Wax (24%)	0.0579
	AMS (44%)	<	Wax (24%)	0.0817
	Resin (24%)	>	Wax (38%)	0.0668
	AMS (44%)	<	Resin (24%)	0.0439

This hypothesis testing revealed similar expected, yet overall weaker, trends. This was expected because when divided, there are overall fewer samples and the averages between the same types of curing compounds are quite close. However, some consistent trends still emerged: such as the AMS (44%) performed significantly better than both Wax (24%) and Wax (38%) and Resin (24%). However, specific significant conclusions based on solids percentage within the same solids type could not be reached. Again, the general trends remained consistent between the 3- and 7-day results.

The effect of the curing treatment on the resulting compressive strength of the specimens is shown in Figure 35 and Figure 36. Although the main parameter of concern when evaluating the effectiveness of curing is moisture loss, compressive strength provides an indication of the effectiveness of the curing on the performance of the concrete. For all treatments, three 2 in × 2 in × 2 in cubes were sawed from the specimens and tested with the average values and standard deviations presented below. Again, as for the moisture loss data, the data was first divided by the resin type in order to observe statistically significant trends. Data from both wax based curing compounds was combined for the “Wax” category and data from both AMS curing compounds was combined for the “AMS” category, while the unnamed resin was averaged by itself and is labeled “Resin”. Each bar represents the compressive strength and the error bars indicate one standard deviation above and below the mean. As expected, the two control curing methods provide the extreme boundaries to frame the results of the curing compounds. This can be seen in both figures with the greatest and least strength resulting from wet and dry cures, respectively, and results from all compounds falling in between. It is also evident from the plots that the wax based compounds produce the lowest strength of the liquid membrane forming curing compounds while the AMS-based curing compounds produced the highest strength for both 3 and 7 day testing.

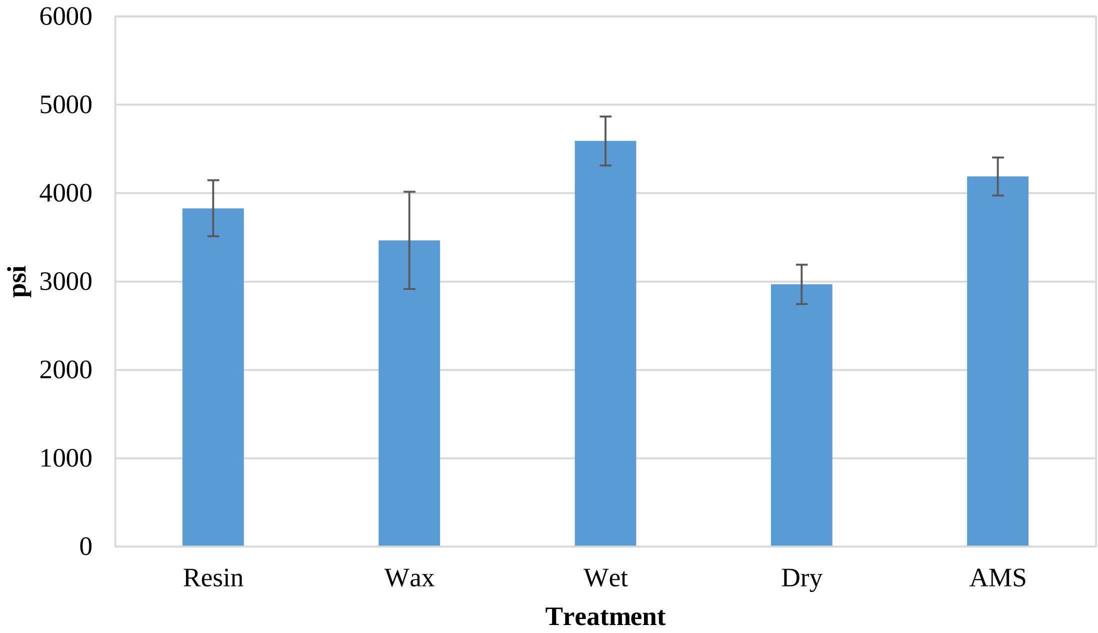


Figure 35. Average 3-day compressive strengths based on solids type.

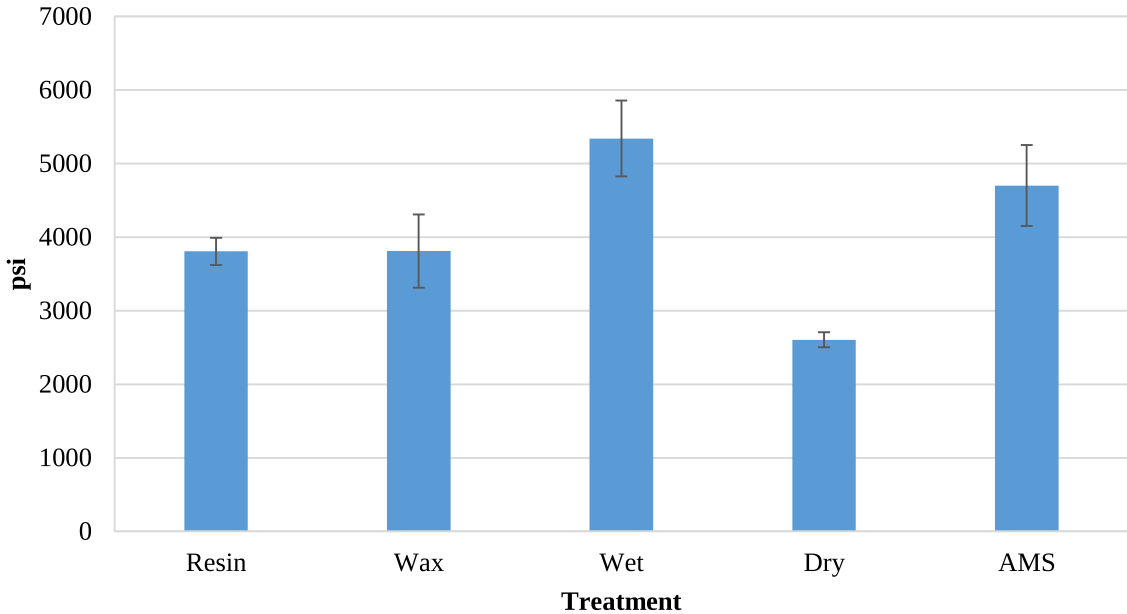


Figure 36. Average 7-day compressive strengths based on solids type.

To confirm these observed trends, hypothesis testing was completed for compression strength for 3 and 7-day strength values. Again, the data was first divided by the resin type in order to observe statistically significant trends. First, the specimens were compared against the wet and dry control curing methods only, again suspected to provide boundaries for the curing methods to fall within. The P-values from significant observations (defined as less than 0.1) for all specimens with respect to the two control curing methods are given in Table 15 below.

Table 15. Significant relationships for compressive strength testing against two control methods.

	Compared compounds			P-value
3-day	Dry cure	<	Wax	0.0163
	Dry cure	<	Resin	0.0255
	Dry cure	<	AMS	0.0005
	Wet cure	>	Wax	0.0002
	Wet cure	>	Resin	0.0128
	Wet cure	>	AMS	0.0002
	Wet cure	>	Dry cure	0.0004
7-day	Dry cure	<	Wax	0.0009
	Dry cure	<	Resin	0.0039
	Dry cure	<	AMS	0.0001
	Wet cure	>	Wax	0.0005
	Wet cure	>	Resin	0.0006
	Wet cure	>	AMS	0.0011
	Wet cure	>	Dry cure	0.0003

All of the relationships between the general types of curing compounds are again as expected. The dry curing method produced the lowest strengths of all curing methods and was statistically less than the wax, resin, and the AMS resin. This again shows that any curing method is more effective than no curing at all. The wet curing method produced strength results that were significantly higher than all other curing methods including the wax-based, resin based, and AMS curing compounds. The results were consistent between 3-day and 7-day results with slightly different P-values. Again, the control values have provided extreme boundaries as expected. The significant relationships between the specific types of curing compounds are given in Table 16 below.

Table 16. Significant relationships for compressive strength testing.

	Compared compounds			P-value
3-day	AMS	>	Resin	0.0286
	AMS	>	Wax	0.0098
7-day	AMS	>	Resin	0.0011
	AMS	>	Wax	0.0015

From this data, it is clear that the AMS-based resin compound produced significantly higher compressive strength values than the wax-based curing compound with P-values of 0.0098 and 0.0015, for 3-day and 7-day results, respectively. Likewise, the AMS-based resin was found to produce statistically higher strength values than the unnamed resin compound for both 3-day and 7-day strength values as well.

The compression strength data was then further divided based on the specific percentage of the solids type. Figures 37 and 38 below give the 3-day and 7-day compression results based on both solids type and solids percentages. Within the same types of curing compounds, the strengths appear to increase with increasing percent solids. For example, the wax based curing compound with 38 percent solids performed better than the wax based curing compound with 24 percent solids. This was also true for the AMS resin, where it can be seen that the compound with greater percent solids had a greater strength at both 3 days and 7 days. The highest compressive strength from the curing compound specimens was obtained from the highest percent solids with the AMS resin.

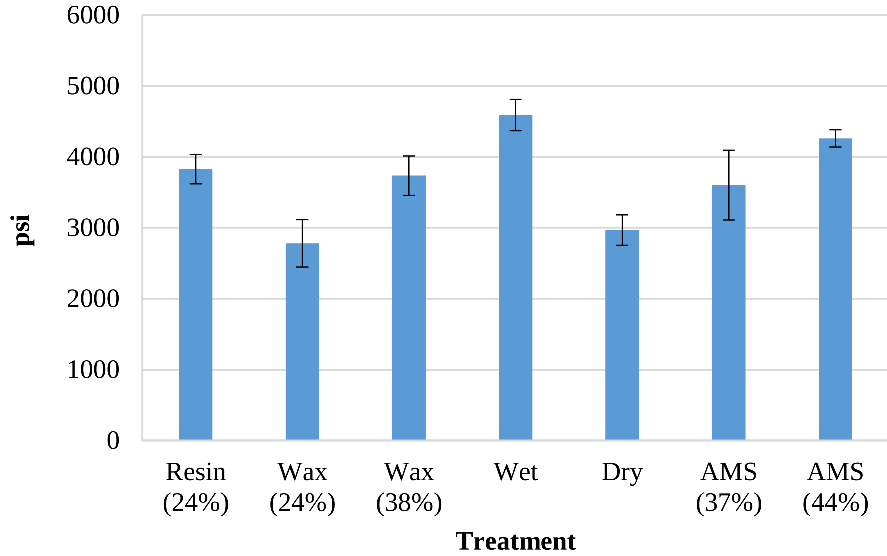


Figure 37. Average 3-day compressive strength vs cure treatment.

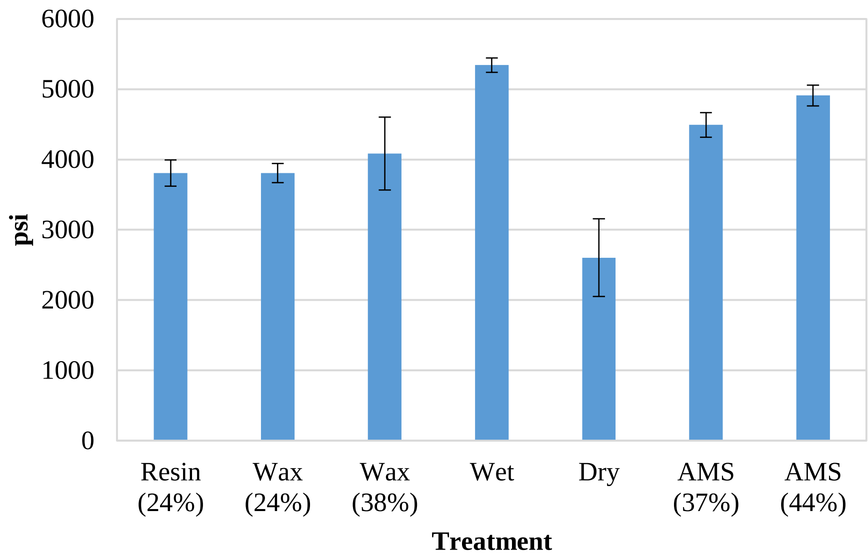


Figure 38. Average 7-day compressive strength vs cure treatment.

Hypothesis testing was then completed for compression strength for 3 and 7-day strength values but with the data divided by specific curing compound rather than the more general resin type. The significant relationships with respect to the two control curing methods only, the wet cure and the dry cure, are first given in Table 17 below.

Table 17. Significant relationships for compressive strength testing for specific solids type and percentage against two control methods.

	Compared compounds			P-value
3-day	Wet cure	>	Wax (24%)	0.0022
	Wet cure	>	Wax (38%)	0.0126
	Wet cure	>	Resin (24%)	0.0061
	Wet cure	>	AMS (37%)	0.0431
	Wet cure	>	AMS (44%)	0.0550
	Dry cure	<	Wax (38%)	0.0161
	Dry cure	<	Resin (24%)	0.0037
	Dry cure	<	AMS (37%)	0.0885
	Dry cure	<	AMS (44%)	0.0014
	Dry cure	<	Wet cure	0.0004
7-day	Wet cure	>	Wax (24%)	0.0003
	Wet cure	>	Wax (38%)	0.0270
	Wet cure	>	Resin (24%)	0.0006
	Wet cure	>	AMS (37%)	0.0028
	Wet cure	>	AMS (44%)	0.0127
	Dry cure	<	Wax (24%)	0.0335
	Dry cure	<	Wax (38%)	0.0214
	Dry cure	<	Resin (24%)	0.0349
	Dry cure	<	AMS (37%)	0.0150
	Dry cure	<	AMS (44%)	0.0099
	Dry cure	<	Wet cure	0.0069

From the relationships given in Table 17, it is clear that, as expected, the wet cure produced specimens with significantly higher compressive strength than all other curing methods. The dry curing method produced a lower strength as compared to all five curing methods. Again, these statistically significant trends are consistent between 3-day and 7-day compression strength testing. The statistically significant relationships between the specific curing compounds only are given in Table 18 below.

Table 18. Significant relationships for compressive strength testing for specific solids type and percentage.

	Compared compounds			P-value
3-day	Wax (38%)	>	Wax (24%)	0.0064
	AMS (44%)	>	AMS (37%)	0.0763
	Resin (24%)	>	Wax (24%)	0.0097
	AMS (37%)	>	Wax (24%)	0.0484
	AMS (44%)	>	Wax (24%)	0.0095
	AMS (44%)	>	Wax (38%)	0.0479
	AMS (44%)	>	Resin (24%)	0.0263
7-day	AMS (37%)	>	Wax (24%)	0.0065
	AMS (44%)	>	Wax (24%)	0.0013
	AMS (37%)	>	Resin (24%)	0.0049
	AMS (44%)	>	Resin (24%)	0.0020
	AMS (44%)	>	Wax (38%)	0.0585
	AMS (44%)	>	AMS (37%)	0.0257

Several additional trends emerge from the compressive strength data for the specific percentages of curing compound. For 3-day compression strength data, it can be seen that higher percentages of solids for the wax and for the AMS resin produced significantly higher strength results than the lower percentages of either curing type. Specifically, the Wax (38%) produced stronger specimens than the Wax (24%) with a P-value of 0.0064 while the AMS (44%) produced stronger specimens than the AMS (37%) with a P-value of 0.0763. Additionally, for 3-day compressive strength testing, the resin performed better than the lower percentage wax and the higher percentage solids AMS performed better than both wax compounds and the unnamed resin. For 7-day compressive strength data, it can be seen that specimens for both percentages of AMS based curing compound produced higher strengths than both percentages of the wax-based compounds and the unnamed resin.

Figures 39 and 40 below present the moisture loss per unit area versus the compressive strength of the mortar samples at 3 and 7 days. From the plots, it is apparent that an inverse relationship exists between the moisture loss and the resulting compressive strength. Both regressions present high coefficients of determination indicating that a decrease in the moisture lost from the mortar sample in turn results in a relative increase in compressive strength of the samples regardless of the age of the specimens. The improved relationship exhibited for the 7-day strengths can be attributed to the fact that the impact of the flaws in the concrete as a result of micro cracking from insufficient curing will be greater when the strengths are higher.

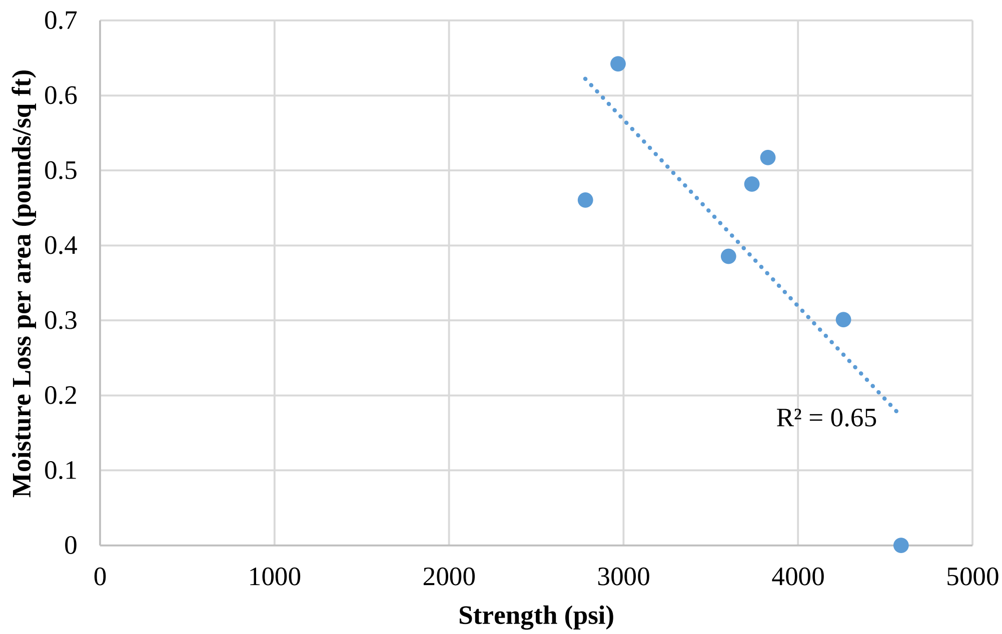


Figure 39. Moisture loss per area vs compressive strength at 3 days.

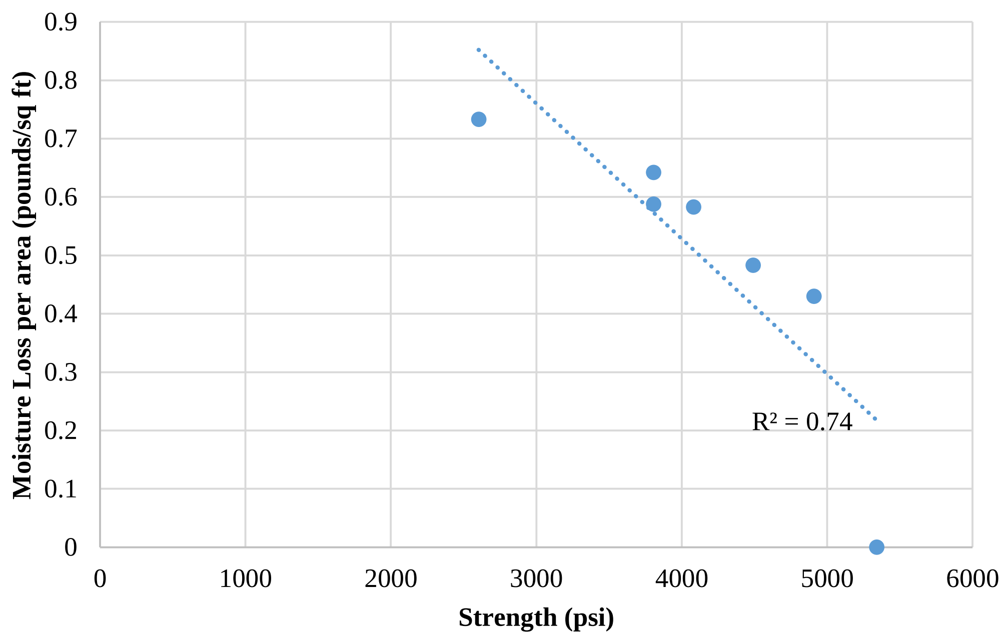


Figure 40. Moisture loss per area vs compressive strength at 7 days.

The results of the permeability testing are presented in Figure 41. Again, although the main parameter of concern when evaluating the effectiveness of curing is moisture loss, the permeability provides an indication of the effectiveness of the curing on the durability of the concrete. A previously stated, the wet and dry treatments provide extreme boundary values while the curing compounds produce results in between these two control curing methods. The wet samples produced the lowest permeability while the dry air cured samples resulted in the highest permeability. The poly alpha methylstyrene treatments resulted in the permeability most like that of the wet samples followed closely by the resin and then both wax treatments. Therefore, the application of the AMS based curing compounds produced the lowest permeability, which is desirable for making the concrete more durable. The variability is relatively high with this test and this is reflected in the results. Figure 41 below shows both the average results for each compound with one standard deviation above and below the mean reflected by a black bar.

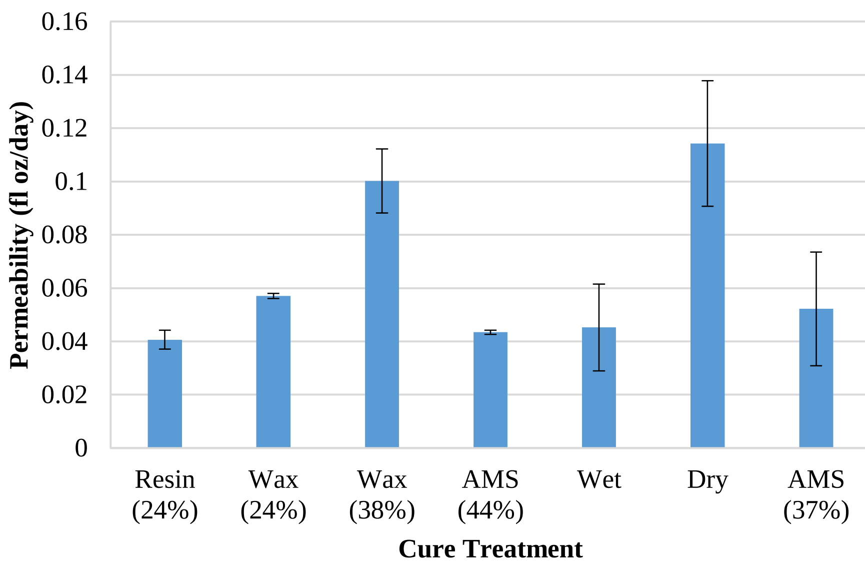


Figure 41. Permeability results for each curing treatment.

Hypothesis testing was then completed for the permeability measurements. The P-values from significant observations (defined as less than 0.1) which emerged from this analysis are given in Table 19 below when compared against the two control curing methods of dry and wet curing.

Table 19. Significant relationships for permeability testing against two control methods

Compared curing methods			P-value
Dry cure	>	Wax (24%)	0.0904
Dry cure	>	Resin (24%)	0.0716
Dry cure	>	AMS (44%)	0.0736
Wet cure	<	Wax (38%)	0.0812
Wet cure	<	Dry cure	0.0989

Significant differences were present between the wet and the dry cure. Additionally, the dry cure performed worse than the lower percentage wax, the unnamed resin, and the higher percentage AMS. The wet cure performed statistically better than the higher percentage wax cure. Comparisons between the specific curing compounds from this testing are given in Table 20 below.

Table 20. Significant relationships for permeability testing.

Compared curing methods			P-value
Wax (24%)	<	Wax (38%)	0.0622
Wax (24%)	>	Resin (24%)	0.0496
Wax (24%)	>	AMS (44%)	0.0202
Wax (38%)	>	Resin (24%)	0.0470
Wax (38%)	>	AMS (44%)	0.0475

It can be seen from this statistical testing that AMS curing compounds produced the lowest permeability measurements of all curing methods. The resin (24%) had significantly lower permeability results than both wax compounds. The AMS (44%) produced significantly lower permeability values than both wax based curing compounds.

Surface observations were also made using a microscope for the 28-day samples. The images for each surface are shown in Figure 42 below. It can be seen that only the dry sample actually experienced surface cracking observable through slight magnification. In some compounds, most notably, the unnamed resin, apparent cracks were not mortar cracks but were splitting of the curing compound, as in, the surface failed to act as an impermeable membrane. The difference in compound material composition is interesting in comparing the AMS compounds because the primary difference between the AMS (37%) and the AMS (44%) made by the manufacturer is a difference in reflectance. Despite being based in the same resin type, it is very clear that the resin appears differently when greater reflectance is desired.

Figure 42. Surface images from 28-day samples for all curing methods.

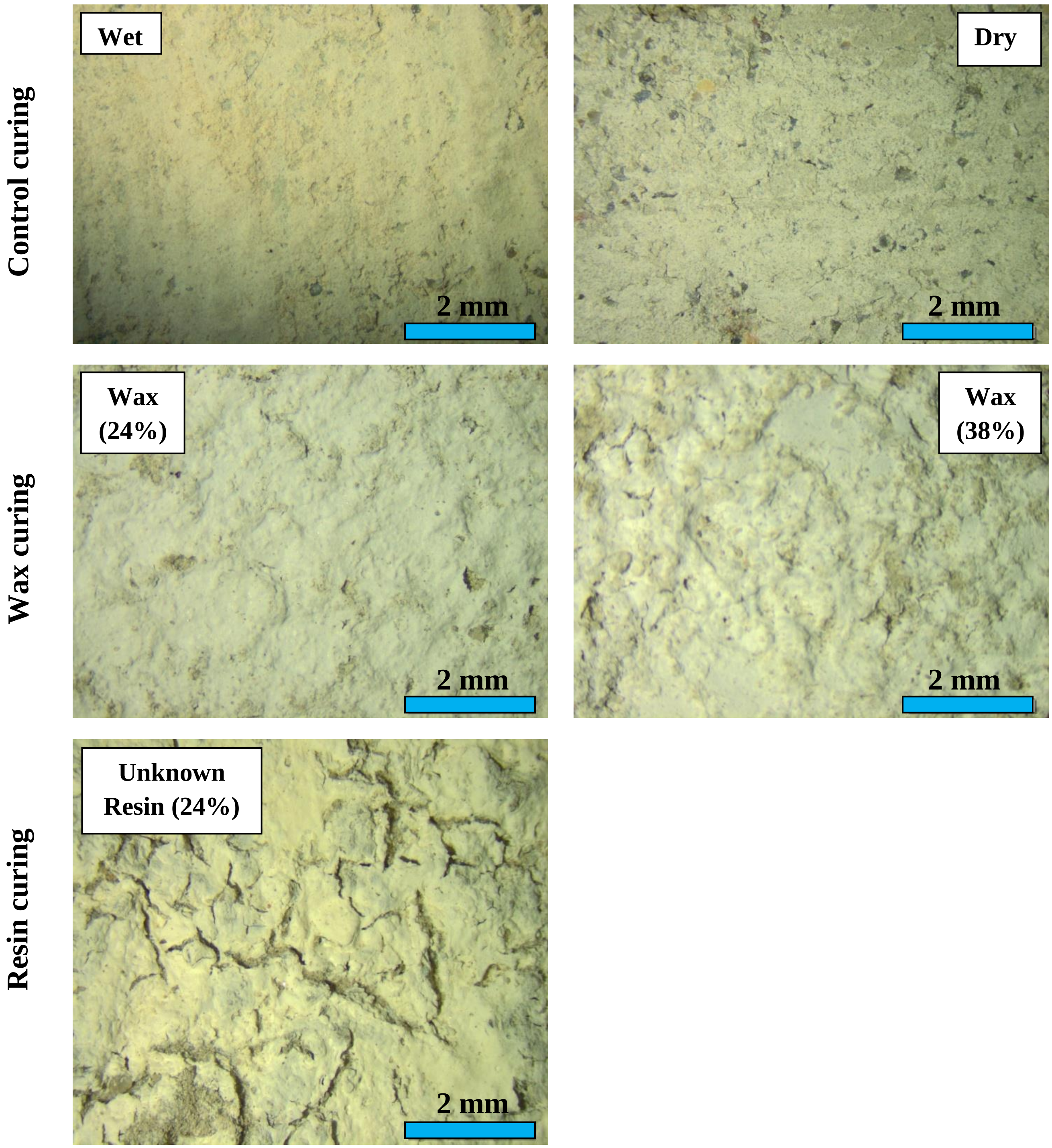
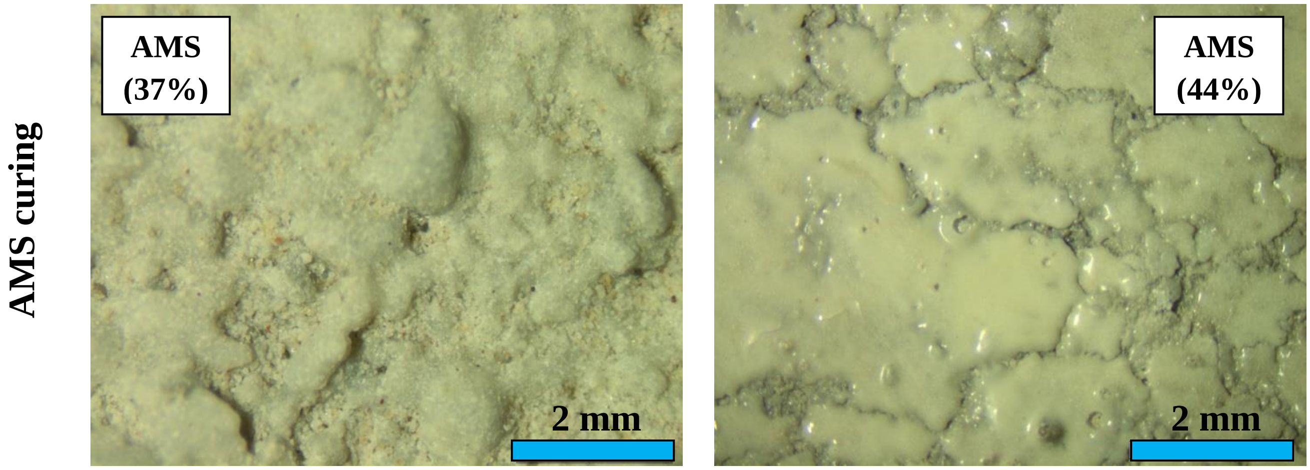


Figure 42. Surface images from 28-day samples for all curing methods (cont).



Overall, the curing compounds with the AMS performed the best with respect to reducing moisture loss, higher compressive strengths and lower permeability. Increasing the percent solids was also helpful in increasing the effectiveness of the curing compound. Above, it was shown that conditions are favorable for plastic shrinkage cracking for a large portion of the time throughout the construction period so the use of an effective curing compound is essential in preventing plastic shrinkage cracking.

6.2.Mix design study

Several critical factors were identified regarding the mixture design to decrease drying shrinkage, reduce the potential for segregation and improve overall durability. This included reducing the w/cm ratio to 0.42 or less and using a more densely graded aggregate. To evaluate the effects of these two mix design parameters, two mixtures were designed and the effect on drying shrinkage was evaluated through casting instrumented beams. Drying shrinkage beams were also cast but sufficient time was not available to measure the ultimate drying shrinkage for the two mixtures.

6.2.a.   Description of the mix design study

One mix was designed to meet Publication 408 Specifications. The second mix design was a revised mix optimizing the two factors of concern; w/cm ratio and aggregate gradation. The information regarding the materials used for the concrete mixes is provided below in Table 21.

Table 21. Material used for concrete mixes.

Coarse aggregate	
Type	River gravel
Top size	1.0 in
Bulk specific gravity (SSD)	2.50
Absorption capacity	2.07 %
Los Angeles abrasion value	34%
Fine aggregate	
Fineness modulus	2.86
Absorption capacity	1.24%
Bulk specific gravity (SSD)	2.62
Cement	
Type	ASTM Type I Portland
Chemical Admixtures	
Air Entrainer	CATEXOL AE 360
Superplasticizer	Sikament SPMN

The standard PennDOT mix followed the requirements given in Section 704.1 of the 408 Standard Specification. The requirements from the specification for Type AA (paving) concrete are summarized in Table 22.

Table 22. PennDOT Specification for concrete paving mixes.

Criteria	Value
Water/cement ratio	0.47
Slump, in	<5[1]
Entrained air content	4.5% to 7.5%
Min. 28-day compressive strength	3500 psi
Minimum cement content	587.5 lbs/yd^3

[1] Pennsylvania’s requirement states that the slump be less than 5 inches for all concrete but can be less than 6.5 inches for concrete containing a water reducing admixture, and less than 8 inches for concrete containing a superplasticizer.

The aggregate gradation required for PennDOT paving projects follows a standard AASHTO No. 57 gradation and is provided in Table 23. However, the only exception from the standard gradation is that for paving concrete, a minimum of 35% must pass the ½ in sieve.

Table 23. Coarse aggregate gradations for PennDOT paving projects.

Sieve Size	Percent Passing
1 ½ in	100
1 ¼ in	
1 in	95-100
¾ in	
½ in	35-60
3/8 in	
No. 4	0-10
No. 8	0-5

The revised mix also fell within these specifications but additional constraints were imposed. A lower w/c ratio of 0.4 was used along with a densely graded Shilstone gradation. A summary of both mix designs is given in Table 24.

Table 24. Mix design for the two mixes considered, per cubic yard.

	PennDOT Mix	Revised Mix
W/c ratio	0.47	0.4
Target air content, %	6	6
Target slump, in	5	2.5
Water, lbs/yd^3	276	232
Cement, lbs/yd^3	588	580
Air Entrainer, oz/ yd^3	8.81	10.44
Superplasticizer, oz/ yd^3	---	87
Fine aggregate, lbs/yd^3	881	1330
Coarse aggregate, lbs/yd^3	1962	1903

The two aggregate gradations used for the standard mix design and the revised mix design are given in Table 25. Their location on the Shilstone coarseness factor chart is shown in Figure 43.

Table 25. Aggregate gradations used for the PennDOT and the revised mixes.

	CA Gradation for the Revised Mix			CA Gradation for the PennDOT Mix		
Sieve size	% passing	Cumulative % retained	% retained	% passing	Cumulative % retained	% retained
1.5 in	100	0		100	0	
1 in	97.86	2.14	2.14	96.98	3.02	3.02
0.75 in	86.59	13.41	11.26	81.1	18.9	15.88
0.5 in	70.15	29.85	16.44	57.93	42.07	23.17
0.375 in	59.71	40.29	10.44	43.22	56.78	14.71
No 4	46.93	53.07	12.79	34.21	65.79	9.01
No 8	36.51	63.49	10.42	24.89	75.11	9.32
No 16	28.58	71.42	7.92	19.49	80.51	5.4
No 30	19.19	80.81	9.4	13.08	86.92	6.41
No 50	6	94	13.19	4.09	95.91	8.99
No 100	1.21	98.79	4.79	0.83	99.17	3.26
No 200	0.4	99.6	0.81	0.27	99.73	0.55

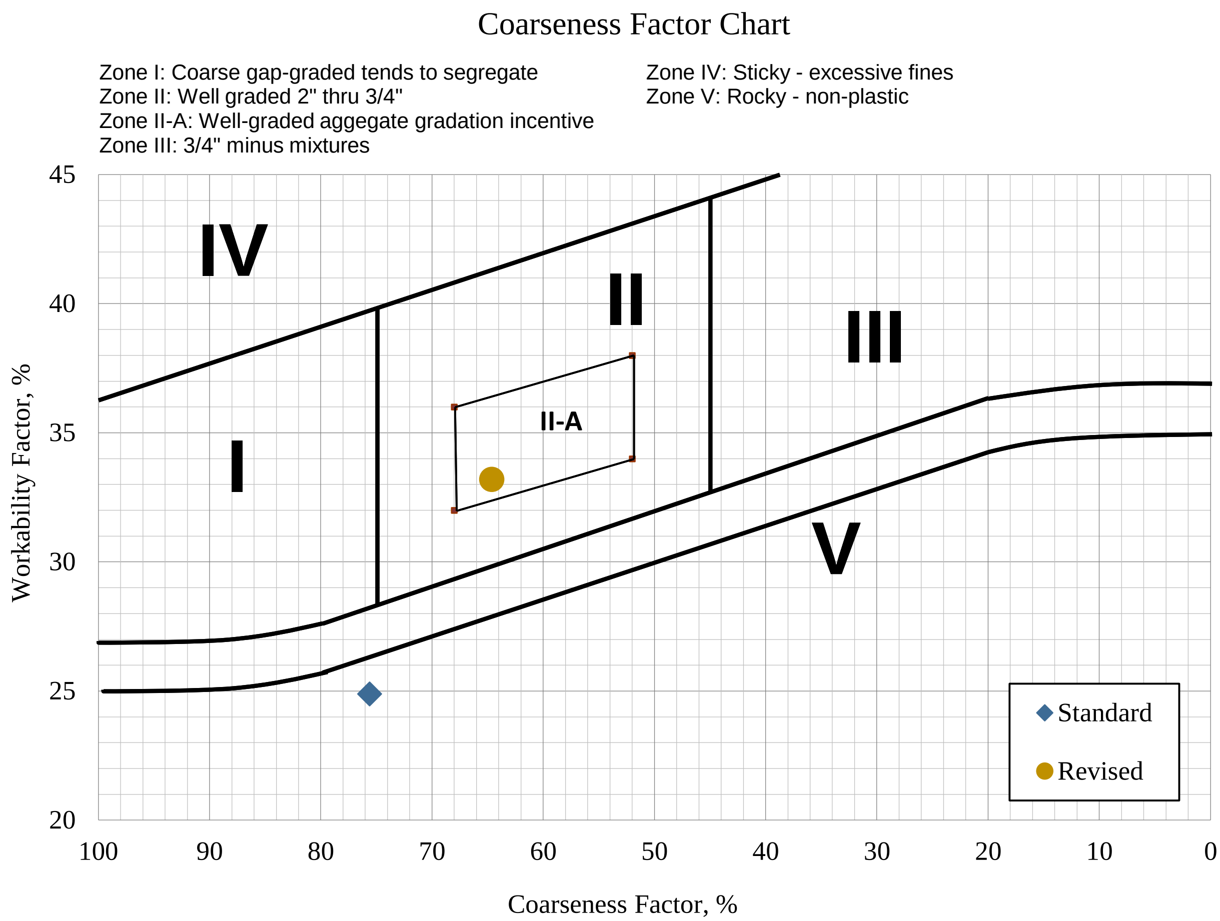


Figure 43. Location of aggregate gradations on Shilestone coarseness factor chart.

Test batches were made and the admixture dosage rates were adjusted until the target slump and air content were reached for each mixture design. Three types of specimens were then cast from each mix. Standard 4 in × 8 in cylinders were cast from each to measure both 28-day compressive strength as well as the elastic modulus for each mix. Additionally, three 4 in × 4 in × 11 in drying shrinkage beams were cast for each mix to be tested in accordance with AASHTO T 160: Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete. Finally, three 3 in × 4 in × 16 in beams were cast for each mix type and were instrumented with both Geokon 4200 strain gages and Sensirion SHT75 relative humidity sensors. The strain gages measure both strain and temperature, while the relative humidity sensors measure both temperature and relative humidity. Each instrumented beam contained one strain gage and six relative humidity sensors with the dimensions for the layout given in Figure

44. The instrumented beam prior to casting is shown in Figure 45 and the instrumented beams following casting are given in Figure 46.

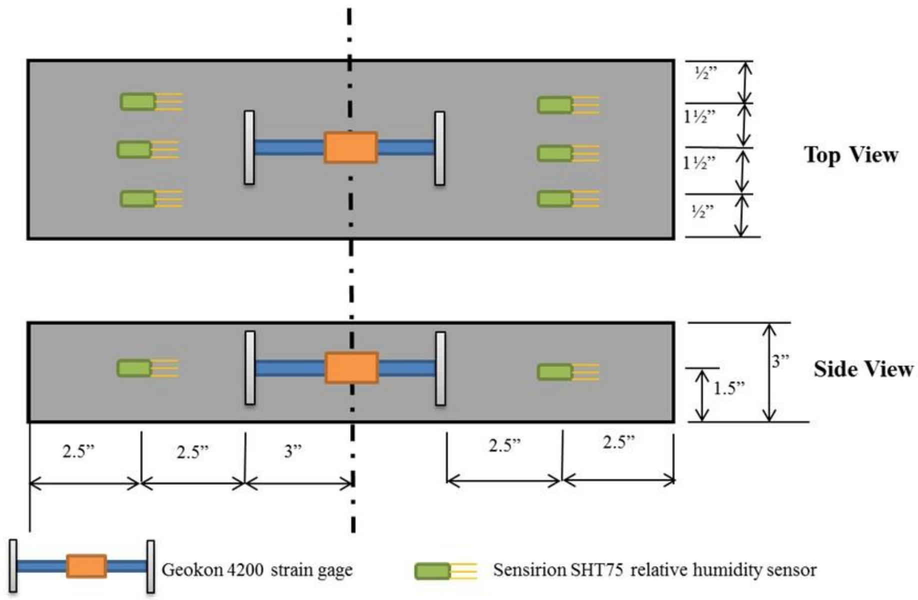


Figure 44. Location of sensors in instrumented beams.

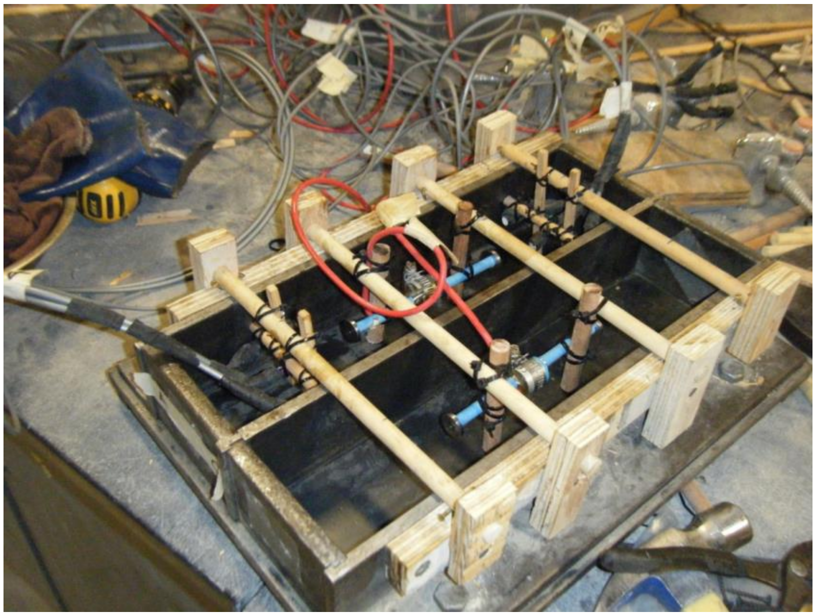


Figure 45. Typical instrumented beams prior to casting.

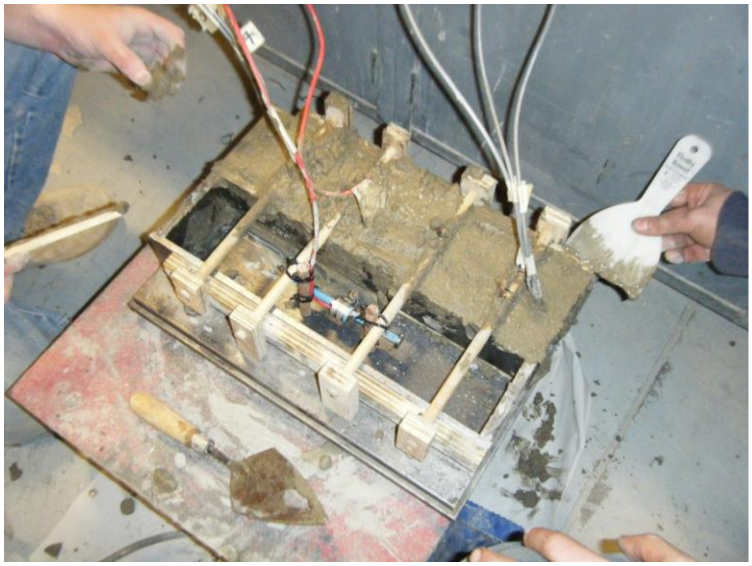


Figure 46. Typical instrumented beams following casting.

6.2.b. Results from the mix design study

Following casting, the cylinders and drying shrinkage beams for the AASHTO T 160 test were placed in a curing room for 28 days. The drying shrinkage beams were then moved to a controlled humidity chamber with 50 percent relative humidity and a constant temperature of 72 ^{o}F. The instrumented beams were covered with wet burlap and a plastic sheet for the first 24-hours after casting and then cured for five days in a water bath. They were then placed into a controlled environmental room under the same requirements as the ASTM C156 for evaluating the curing compounds. The temperature, relative humidity and strain were monitored using a CRX3000 to record the sensor data every 15 minutes.

The results from the standard 4 in × 8 in cylinders for the 28-day compressive strength and elastic modulus for each mix are presented below in Table 26. As can be observed, the revised mix resulted in higher strengths and stiffnesses as compared to the PennDOT mix. However, some variability is observed between the two revised mix batches on 11/23 and 11/24. It should also be noted that the compressive strengths of the PennDOT mix did not reach the specified 28-day compressive strength of 3500 psi required for Class AA concrete. Additional PennDOT mix specimens from a different date were created and tested, however, due to an issue with the equipment, the results are not reliable.

Table 26. 4 in × 8 in cylinder 28 day test results for Revised and PennDOT mixes.

		Revised Mix 11/23	Revised Mix 11/24	PennDOT Mix 11/24
Compressive strength	Average	4120 psi	4960 psi	3140 psi
	Standard deviation	100 psi	N/A	N/A
	Number of samples	4	2	2
Elastic modulus	Average	3.4×10^6 psi	4.3×10^6 psi	2.4×10^6 psi
	Standard deviation	2.5×10^5 psi	N/A	N/A
	Number of samples	4	1	2

The temperature and relative humidity data for each beam is plotted in Figures 47 through 52. It is important to note that different mixes were cast on different days in order to randomize the mixing procedures. Therefore, instrumented beams were cast across several days and the plots have been zeroed by the age of the specimen to when each was cast.

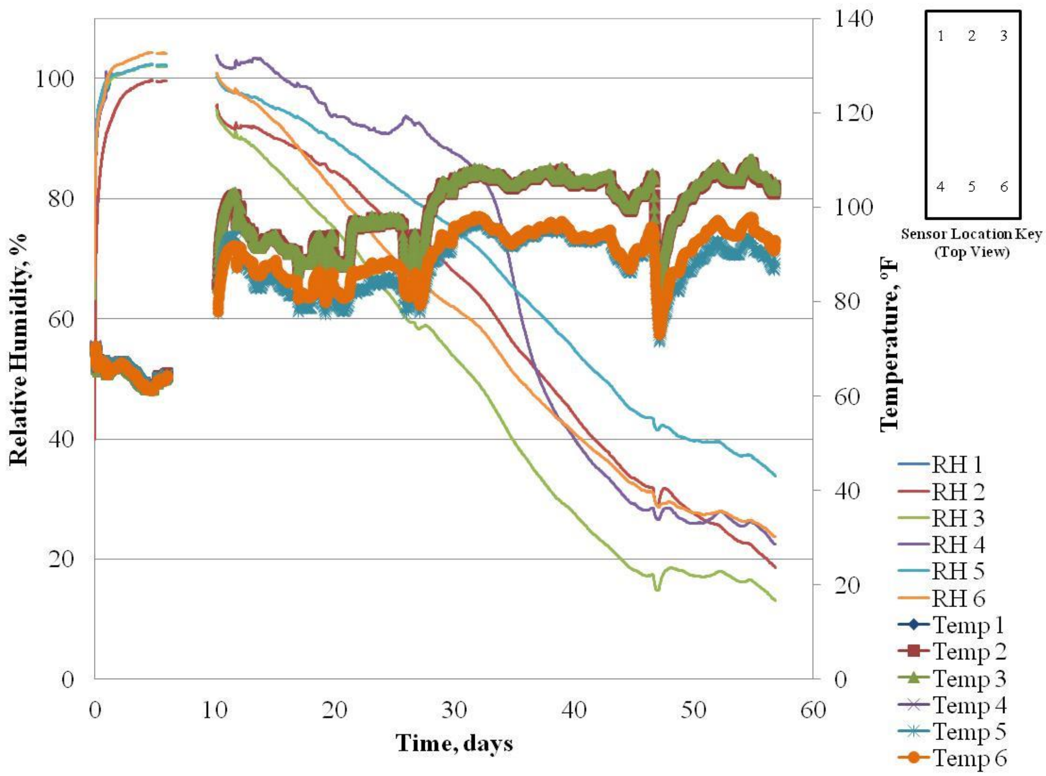


Figure 47. Temperature and humidity data for Beam 1 of the PennDOT mix.

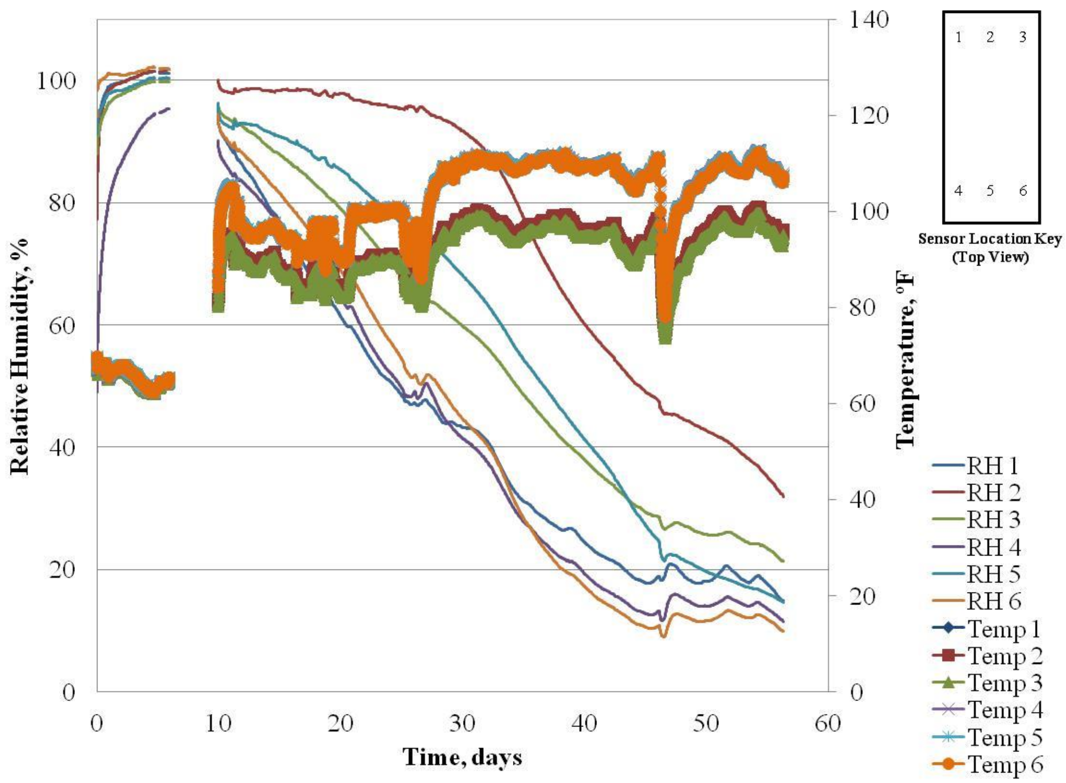


Figure 48. Temperature and humidity data for Beam 2 of the PennDOT mix.

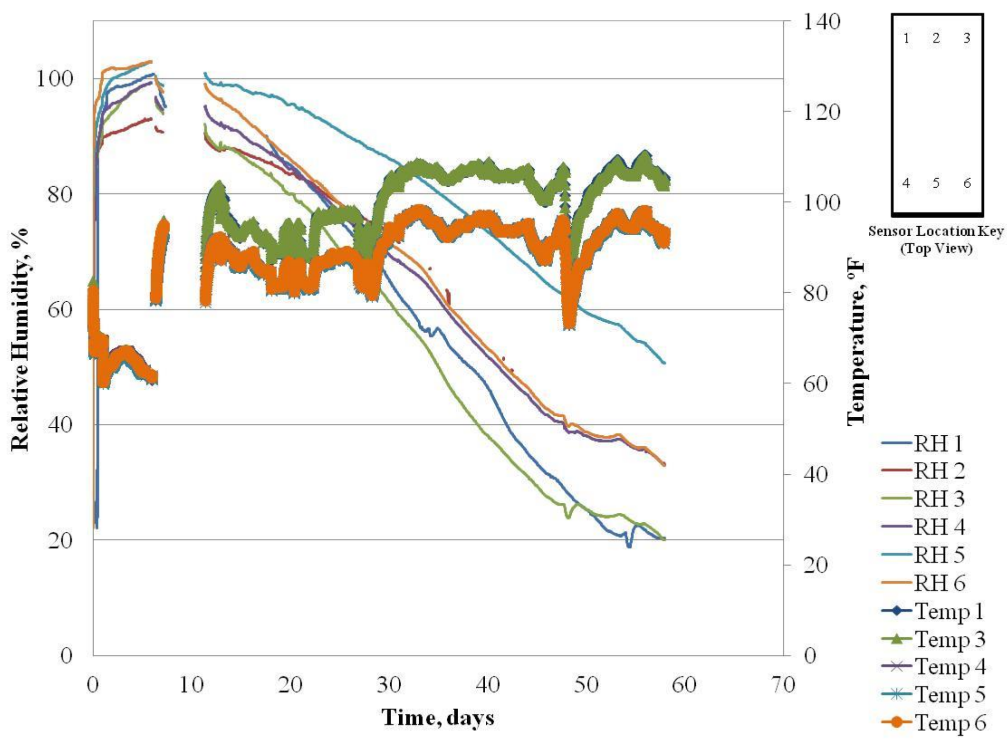


Figure 49. Temperature and humidity data for Beam 3 of the PennDOT mix.

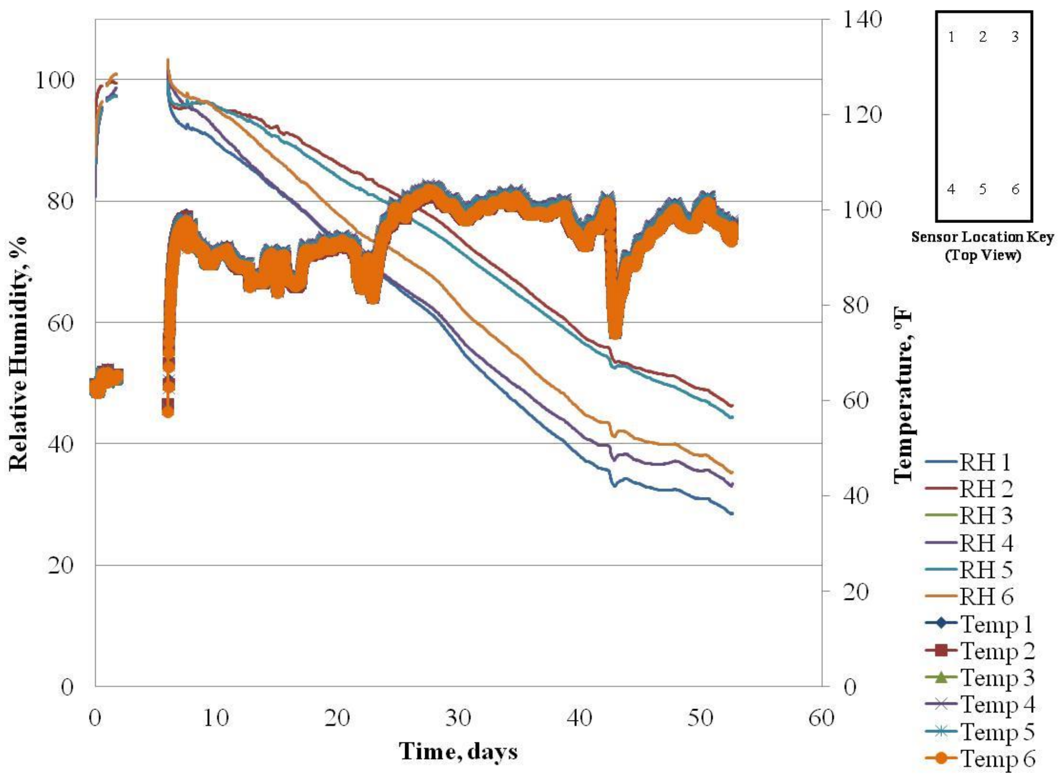


Figure 50. Temperature and humidity data for Beam 1 of the revised mix.

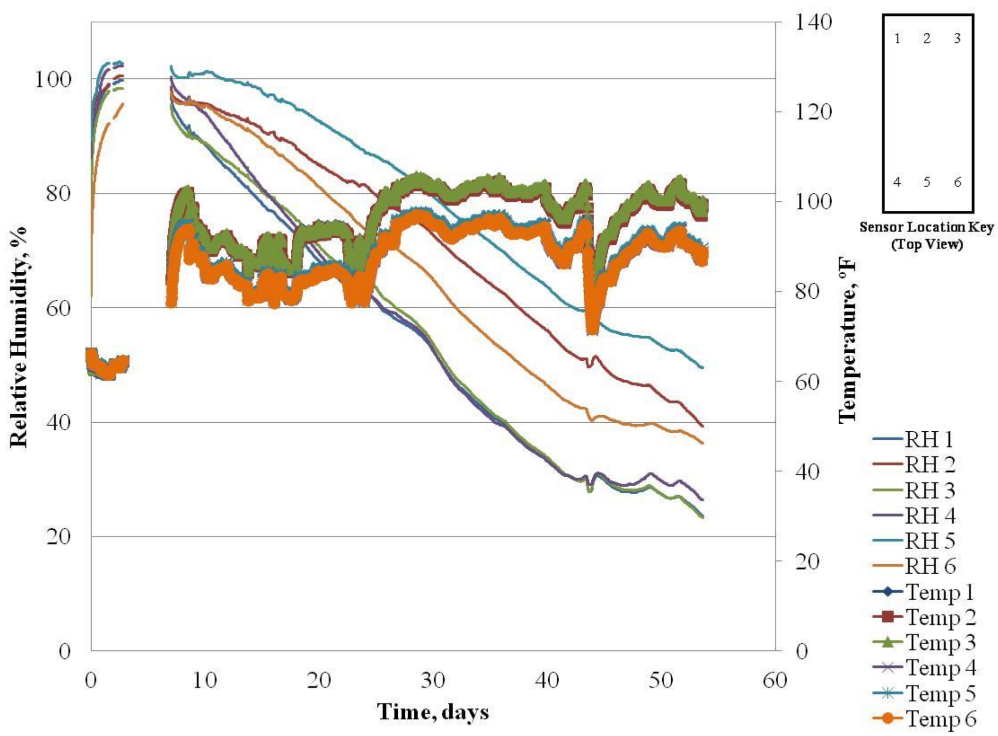


Figure 51. Temperature and humidity data for Beam 2 of the revised mix.

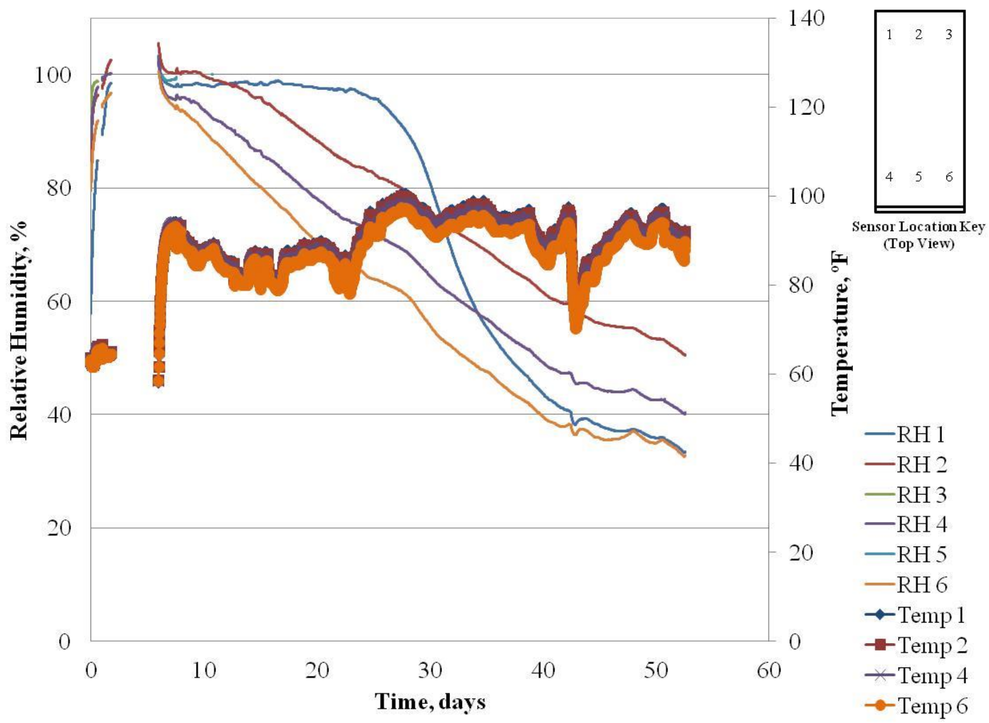


Figure 52. Temperature and humidity data for Beam 3 of the revised mix.

It can be seen in these figures that the relative humidity is initially 100 percent when originally cast and then decreases over time due to the high temperature and low relative humidity in the curing chamber. The sensors show the relative humidity in the central portion of the beam to be higher than that measured near the surface. As the beams continue to be exposed to these conditions in the chamber, the moisture content in the beam will become constant. These specimens can then be re-exposed to wet conditions so that the recoverable drying shrinkage can be established for each mixture design. Therefore, all results thus far only represent the total strain, and currently there is no method of knowing the portion of recoverable strain.

It should be noted that the placement of the beams within the controlled environmental room had some effect on the results. Due to limitations of the cord lengths of the relative humidity sensors, the specimens were located near the door of the environmental room which resulted in some observed temperature fluctuation over the course of the experiment. Therefore, while the relative humidity measurements on either edge of the instrumented beam should be theoretically very close, a gradient present due to the exposure conditions for the PennDOT mix beams 1, 2 and 3, and the revised mix beam 2. Additionally, there were a few days of extremely cold temperature in Pittsburgh which affected the temperature of the environmental chamber and resulted in a significant temperature drop around day 45 as can be observed in all six beam figures. It should also be noted that due to an error with the data acquisition system, approximately 4 days of data was lost early in the experiment. This was typically around 10 days after casting for most beams but fluctuated slightly since not all beams were cast on the same day.

The drying shrinkage measured to date can be observed in Figure 53 for both mixes. It should be noted that the strain gage in mix beam 2 of the revised began to malfunction after 27 days. Therefore no data is reported after this time for that particular beam. The strain is as zero at the time the beams were removed from the water bath. The 5-day wet cure resulted in swelling for both mixes, which is indicated by the positive strain at the time of casting. The PennDOT mix exhibited a higher degree of swelling. This is because the w/c ratio is substantially higher and therefore the permeability is higher. This allows greater access of the cure water to the interior of the concrete. Once the specimens are placed in the high temperature/low relative humidity room, drying shrinkage is observed. Although the initial drying shrinkage is lower for the PennDOT mix, it appears that the drying shrinkage trends are beginning to cross. The relative humidity data for the six beams plotted together is shown in Figure 54. A longer time period of evaluation is necessary to understand the complete behavior of the two mixes.

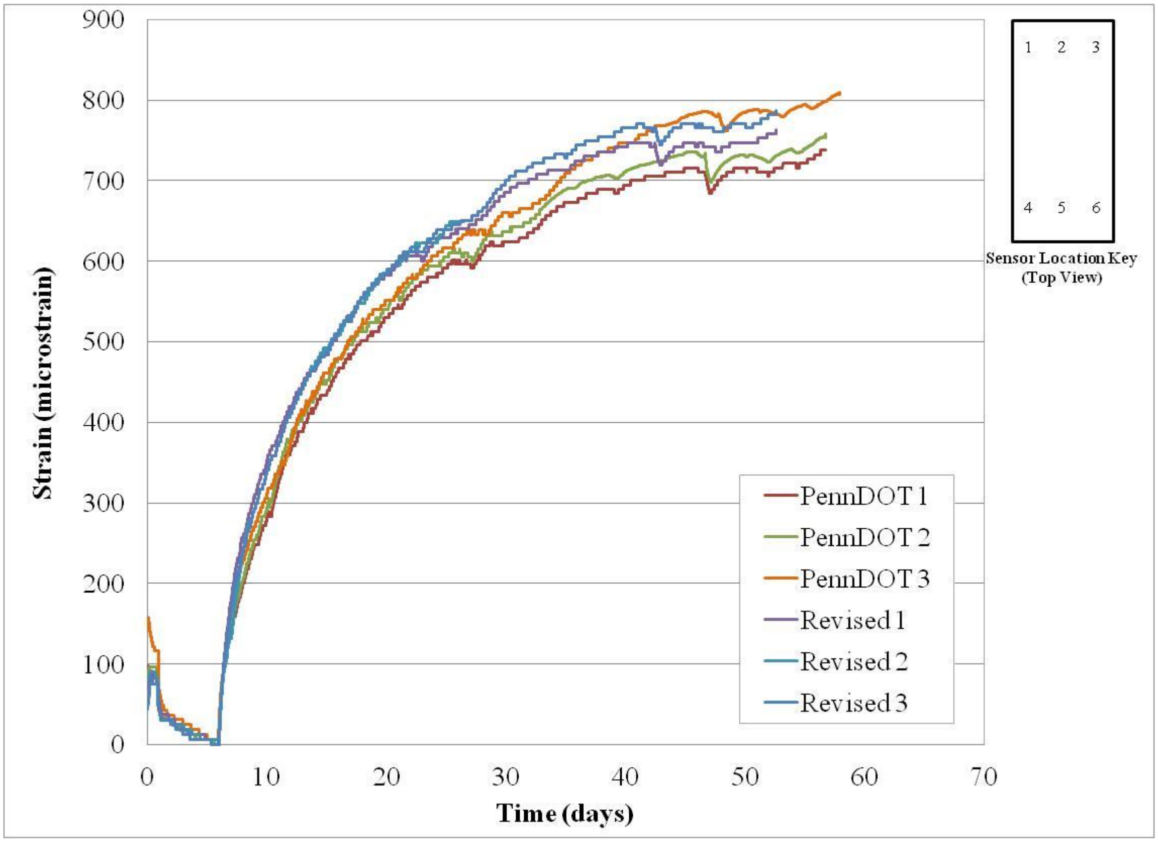


Figure 53. Drying shrinkage measured for the two mixes.

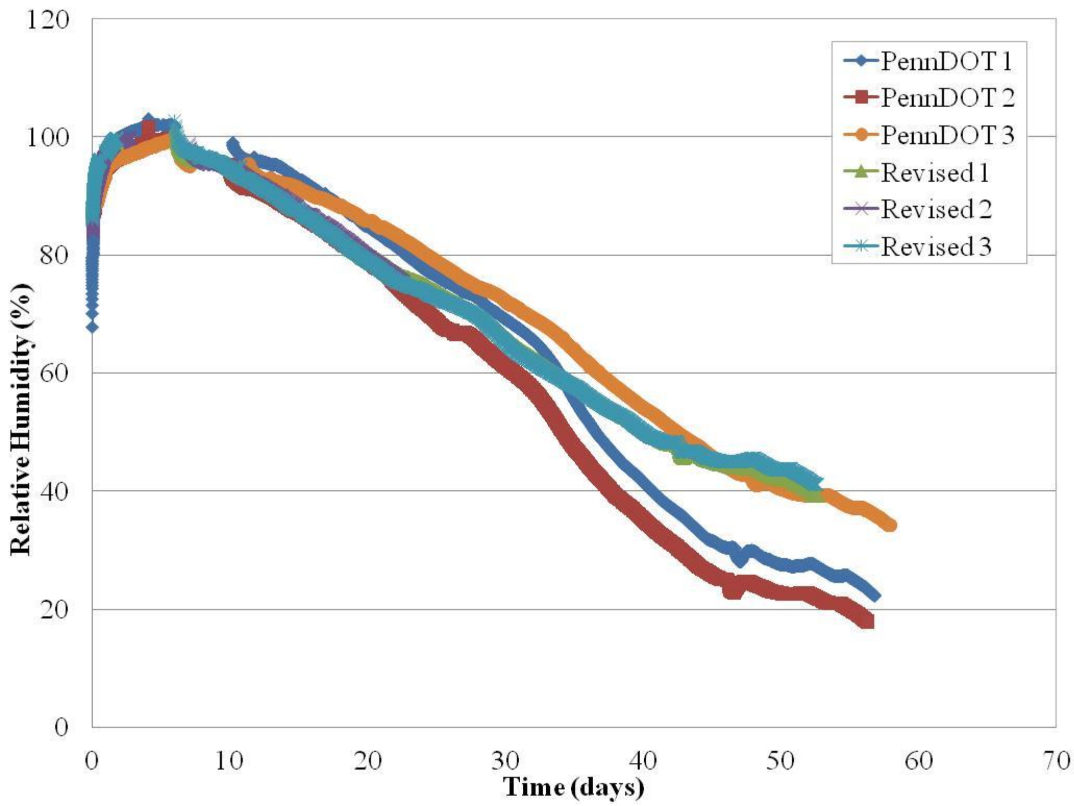


Figure 54. Relative humidity measured for the two mixes.

Figure 55 presents the difference in strain between the PennDOT and revised mix designs. The average strain values from the three beams of each mix design was then used and the difference was determined by subtracting the average for the revised beams from the average of the PennDOT beams. The strain in the beams made with the PennDOT mix was higher than the revised mix beams for the first 6 days. This indicated that the PennDOT mix beams showed more swelling in the water bath than the revised mix beams. When the beams were removed from the water bath and placed in the climate controlled environment, the average strain in the revised mix beams increased faster than the average strain in the PennDOT mix beams for four days. Ten days after paving the average strain in the revised mix beams was 60 microstrain larger than the average strain in the PennDOT mix beams. From this time forward, the average strain in the revised mix beams has been increasing slower than the PennDOT mix beams. It can be seen in Figure 55 that the difference in strain between the revised mix and PennDOT mix is decreasing with time and it appears that the drying shrinkage for the PennDOT will eventually exceed that for the revised mix. It should be noted that this experiment has only considered the total strain, and has made no distinction between recoverable and non-recoverable shrinkage strain.

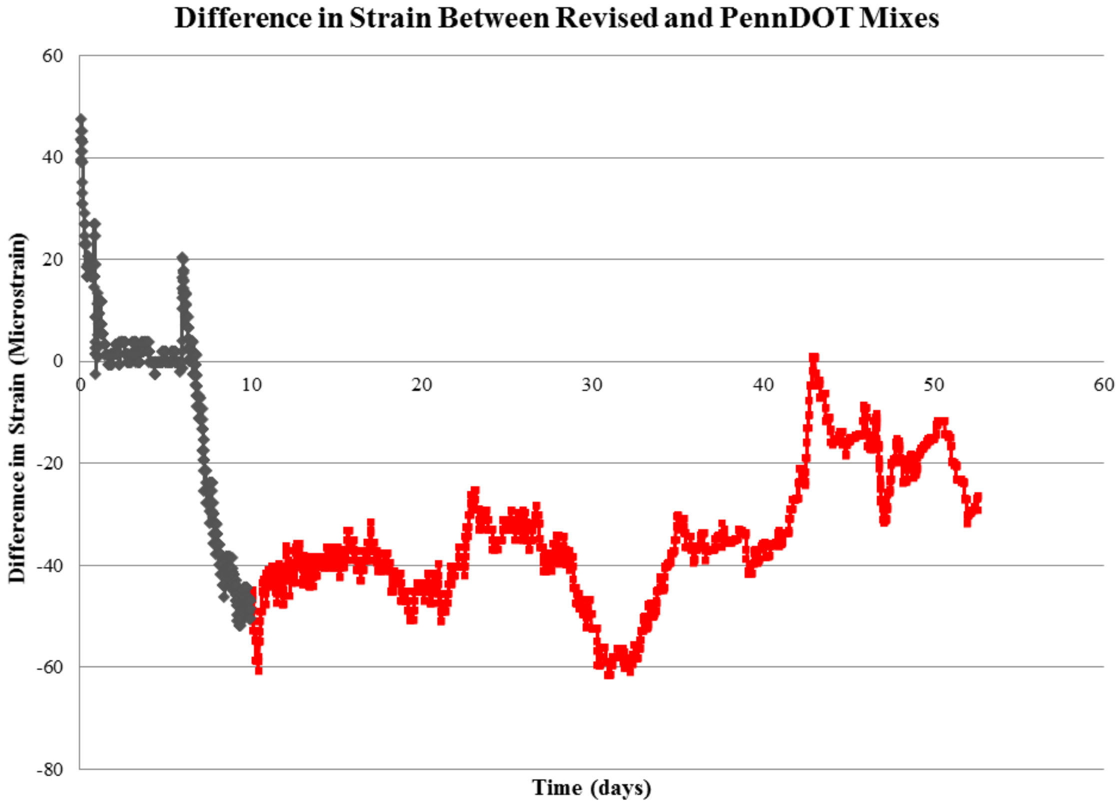


Figure 55. Difference in strain between the revised and PennDOT mixes.

7. RECOMMENDATIONS

As a result of the work performed under this project, the following recommendations are being made regarding the current specifications and guidelines for Portland cement concrete pavements. First the recommendations regarding construction will be presented followed by recommendations for revising the concrete mix design used for slip form paving.

7.1 Construction

7.1.2 Concrete finishing

The use of a wet burlap drag behind the paver should be discontinued. The wet burlap is being used to add a significant amount of moisture to the surface, which results in excess bleed water being worked into the pavement surface. The excess surface water increases the w/cm ratio on the surface, which increases the potential for plastic shrinkage cracking and a nondurable wearing surface. Proper curing should include avoiding the addition of water to the pavement surface to aid in finishing.

7.1.2 Curing

The current specification for curing compounds could be improved by including additional requirements outside the straightforward testing requirements outlined in ASTM C309 for percent solids, water retention, reflectance, and settling rate as some states have already included these requirements. Additionally, the above study showed the use of poly alpha methylstyrene resin improved the water retention characteristics. It is suggested that this resin be specified in the future. The requirements shown in Table 27 should be incorporated into future specifications. Greater attention should also be paid to the application rate actually being used in the field. Finally, it has been shown in previous studies that after a 6-month shelf-life these curing componds settle to the solids can no longer be suspended through agitation. Most manufacturers also recommend a 6 month shelf life. It is recommended that this be enforced by PennDOT. Another concern is that if is stored for over 6 months, there is a likelihood it could have been stored outside and froze. This also reduces its effectiveness and should be avoided.

Table 27. Requirement for poly alpha methylstyrene curing compound.

Total Solids (% by weight of compound):	42 minimum
% Reflectance in 72 hours (ASTM E1347)	65 minimum
Loss of Water, lb/s.f. in 24 hours (ASTM C156)	0.03 maximum
Loss of Water, lb/s.f. in 72 hours (ASTM C156)	0.08 maximum
VOC content (lb/gal)	2.93 maximum
Infrared Spectrum, Vehicle	100% poly alpha methylstyrene

The use of hand wand sprayers is currently not allowed for mainline paving operations as control of the application rate as well as the uniformity of cover is exceedingly difficult to control. However, this is not being enforced in the field and a better attempt should be made to adhere to this specification. The hand wand may still be the best alternative for certain applications, such as spall repairs, concrete patching, and mountable curb and islands. In such cases, the specifications should require strict guidance on how much compound should be used for certain surface areas to avoid obtaining an uneven misting of the surface.

7.2 Mixture Design

7.2.a Aggregate gradation

Using a more uniformly graded coarse aggregate along with a lower w/cm ratio and cement content will help reduce the potential for segregation and drying shrinkage and make the concrete more durable. Currently most of the midsize aggregate is commonly scalped from the aggregates used for concrete paving so that it can be used in asphalt concrete mixes. Retaining this material so that the aggregate is more densely graded reduces the potential for segregation and the paste demand, thereby increasing the durability. The Shilstone method can be used to characterize the aggregate gradation. Using gradations that fall within Zone II on the workability coarseness factor chart will reduce the cement demand needed to achieve the desired workability. Reducing the cement content will reduce drying shrinkage and increase durability.

7.2.b w/cm ratio

Reducing the allowable w/cm ratio will reduce the porosity of the paste and therefore increase the durability but increase the importance of proper curing. The durability can also be increased by decreasing the paste to aggregate ratio. The maximum w/cm ratio of 0.40 should be targeted with it not exceeding 0.42 or dropping below 0.38 for all Class AA concrete.

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Table A. Summary of mix design recommendations by state specification.

State	w/c	Slump	Entrained air	28 day f'_c
AL	0.45	2	2.5-6%	4000
AK	0.5			
AZ		0-4.5		4000
AR	0.45		6%+/- 2	
CA				3600
CO	0.44	project-specific	4% to 8%	4200
CT	0.49	2.5	5% to 6%	3600
DE	0.45	1 to 2.5	4% to 7%	3500
FL	0.5	2	1% to 6%	3000
GA	0.47	<2.5	4-5.5%	3000 psi +/- R
ID	0.44	<2	4 to 7	4500
IL	0.42	2 to 4	5% to 8%	3500
IN	0.56	1.5	3.5% to 6.5%	4500
KS	0.49	2.5	5.5	4000
KY	0.49	1.5-2	6 +/- 2	3500
LA	0.53	1-2.5	5 +/- 2	4000
MD	0.5	1.5-3	6.5 +/- 1.5	4200
MN	0.4	2	7.5 +/- 1	4500
MS	0.48	3	3% to 6%	3500
MT	0.53	1.5	4% to 7%	2000
NE	0.45	0.6-1	5.5-7.5	
NV	0.47	1 to 4	4 to 7	3000
NJ		0.5-2.5		
NM		2-2.5		3000
NY	0.44	2.5-3.5	6.5 (5-8)	4000
NC	0.56		1.5	4500
ND			5-8%	
OH	0.5	1 to 3	6 +/- 2%	
OK	0.48	1 to 3	6+/- 1.5	3000
OR	0.44		5.5 +/- 1	4000
PA	0.47	< 5	6 +/- 1.5	3500
RI	0.42	1 to 3	5.5+/-1.5	4000
SC	0.45		4.5 +/- 1.5	4000
SD	0.45	2	6.5+/- 1.5	4000
TN	0.49	0-2	5% (3-8)	3000
TX	0.45	1.5	4.5-5.5	4400
VA	0.49	2	6 +/- 2	3000
WA	0.44		5.5% (3-7)	3000
WV	33 gal/cy	1-2 in		3000

Table B. Summary of curing recommendations by state specification.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
AL	Burlap cloth, waterproof paper, polyethylene sheet, impervious membrane	AASHTO M 148, Class A, Type 2	135 ft^2/gallon in 2 applications	burlap drag, then groove	mechanical sprayers with fully atomizing type with tank agitator. Hand spraying for irregular areas allowed.	must harden within 30 minutes, must cure within 30 minutes of paving
AK	burlap cloth, sheet materials, liquid membrane forming compounds	AASHTO M 148, Type 1 (except linseed oil)	1 coat, 2 passes, 135-150 $ft^{2/}$gallon	brush, broom, burlap drag OR artifical turf	mechanical sprayers with fully atomizing type with tank agitator. Hand spraying for irregular areas allowed.	immediately after finishing operations and as soon as surface marring will not occur
AZ	water, liquid membrane	AASHTO M 148, Class A, Type 2	1 or more applications of 100 ft^2/gallon	burlap drag, tines,	calibrated sight glass curing compound container	within 15 minutes of texturing,
AR	polyethylene-burlap mats, liquid membrane, polyethylene sheeting, copolymer blankets	AASHTO M 148, Type 2 or Type 1-D	125 ft^2/gallon	textured drag followed by grooving	mechanical sprayers with fully atomizing type with tank agitator. Hand spraying for irregular areas allowed.	immediately after finishing
CA	waterproof membrane or curing compound	ASTM C 309 Type 2 Class B	150 ft^2/gallon	burlap drag followed by steel tining	Use mechanical sprayers with operational pressure gage and the ability to control the application pressure.	immediately after finishing before moisture sheen disappears
CO	burlap, impervious membrane forming compound, or sheet	AASHTO M 148 Type 2	150 ft^2/gallon	plastic turf drag and longitudinal metal tining	fully automated spraying equipment with a tank agitator and wind guard. Hand spraying of irregular widths is permitted.	within 30 minutes of finishing
CT	moist curing, cover sheet, liquid membrane forming (perferred)	AASHTO M 148 Type 2, class B OR water-soluble linseed oil conforming to Type 2 requirements	1 or 2 applications: 150 $ft^{2/}$gallon	burlap drag followed by metal tining	approved self-propelled mechanical pressured sprayer to provide agitation and to prevent settlement. Approved hand-held sprayers	within 30 minutes of finishing and not more than 30 minutes between applications

Table B. Summary of curing recommendations by state specification, cont.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
					permitted where mechanical sprayer is impractical	
DE	waterproof paper, liquid membrane forming compounds	AASHTO M 148 Type 2	2 applications: 200 ft^{2}/gallon	mechanized texturing device with a metal comb	automatic, self-propelled spraying machine with multiple nozzles to ensure uniform coverage and wind guard. Hand sprayers permitted only for odd widths and slab shapes	as soon as possible after texturing without marring the surface
FL	white pigmented curing compounds, burlap mats, formwork	ASTM C 309 Type 2	200 ft^{2}/gallon	damp burlap drag consisting of 2 layers of burlap	mechanical sprayer	Following finishing by less than 30 minutes
GA	impervious membranes, white polyethylene sheeting, burlap, cotton fabric	AASHTO M 148	150 ft^{2}/gallon	steel tining	fully atomizing spraying equipment, hand sprayer allowed for odd widths, shapes and behind formwork	immediately after finishing
ID	system 2 white pigment membrane forming compound	AASHTO M 148, Type 2 Class B (white pigment)	2 applications: 75 ft^{2}/gallon	burlap drag, broom, tine	"engineer approved machine method" hand sprayer allowed for odd widths and shapes	after finishing before initial set
IL	waterproof paper, polyethylene sheeting, wetted burlap, membrane-forming liquid, wetted cotton	AASHTO M 148 Type 2 Class A	250 ft^{2}/gallon	artificial turf carpet drag followed by metal tining comb	self propelled with at least 25 gallon tank maintaining a constant pressure. Spray unit rigidly attached and equipped with mechanical agitators. Wind screen required. Smaller container with constant pressure is permitted for irregular widths and	after finishing and immediately after the water sheen has disappeared from surface

Table B. Summary of curing recommendations by state specification, cont.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
					sections	
IN	White pigmented liquid membrane forming compound	White pigmented liquid membrane forming compound	2 applications: 150 $ft^{2/}$gallon	double thickness burlap drag followed by metal tining	not specified	within 30 minutes following finishing or as soon as surface marring will not occur
IO	white pigmented liquid curing compound	white pigmented curing compound	135 $ft^{2/}$gallon	grooving/tining	approved mechanical spraying equipment on forms or outside of edges. Hand spraying permitted for vertical edges, hand finished sections.	no more than 30 minutes after finishing
KS	burlap, sheet materials, liquid membrane	AASHTO M 148, 1-D or 2	150 $ft^{2/}$gallon	burlap drag, tining	approved hand sprayers only for sides of slab and damaged areas	immediately after free water has left surface
KY	burlap, curing blankets, membrane compound	AASHTO M 148 type 2	120 ft^2/gallon in 1 or 2 applications (1 gallon/150 ft^2 if not textured)	burlap drag, tining	container with capacity >10 gallons that can maintain a constant pressure with agitation devices	no more than 30 minutes after finishing
LA	white pigmented curing compound (wax based)	AASHTO M 148 type 2 and approved product list in QPL 65	100 ft^2/gallon	carpet drag, burlap drag, tining	fully atomized with a tank agitator, hand spraying permitted for irregular widths	immediately after finishing when no marring will occur less than 30 minutes after finishing
MD	liquid membrane, burlap, cotton mats, sheets	AASHTO M 148	2 applications, 1/2 gallon/200 ft^2	texture drag	approved spraying machine having drive wheels that straddle the freshly placed concrete. Hand spraying of irregular areas permitted	following texturing and edging

Table B. Summary of curing recommendations by state specification, cont.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
MI	white membrane curing	ASTM C 309 Type 2	2 applications of 1 gallon/225 ft^2 each	drag with 1-2 layers of approved damp fabric followed by grooving	Use mechanical sprayer for concrete pavement more than one lane width.	after texturing after free water has left surface
MN	linseed oil or polyalphamethylstyrene compound, plastic curing blankets	ASTM C 309 Type 2, class B: 100% polyalphamethylstyrene,	150 ft^2/gallon	carpet or broom drag with specified texture depth	fully automatic, self-propelled mechanical power sprayer with wind shield	after finishing
MS	burlap, sheeting, liquid membrane	AASTHO M 148 Type 2	120 ft^2/gallon	damp burlap or cotton fabric drag, broom, or belt followed by tining	fully atomizing type spraying equipment with a tank agitator. Hand spraying permitted for odd widths.	immediately after finishing when no marring will occur
MT	membrane only	AASTHO M 148 Type 2	150 ft^2/gallon	artificial carpet and burlap drag	not specified	immediately after free water has left surface
NE	liquid membrane, burlap, sheets	AASTHO M 148 Type 2	200 ft^2/gallon in 1 or 2 applications (1 gallon/135 ft^2 if tined)	burlap, carpet, or canvas texturing drag, tining	approved mechanical sprayer, hand power is permitted in an emergency and on narrow or variable width sections	immediately after free water has left surface
NV	white pigmented wax-based curing compound, membrane material	ASTM C 309 Type 2 A	150 ft^2/gallon in 2 applications	burlap drag	power operated spraying equipment with an operational pressure gage to control the pressure	immediately after free water has left surface
NH	cotton mats, water, burlap, liquid curing compound, sheets	AASHTO M 148 Type 1D or 2, class B	200 ft^2/gallon	not specified		
NJ	curing compound, wet burlap, sheeting	AASHTO M 148 Type 1D	200 ft^2/gallon: 2 applications of 100 ft^2/gallon each	broom	not specified	after float finishing when marring will not occur, applied within 30 minutes
NM	curing compound, sheet materials	AASHTO M 148 Type 1D or 2, class B	as recommended by manufacturer	tining or grooving	pressure tank or pump with a feed tank agitator and a thoroughly atomizing nozzle	immediately after finishing as soon as possible

Table B. Summary of curing recommendations by state specification, cont.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
NY	white pigmented curing compound,curing cover	drying: within 4 hrs, min temp 40 F. permeability <=0.04g/cm2/3 days. Reflectance = 60%, durability = intact for 7 days before powdery	150 ft^2/gallon	artificial turf drag, tining	atomized mechanical sprayers with consistent pressure without hand pumping equipped with tank agitators to continuously mix the curing compound. Self-propelled for slipform paving.	apply to freshly placed, damp concrete
NC	curing compound, burlap, polyethylene sheeting	AASTHO M 148 Type 2 except water retention test AASHTO T 155 restricts water loss to not more than 0.007 oz/in2	150 ft^2/gallon	burlap drag and steel tining	not specified	immediately after free water has left surface
ND	wetted fabric or impervious membrane	AASHTO M 148 Type 2, Class B white pigmented. Polyalphamethylstyrene: total solids>-42%, 65% reflectance in 72 hrs, max 0.15 kg,m2 water loss in 24 hrs and 0.40 in 72 hrs, VOC < 350 and Infrared show 100% alpha=-methylstyrene	150 ft^2/gallon	grass carpet, metal tining	self-powered machine with a mechanical pressure distribution system. Hand sprayer may be used for pavement sides or areas where a machine is impractical	immediately after finishing when no marring will occur
OH	wet burlap, waterproof paper, polyethylene sheeting	ASTM C 309 plus: min 25% solids, water loss less than 0.15 kg/m2 in 24 hrs and 0.4 at 72 hrs, min reflectance of 65%, rate of settling	150 ft^2/gallon	broom followed by grooving	self propelled mechanical sprayer with wind shield. Agitate compound thoroughly before use	immediately after free water has left surface

Table B. Summary of curing recommendations by state specification, cont.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
OK	cotton or bulap mats, impervious membrane, white polyethylene sheeting	AASTHO M 148 Type 2 with at least 65% reflectance according to ASTM E 97 and at least 90% water retension in accordance with OHD L-17	200 ft^2/gallon	texture drag, grooving	fully atomizing equipment with a tank agitator. Hand sprayer permitted for vertical surfaces, irregular areas, and edges	immediately after finishing when no marring will occur
OR	impervious membrane or polyehtylene sheeting	AASHTO M 148, Type 2 class A	150 ft^2/gallon	steel tining	mix thoroughly	immediately after finishing while concrete is still moist
PA	white polyethylene sheet, burlap, polypropylene backed fiber, liquid membrane forming curing compound	AASHTO M 148, Type 2 (white, but black allowed if overlayed)	150 ft^2/gallon	provide a textured finish with specified grooves	self-propelled mechanical spreader with atomizing spray equipment with a tank agitator and a wind hood. Manual spraying permitted for small or irregular areas.	immediately after free water has left surface
RI	water, curing compound, waterproof membrane, forms in place	non-pigmented chlorinated rubber base-clear comforming to AASHTO m 148	according to manufacturer's recommendation	broom, or belt, or drag finish	power operated atomizing spray equipment with operational pressure gauge and means of controlling pressure	immediately after free water has left surface
SC	burlap cloth, waterproof paper, polyethylene sheet, liquid membrane forming compounds	AASHTO M 148 Type 2	150 ft^2/gallon	grooving by metal comb	mechanical sprayers spanning the width of the pavement for uniform application with self-propelled equipment	immediately after finishing and after surface water has disappeared
SD	burlap, liquid membrane curing, linseed oil emulsion, polyethylene sheeting	AASHTO M 148 Type 2	150 ft^2/gallon	carpet drag, tining	mechanical sprayers with fully atomizing type with tank agitator. Hand spraying for irregular areas allowed.	immediately after finishing when no marring will occur less than 30 minutes after finishing

Table B. Summary of curing recommendations by state specification, cont.

State	Allowable types	Liquid forming membrane cure spec	Application rate	Texturing	Application method	Application timeline
TN	cotton or burlap mats, waterproof paper, impervious membranes, white polyethylene sheeting	AASHTO M 148 Type 2	according to manufacturer's recommendation	burlap drag, grooving	Use mechanical sprayers with operational pressure gage and the ability to control the application pressure.	immediately after finishing when no marring will occur less than 30 minutes after finishing
TX	white pigmented curing compound	AASHTO M 148 Type 2	2 applications of 180 ft^2/gallon	carpet drag, tining	self-propelled machine with pressurized spraying equipment with atomizing nozzles. Hand spray allowed for small, irregular areas	immediately after texturing after free moisture has disappeared. Within 10 minutes of texturing
VA	waterproof paper, polyethylene film, burlap, liquid membrane curing compound	White pigmented	100-150 ft^2/gallon	burlap drag, tining	mechanical sprayers on movable bridges with fully atomizing equipment with tank agitator and gage	immediately following texturing
WA	water, curing compound, polyethylene sheet	AASHTO M 148 Type 2	150 ft^2/gallon	burlap drag, broom, tine	pressure tank or pump type equipped with a feed tank agitator with two-line nozzle	immediately after finishing when no marring will occur
WV	burlap mats, waterproof paper, straw, white pigmented impervious compound, white polyethylene sheet	AASHTO M 148 Type 2 Class A	150 ft^2/gallon (burlap drag) and 125 ft^2/gallon (grooved)	either burlap drag or groove finish.	mechanical sprayers with fully atomizing type with tank agitator. Hand spraying for irregular areas allowed.	immediately after finishing when no marring will occur
WY	premium white impervious curing compound	AASHTO M 148 Type 2 Class B	150 ft^2/gallon	burlap drag followed by carpet drag, brooming, or tining.	Use a mechanical sprayer	after finishing