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Research

A Review of the Curing Compounds and Application Techniques Used by the Minnesota Department of Transportation For Concrete Pavements

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A Review of the Curing Compounds and Application Techniques Used by the Minnesota Department of Transportation for Concrete Pavements

Final Report

Prepared by

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EXECUTIVE SUMMARY

The Minnesota's Department of Transportation's (Mn/DOT) recent implementation of a 0.40 maximum water-to-cementitious ratio specification for concrete pavements has raised some concerns regarding the availability of bleed water at the pavement surface and the moisture retained in the concrete for strength development with current curing practices. A study was initiated in the spring of 1998 to evaluate Mn/DOT's concrete pavement curing requirements. First, an assessment of the effectiveness of various compounds frequently used on state funded projects was performed and the test methods used to evaluate these compounds were examined. Changes were made to Mn/DOT's curing specifications based on the findings of the first portion of this study and implemented during the 1999 construction season. Methods used by contractors to apply curing compounds were also reviewed to insure that a uniform coat of acceptable thickness is applied and recommendations were made for improving these methods. This paper summarizes the findings of this study and the resulting changes that were made to Mn/DOT concrete pavement curing specifications. Recommendations for further improvements are also provided.

Introduction

Curing consists of maintaining an appropriate temperature and moisture content in the concrete for a defined period of time so the concrete will develop in such a way that the desired material properties can be obtained. The scope of this project is limited to the moisture-related aspects of curing. A pavement has a high surface area-to-volume ratio, which makes it difficult to maintain a uniform moisture content throughout the pavement. Plastic shrinkage occurs when the rate of water loss from the surface exceeds the rate at which bleed water is available. The four primary factors that affect plastic shrinkage are concrete temperature, air temperature, wind velocity and relative humidity. Plastic shrinkage cracking will occur if the concrete is too stiff to flow but has not yet developed enough strength to withstand the tensile stresses that develop due to non-uniform shrinkage. Plastic shrinkage cracks are typically 25 to 50 mm (1 to 2 in) deep and run parallel to one another 0.3 to 1 m (1 to 3 ft) apart (Mehta and Monteiro, 1993). Precautionary measures should be taken to prevent shrinkage cracking when the rate of evaporation of the bleed water exceeds 1 $kg/m^2/hr$ (2 $lb/ft^2/hr$) (Kosmatka and Panarese, 1992).

Curing compounds are used to help prevent shrinkage cracking by reducing the evaporation of water from the concrete. A curing compound should be applied as soon as bleed water ceases to collect on the pavement surface. If the compound is applied too soon, tensile stresses develop where the bleed water collects between the pavement surface and the membrane thereby creating pinholes in the membrane. The increase in rate of evaporation due to the pinholes increases the potential for shrinkage cracking. Shrinkage cracks can also develop if the curing compound is applied too late after an excessive amount of evaporation has already occurred.

The Minnesota's Department of Transportation's (Mn/DOT) recent implementation of a 0.40 maximum water-to-cementitious ratio specification (Special Provision for Specification 2301 modified on 01.26.98) for concrete pavements has raised some concerns regarding the availability of bleed water at the pavement surface and the moisture retained in the concrete for strength development with current curing practices. A study was initiated in the spring of 1998 to evaluate Mn/DOT's concrete pavement curing requirements. First, an assessment of the effectiveness of various compounds frequently used on state funded projects was performed and the test methods used to evaluate these compounds were examined. Changes were made to Mn/DOT's curing specifications based on the findings of the first portion of this study. These changes were implemented during the 1999 construction season. Finally, the methods used by contractors to apply curing compounds were also reviewed to insure that a uniform coat of acceptable thickness is applied. This paper summarizes the findings of this study and the resulting changes that were made to Mn/DOT concrete pavement curing specifications. Recommendations for further improvements are also provided.

Characteristics of Curing Compound

Concrete pavements are commonly cured using membrane forming curing compounds. Membrane-forming curing compounds typically consist of a wax or resin that is emulsified in water or dissolved in a solvent. The compound is applied to the pavement surface and then the water or solvent constituent evaporates leaving the wax or resin to form a membrane over the surface of the pavement. This membrane helps retain moisture in the concrete. Emulsified linseed oil cure/sealer compounds are also used for curing concrete pavements. The oil lowers the rate of evaporation by sealing the concrete pores while the sealant helps prevent deterioration caused by freeze-thaw cycling and deicing chemicals during the critical period of early strength development.

Liquid membrane-forming compounds are classified according to the color of the compound and the type of solid constituent present for forming the membrane. Table 1 shows the American Society for Testing and Materials (ASTM) C 309 and American Association of State Highway and Transportation Officials (AASHTO) M 148 classifications for membrane-forming compounds. The ASTM and AASHTO classifications are equivalent. Mn/DOT requires a Type 2, Class B membrane curing compound as their standard cure for concrete pavements (Mn/DOT Specification 2301.3) while a white pigmented, linseed oil emulsion meeting AASHTO M 148 is used for extreme weather curing (Mn/DOT Specification 3755.2). The extreme weather cure/sealer compound must be a blend of boiled linseed oil and heavy-bodied linseed oil emulsified in a water solution. An extreme weather cure is mandatory for all pavements constructed after September 15 north of the 46-degree parallel, after October 1 south of the 46-degree parallel and before April 15 for all locations in the state (Mn/DOT Specification 3741.2).

Table 1. ASTM C 309 and AASHTO M 148 curing compound classifications.

COLOR		**SOLID CONSTITUENT**	
Type	***Description***	***Class***	***Description***
1	Clear or Translucent w/out Dye	**A**	No Restriction
1-D	Clear or Translucent w/ Fugitive Dye	**B**	Resin
2	White Pigmented		

<u>Curing Compound Test Specifications</u>

Mn/DOT specifications require the use of Type 2, Class B curing compounds that meet ASTM C 309 requirements and extreme weather curing compounds that meet AASHTO M 148 specifications even though ASTM C 309 and AASHTO M 148 are identical, as seen in table 2. Mn/DOT requires extreme weather curing compounds consist of 50 ± 4 percent oilphase and 50 ± 4 percent waterphase, by volume. The oilphase must contain 80 percent boiled linseed oil and 20 percent Z-8 viscosity linseed oil, by mass (Mn/DOT Specification 3755.2). Boiled linseed is added to increase the set time while the more viscous linseed provides a greater contribution towards sealing the pavement. Mn/DOT does not test to determine the percentage of each constituent in the oilphase.

Curing Compounds Used by Mn/DOT

Mn/DOT has predominately used five different curing compounds since 1996, all of which have been manufactured by W.R. Meadows, Carter-Waters or Vexcon. Table 3 contains descriptions of each curing compound used on state projects along with the results from water retention testing performed by Mn/DOT on these compounds. Comparisons between their performance are provided below.

Water Retention

ASTM C 156 and AASHTO T 155 test procedures for determining water retention under ASTM C 309 and AASHTO M 148, respectively, are identical (see table 2). There is a large amount of variability inherent in this test with a single-operator standard deviation of 0.13 kg/m^2 (0.03 lbs/ft^2) and a multi-laboratory standard deviation of 0.30 kg/m^2 (0.06 lbs/ft^2). These standard deviations are extremely large considering ASTM C 309 and AASHTO M 148 require a water retention for Type 2 Class B curing compounds of less than 0.55 kg/m^2 (0.11 lbs/ft^2). Despite the difficulties in measuring water retention, ASTM C 309 still appears to be the most promising means of evaluating curing compounds, even with the large amount of variability in this test method.

The water retention values in table 3 were determined by the Mn/DOT. Several observations were drawn from this data. First, Carter-Waters 250/240R Linseed and W.R. Meadows 1250 curing compounds exhibited the lowest water loss. Only 3 of the 141 samples tested failed but 22 other samples had evaporation rates greater than 0.5 kg/m^2 (0.10 lbs/ft^2). All three failures were samples of Vexcon Enviocure 1000. The 22 samples with evaporation rates greater than 0.5 kg/m^2 (0.10 lbs/ft^2) consisted of 15 Carter Waters 250/240R samples, 4 Vexcon Enviocure 1000

Table 2. Comparison between ASTM C 309 and AASHTO M 148 specifications for Type 2 liquid membrane-forming compounds.

	AASHTO M 148		ASTM C 309		
	Test Method	**Requirement**	**Test Method**	**Requirement**	**Comments**
Water Retention	AASHTO T 155	0.55 kg/m^2 in 72 hrs	ASTM C 156	0.55 kg/m^2 in 72 hrs	The AASHTO T 155 and ASTM C 156 are identical tests.
Reflectance	ASTM E 97	> 60 percent	ASTM E 97	> 60 percent	Only performed on Type 2 curing compounds.
Drying Time	AASHTO T 155 Sec. 10.3	< 4 hrs	ASTM C 156 Sec. 10.3	< 4 hrs	The AASHTO T 155 and ASTM C 156 are identical tests. Mn/DOT specifications do not require drying time testing for extreme weather curing compounds. *(The Mn/DOT materials lab does not perform drying time testing on curing compounds.)*
Long-Term[1] Settling	ASTM D 1309	> 4 (storable for at least 180 days w/out deterioration)	ASTM D 1309	> 4 (storable for at least 180 days w/out deterioration)	In case of dispute, use ASTM D 869. *(Mn/DOT does not perform long-term settling testing on curing compounds.)*
Non-volatile Content	ASTM D 1644 Method A	n/a	ASTM D 1644 Method A	n/a	
Flash Point	ASTM D 56	10°C	ASTM D 56	10°C	*(Mn/DOT does not perform flash point testing on curing compounds.)*

lbs/ft^2 = 4.8819 kg/m^2; °F = °C(1.8) + 32

[1]Water-emulsion type compounds can not be used once they have been allowed to freeze.

Table 3. Curing compounds tested by Mn/DOT between Jan. 30, 1996 and May 7, 1998.

Product: Description	**Ave. Water Loss[3] (kg/m^2)**	**Sample Stan. Dev. (kg/m^2)**	**No. of Samples**	**No. of Failures**
W.R. Meadows 1250 – White: Solvent-emulsion with a resin base Cost ≈ $0.63 per liter (VOC[1]= 120 g/L)	0.20	0.08	40	0
W.R. Meadows 2230 – White: Solvent-emulsion with a resin base Cost ≈ $0.77 per liter (VOC[1]= 260 g/L)	0.24	0.17	10	0
W.R. Meadows Lin-seal – White: Linseed oil emulsified in water Cost ≈ $1.25 per liter (VOC[1]= 0.36 g/L)	0.32	0.08	16	0
Carter-Waters 250/240R – White: Solvent-emulsion with a resin base Cost ≈ $0.63 per liter (VOC[1]= 720 g/L)	0.42	0.11	51	0
Carter-Waters 250/240R Linseed Oil – White: Linseed oil emulsified in water Cost ≈ $1.25 per liter (VOC[1]≈ 300 g/L)	0.20	0.05	12	0
[2]*Vexcon Enviocure1000 – White*: Solvent with a resin base Cost ≈ $0.63 per liter (VOC[1]≈ 350 g/L)	0.49	0.28	12	3

$lbs/ft^2 = 4.8819\ kg/m^2$; lbs/gal = 119.8 g/L; gals = 3.785 L

[1] Volatile Organic Compounds (VOC) - The VOC content must be less than 350 g/L (2.9 lbs/gal) to comply with current air pollution control regulations on architectural coatings.

[2] Although this product was tested, it was never used on a project.

[3]Mn/DOT requires the water loss after 72hrs to be less than 0.55 kg/ m^2 (0.11 lbs/ft^2).

samples and 1 W.R. Meadows 1250 sample. This indicates that some of the curing compounds are consistently outperforming other compounds even though the poorer performing compounds are generally within the 0.55 kg/m^2 (0.11 lbs/ft^2) specification requirements. Reducing the maximum allowable evaporation loss would help prevent the use of these marginal curing compounds.

Twenty of the 22 samples that had an evaporation rate greater than 0.5 kg/m^2 (0.10 lbs/ft^2) were tested in the first part of the construction season. ASTM C309 specification requires Type 2 compounds have a maximum shelf-life of 6 months because the white pigment tends to separate from the solution. It is likely that the curing compounds used in the first portion of the construction season are left over materials from the prior construction season. This would mean these curing compounds were stored a minimum of 6.5 months (October 1 through April 15). Mn/DOT has not previously enforced the 6-month shelf-life requirement specified in ASTM C 309. The high evaporation rates for specimens tested in the first portion of the construction season indicate separation is occurring. It is recommended that shelf-life be enforced.

The need to limit Type 2 compounds to a 6-month shelf-life was verified by a study performed at the University of Texas, Austin (Loeffler and Papaleontiou, 1981). A portion of that study was devoted to determining the shelf-life of Type 2 (white pigmented) and Type 1-D (translucent) curing compounds stored in 208-liter (55-gallon) drums. Visual inspections and a comparison of the solids content of samples pulled from the top, center and middle of each drum after thorough agitation were made throughout a one-year period. Type 2 curing compounds could not be re-mixed to a homogenous consistency after three to six months of storage. As a result of that study, it was determined that the shelf-life of Type 1-D curing compounds should be limited to no more than 1 year and the shelf-life of Type 2 compounds be limited to no more than 6 months. That study also concluded at least 30 minutes of agitation was required before the Type 2 compounds were uniform throughout the drum, emphasizing the importance of constantly agitating and re-circulating the compound from the spray head to the drum during application, particularly for Type 2 compounds. (Transportation Research Committee on Batching, Mixing, Placing and Curing of Concrete, 1979)

Volatile Organic Compounds

The Volatile Organic Compounds (VOC) content can be determined using ASTM D 1644, Method A. Mn/DOT does not measure the VOC content for each curing compound used, instead they rely on the manufacturer's reported VOC values. In 1998, the Environmental Protection Agency (EPA) proposed legislation which was passed by congress, that law restricts the amount of VOC allowable in both curing and curing and sealing compounds. The VOC content of curing compounds must be below 350 g/L (2.9 lbs/gal) and below 700 g/L (5.8 lbs/gal) for concrete curing/sealing compounds to be in accordance with Rule 40 CFR Part 59 National Volatile Organic Compounds Emission Standards for Architectural Coatings. Vexcon Enviocure 1000 and Carter-Waters 250/240R are the only two of the six products evaluated which do not meet current air pollution control regulations.

Reflectance

A white-pigment is added to Type 2 curing compounds to help reflect radiant heat. This helps to decrease early thermal stresses and reduce the rate of evaporation. The reflectance of each curing compound is tested by Mn/DOT according to ASTM E 97. A 72-hour reflectance greater than or equal to 60 percent is required. Table 4 contains a statistical summary of the reflectance testing performed by Mn/DOT for the curing compounds used between January 30, 1996 and May 7, 1998. Most of the curing compounds tested performed satisfactorily with the exception of the Vexcon Enviocure, which had two failures, as is seen in table 4.

Table 4. Reflectance testing performed by Mn/DOT between Jan. 30, 1996 and May 7, 1998.

Product	Ave. Reflectance (%)	Sample Stan. Dev. (%)	No. of Samples	No. of Failures
W.R. Meadows 1250 – White	68	2.81	40	0
W.R. Meadows 2230 –White	68	2.46	10	0
W.R. Meadows Lin-seal – White	68	2.03	16	0
Carter-Waters 250/240R – White	67	2.73	51	0
Carter-Waters 250/240R Linseed Oil – White	62	2.10	12	0
Vexcon Enviocure – White	63	4.51	12	2

[1]Mn/DOT required the reflectance to be greater than or equal to 60% prior to 1998.

Oilphase Content

The extreme service cure/sealer compounds currently being used consist of boiled linseed oil and high viscosity, heavy bodied linseed oil emulsified in a water solution, as previously discussed. The oilphase must make up 50 ± 4% of the solution, by volume. The other 50 ± 4% is the waterphase. These volumes are exclusive of added pigments. The oilphase must be 80 percent boiled linseed oil and 20 percent Z-8 viscosity linseed oil. Linseed oil has a short set time because of its high degree of saturation. Boiled linseed consists of blown oil (oil heated and then blown with air) and driers. Boiled linseed is added to increase the set time and decrease the viscosity. Mn/DOT currently only performs testing to check the percent oilphase. Table 5 shows the results of testing performed by the Mn/DOT lab between Jan. 1, 1996 and May 5, 1998. The W. R. Meadows Lin-seal cure/sealer membrane tends to contain a lower oilphase content than the Carter-Waters Linseed Oil. Table 3 shows the water loss was also greater for the W.R. Meadows than the Carter-Waters Linseed Oil.

Table 5. Percent oilphase for compounds used between Jan. 2, 1996 and May 7, 1998.

Product	Average (% by volume)	Sample Stan. Dev. (%)	No. of Samples	No. of Failures
W.R. Meadows Lin-seal - White	45	1.06	16	9
Carter-Waters 250/240R Linseed Oil – White	51	1.83	12	0

[1]Mn/DOT requires the content of the oilphase be 50 ± 4% by volume.

Cost

The cost of each compound used by Mn/DOT was examined to determine if a relationship between cost and performance exists. An estimate of the cost of each type of curing compound used between Jan. 1, 1996 and May 5, 1998 is tabulated in table 3. Resin base curing compounds are less than half the price of the linseed oil curing compounds. The cost of the resin base compounds is approximately $0.63 per liter ($2.40 per gallon) and the linseed oil compounds cost approximately $1.25 per liter ($4.75 per gallon). Prices do not differ significantly between manufacturers for the curing compounds sampled. Therefore, there does not appear to be a relationship between cost and quality.

Revisions to Mn/DOT Curing Specification 3754 for Standard Cure

The performance review of curing compounds used by Mn/DOT indicated that almost half of the products had marginal water retention characteristics. Marginal water retention is not acceptable with the 0.40 water-to-cementitious ratio Mn/DOT has adopted for concrete pavements. The products with a higher water loss tended to have larger standard deviations than the products with a lower water loss, but there was a distinct division between products that performed well and products that would consistently fall near the 0.55 kg/m^2 (0.11 lbs/ft^2) water retention requirements. Based on the findings from the first portion of the study, an attempt was made to improve the water retention characteristics of the curing compound being used by modifying Mn/DOT's curing specifications.

Curing specifications used by other states were reviewed in attempt to determine how Mn/DOT could change their specifications to insure curing compounds with good water retention characteristics were consistently being used regardless of the manufacturer. It was found that the California Department of Transportation (Caltrans) requires the curing compound resin to consist of 100 percent poly-alpha-methylstyrene. A curing compound meeting this requirement was tested at the Mn/DOT Central Laboratory and proved to have high water retention characteristics. This curing compound was then tested in the field during the summer of 1998 and it was determined that the resin has good sprayability, which resulted in a uniform coverage. Based on these findings Mn/DOT's, curing specification was changed to require only curing compounds with a resin consisting of 100 percent poly-alpha-methylstyrene, as determined by comparing the infrared scan for the dried vehicle to the scan on file at the Mn/DOT Central Laboratory. Curing compound manufacturers then began submitting samples of their products with the poly-alpha-methylstyrene resin to Mn/DOT for approval. Not all of the curing compounds submitted performed as well as anticipated. It was believed that this was caused by an insufficient quantity of resin in the curing compound or due to poor settling characteristics. Once a minimum total solids content of 42 percent by weight and a maximum settling of 2 ml per 100 ml in 72 hours was added to the specifications the water retention characteristics of the curing compounds improved. Curing compounds meeting this specification cost $1.72 per liter ($6.50 per gallon) which is $1.10 per liter ($4.10 per gallon) higher than the curing compounds traditional used by Mn/DOT. This is a small investment when compared to the total project cost.

The water retention requirements were increased in the revised specification, requiring a maximum allowable water loss of 0.15 kg/m^2 (0.03 lbs/ft^2) in 24 hours. The standard 72-hour maximum allowable water loss was also decreased from 0.55 kg/m^2 (0.11 lbs/ft^2) to 0.40 kg/m^2 (0.08 lbs/ft^2). The shelf-life was also limited to 6 months or the calendar year the product was produced, whichever is greater. The intent is to keep curing compounds from being used once they have settled to the point that it is no longer possible to agitate it back into a uniform solution. The last modification was to increase the required 72-hrs reflectance requirement from 60 percent to 65 percent. The Mn/DOT Concrete Office modified the 1995 Mn/DOT Curing Specification 3754 in March of 1999 to incorporate these changes. A summary of the changes made is presented in table 6.

Table 6. Summary of 1999 revisions made to Mn/DOT Curing Specification 3754.

Property	Requirement
Total Solids	**Min.:** 42 % by weight of compound
Reflectance	**Min.:** 65% in 72 hrs
Water Loss	**Max.:** 0.15 kg/m^2 in 24 hrs
Water Loss	**Max.:** 0.40 kg/m^2 in 72 hrs
Settling Test	**Max.:** 2 ml per 100 ml in 72 hrs
V.O.C. Content[1]	**Max.:** 350 g/L (700 g/L for a cure/sealer)
Infrared Spectrum of Vehicle	100 % poly-alpha-methylstyrene
Shelf Life	Greater of 6 mths. or the calendar year the product was produced

lbs/ft^2 = 4.8824 kg/m^2; lbs/gal = 119.8 g/L
See Appendix A for testing procedures used to measure each property.
[1]Regulation of the Environmental Protection Agency

Applying Curing Compounds

The first portion of this study identified and evaluated the curing compounds used by Mn/DOT between January 1996 and May 1998. Based on the findings, modifications were made to Mn/DOT's curing specifications so that a curing compound with high water retention characteristics is consistently being used. The second portion of this study focuses on how curing compounds should be applied to the pavement surface so that a uniform coverage of adequate thickness is obtained. A curing compound with good water retention characteristics is of no use unless it is applied correctly. Unfortunately the importance is often overlooked. In many cases, inspections of this process are limited to counting the empty barrels along the side of the pavement to ensure an adequate volume of curing compound has been put through the sprayer. Many factors such as wind and dirty/worn nozzles will affect how much of the cure ends up on the pavement surface and the ability to obtain a uniform coverage.

Typical application rates for curing compounds range between 2.5 m^2/L and 5 m^2/L (102 ft^2/gal and 204 ft^2/gal) (1988, Senbetta). Mn/DOT requires curing compounds be applied with an approved fully automatic spraying machine at a minimum rate of 4 m^2/L (163 ft^2/gal). This applies to all pavement surfaces regardless of the type of tining or texturing performed.

Increasing surface friction by tining or other means of texturing increases the surface area. Mn/DOT was tining with a randomized spacing of 16 to 26 mm (0.625 to 1.063 in) and a tine depth of 3 to 8 mm (0.12 to 0.30 in). Tining spaced 20 mm (0.75 in) apart and 5 mm (0.2 in) deep would increase a surface area of 1 m^2 to 1.5 m^2 (11ft^2 to 16 ft^2). Therefore the same coverage which provided 4 m^2/L (163 ft^2/gal) for an untextured surface would result in 6.0 m^2/L (237 ft^2/gal) for a surface textured according to Mn/DOT specifications. Without correcting the application rate for increased surface texture, the curing coverage obtained can be substantially less than desired. As of 1999, Mn/DOT requires only astro-turf drag texturing and no longer requires tining. The effect of surface texture on the application rate is still an important aspect to consider as Mn/DOT's surface texture specifications continue to evolve.

Not only is it important that the correct application rate is applied, but the engineer must also ensure the curing compound is applied in such a manner that a uniform coverage is obtained and the loss of curing compound due to wind action is reduced. The five primary factors that affect the ability to obtain a uniform coverage are listed below.

- Nozzle type
- Nozzle spacing and boom height
- Nozzle orientation
- Cart speed
- Wind shield

Nozzle Type

Many different nozzle types are available. Each type of nozzle has a specific spray angle, flow rate, spray pattern and droplet size, which affect how uniform the compound can be applied across the pavement surface. Most nozzles have full cone, hollow cone, fan or flat spray patterns. See figure 1. Cone and fan spray patterns are commonly used for band spraying while flat spray nozzles are typically used for broadcast spraying. See figure 2. Therefore, it is recommended that a flat spray nozzle used for applying curing compound to the pavement surface.

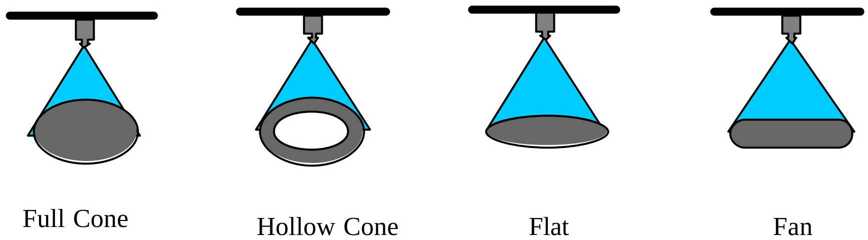


Figure 1. Typical nozzle spray patterns.

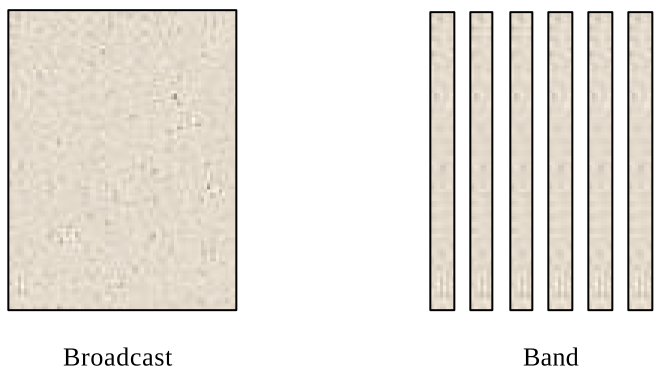


Figure 2. Broadcast vs. band spraying.

The goal in choosing the correct nozzle is to find a nozzle that produces a droplet large enough to prevent drift but small enough to maintain uniform coverage. Droplets with a diameter smaller than 200 microns (8 mils) are considered potential drift contributors (Spraying Systems Co., 1997). Droplet size is usually characterized by what is referred to as the volume median diameter. The volume median diameter is a statistical value for describing the size distribution of the droplets. The volume median diameter is the droplet diameter, which 50 percent by volume have droplets with larger diameters than the median and 50 percent by volume have droplets with smaller diameters than the median. A small volume median diameter improves surface coverage while a large median diameter will prevent off-target drift. Factors that need to be considered when determining the droplet size are pump pressure, spray angle and flow rate. Increasing the spray angle or pump pressure or decreasing the flow rate can decrease the droplet size. Nozzle manufacturers will provide volume median diameters for nozzles at different pump pressures. A 4-digit number is typically used to designate the type of nozzle. The first 2 digits represent the spray angle in degrees and the last 2 indicate the flow rate in gallons per minute at a specified pump pressure (generally 276 kPa (40 psi)). See figure 3 for a pictorial definition of spray angle. For example, an 8002 nozzle would have an 80° angle of spray and a flow rate of 0.2 gallons per minute (with the first zero in front of the 2 representing a decimal).

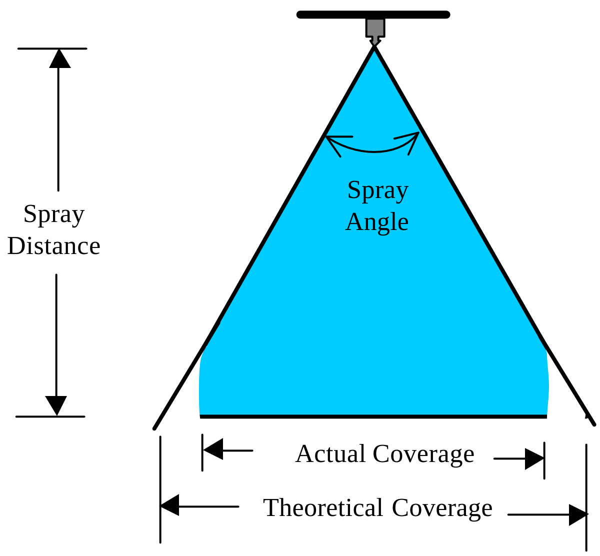
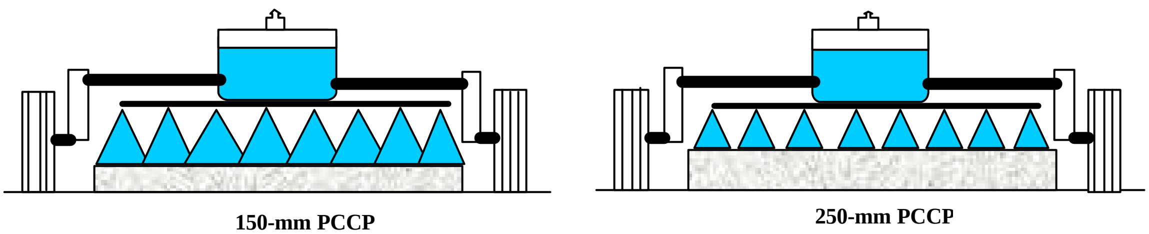


Figure 3. Spray coverage.

Nozzle Spacing and Boom Height

The nozzle spacing and height should also be considered when choosing the type of nozzle to be used. There should be a 30 percent overlap of the spray pattern edge because, as shown in figure 3, the theoretical coverage determined based on the spray angle and height are not the same as the actual coverage. Once a nozzle setup has been established, the height of the nozzles must be adjusted for each project if the thickness of the pavements changes to maintain a 30 percent overlap of adjacent spray patterns. For example, if the sprayer was setup for a 150-mm (6-in) pavement as shown in figure 4.a and then the same sprayer was used on a 250-mm (10-in) pavement, figure 4.b, the sprayer boom should be raised to maintain a 30 percent overlap.

It is recommended the inspectors calculate the actual overlap and enforce the 30 percent limit. It is recommended the inspectors calculate the actual overlap and enforce the 30 percent overlap limit.



a.) Nozzle heights adjusted to obtain 30% overlap of adjacent spray patterns.

b.) Nozzles must be raised to retain 30% overlap for the 250-mm PCCP.

Figure 4. Maintaining adequate boom heights.

Nozzle Orientation

The orientation of the nozzle orifice once it is on the sprayer must also be considered. This is extremely important for nozzles with the flat spray pattern typically used for broadcast spraying since the spray pattern is more 2-dimensional, than other spray patterns such as the cone nozzles, which are more 3-dimensional. The orifice slots must be perpendicular to the direction in which the spray cart is moving. Although this may seem obvious, it is often overlooked. In attempt to insure a uniform coverage Mn/DOT 1995 Specifications 2301.3 states

"*The equipment shall be operated in a manner that will direct the membrane compound to the surface from two different lateral directions. When a single set of nozzles is mounted on a bar that extends longitudinally over the pavement, the compound shall be applied in two passes of the nozzles over the* *surface, one in each direction. When two sets of nozzles are mounted on two transverse lines over the pavement in a staggered manner and the membrane compound from either set of nozzles will uniformly cover the pavement surface, application may be accomplished in one pass of the unit."*

Directing the membrane from two different lateral directions becomes increasingly important for tined surfaces to insure the two vertical surfaces created during the tining process are coated. Therefore, it is recommended that this specification be more strictly enforced.

Cart Speed

The required cart speed is a function of the type of nozzle chosen and pump pressure. Part of Mn/DOT Specification 2301.3 states "*If used, the spray bar drive system shall operate independently of the wheels or track drive system.*" This specification insures the pressure used for spraying is independent of the cart speed. If a pump is used then the pressure should be adjustable. Changes in pressure can then be used to control droplet size while the cart speed is adjusted separately to control the quantity of curing compound applied. Equation 1 can be used to determine the required cart speed once a nozzle has been chosen and the pump pressure is known. Nozzle manufacturers typically provide tabulated information, which give flow rates for each nozzle at various pump pressures. These flow rates are used along with equation 1 to determine cart speed. Although Mn/DOT does not require it, a pressure gage should be included on each cure cart so that the coverage rate can be monitored by a more accurate means then counting empty cure barrels along the side of the pavement. The coverage rate should be controlled by the cart speed not the pump pressure since changing the pump pressure will change the droplet size, thereby increasing drift potential or decreasing the uniformity of the coverage. Controlling the coverage rate with the pump pressure is also not very efficient since to double the coverage rate the pump pressure must be increase by a factor of four.

$$v = \frac{Coeff. \times F}{C \times w} \qquad \textit{Equa. 1}$$

v = Cart speed, kilometers per hour (miles per hour)
Coeff. = 6 when using SI units (0.13636)
F = Flow rate, liters per minute per nozzle (gallons per minute per nozzle)
C = Desired coverage, liters per square meter (gallons per square foot)
w = Nozzle spacing, cm (inches)

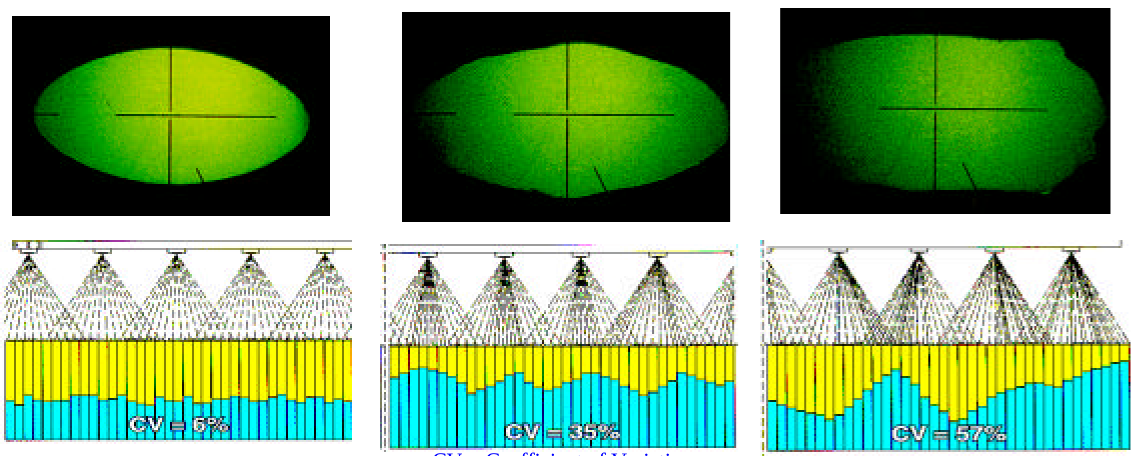
Wind Shield

Mn/DOT requires a shield to control the loss of curing compound due to wind action. Most contractors have addressed this by attaching a plank, which rests behind the nozzles, to the curing cart. This has not proved to be an effective means of shielding the wind. It may be possible to correct this by writing a more stringent specification that gives a more detailed description of the type of shield that must be used. Other problems occur when the wind shield is located too close to the nozzle and interferes with the spray. This results in drips of compound coming off the cart instead of a uniform distribution of droplets.

Non-uniform Coverage

Mn/DOT's current specifications have not eliminated streaks in curing compound coverage. Dirty or damaged nozzles or nozzle setups that do not follow the specification stated above are commonly the cause. Nozzles can be damaged by everyday wear or through improper cleaning techniques. A soft bristled brush or toothpicks should always be used to clean clogged nozzles. Never use metal objects. Even toothpicks have been shown to distort the orifice when softer nozzle materials, such as plastic are used (Agricultural Spray Products Catalog, 1997). Both wear and damage to the orifice will increase the size of the orifice resulting in a larger but more erratic output. Figure 5 depicts the change in shape of the orifice caused by damage and wear and the effect this has on the distribution of the spray pattern. Nozzle tips should be replaced when the flow exceeds the flow of a new tip by 10 percent (Agricultural Spray Products Catalog, 1997). The flow rate can be checked by placing an accurate graduated container under the nozzle for a timed duration. It is recommended that the nozzle tips be checked on a routine basis for wear damage.

VIEW THROUGH AN OPTICAL COMPARATOR



CV = Coefficient of Variation

SPRAY PATTERN

(Adopted from Agricultural Spray Products Catalog, 1997).

Figure 5. Nozzle orifice wear and damage.

Field Test

During the summer of 1998, an attempt was made to improve the uniformity of the coverage by requiring three passes of the curing compound application cart in the longitudinal direction while maintaining the standard application rate (1.33 m^2/L (54 ft^2/gal)) per pass on a test project. This project also included a section requiring three passes while increasing the application to 2.66 m^2/L per pass (109 ft^2/gal per pass). It was determined that neither increasing the number of passes or increasing the application rate provided a more uniform coverage. The cart did not wander enough to reduce the streaks on the pavement surface after multiple passes, as is seen in figure 6. Increasing the number of passes also increases the time required to apply the curing compound, thereby, increasing the amount of evaporation that occurs before the pavement is completely covered. Increasing the application rate resulted in puddles of curing compound in some areas while other areas were still not sufficiently covered. From this field test, it was determined that the best way to insure a uniform coverage of adequate thickness is to make sure the nozzles do not have excessive wear or damage, the cure cart setup meets Mn/DOT specifications and the cart speed, pump pressure, flow rate and nozzle spacing being used will produce the desired coverage thickness.

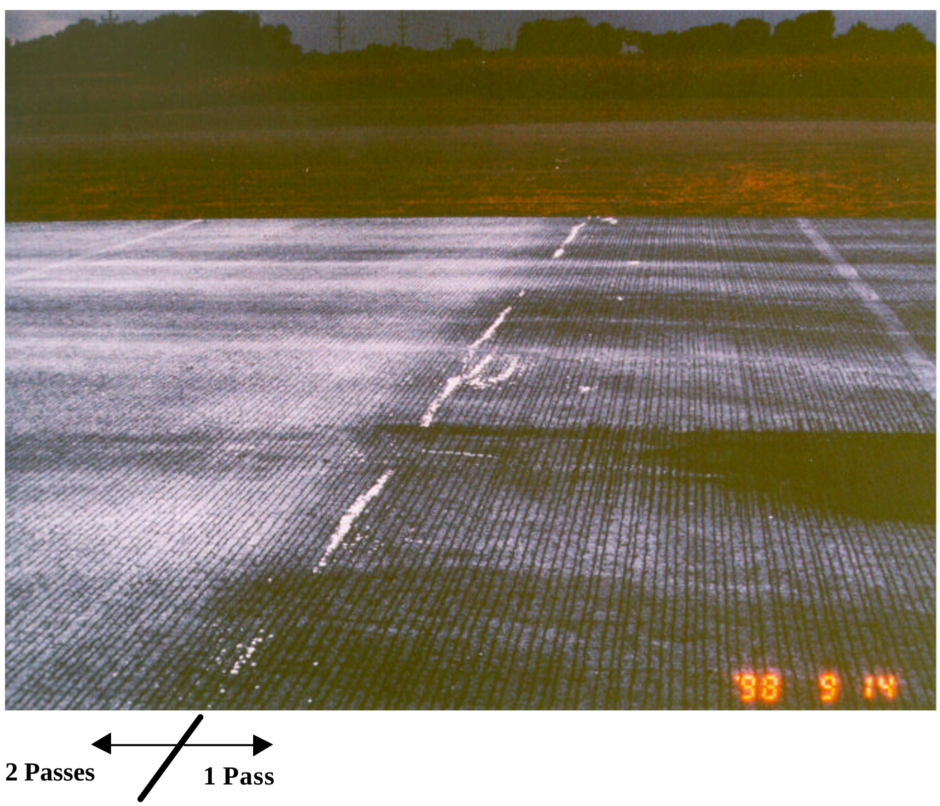


Figure 6. Using multiple passes of the curing cart to apply curing compounds.

Summary

The importance of properly curing concrete pavements can not be over emphasized, especially with Mn/DOT's 0.40 maximum water-to-cementitious ratio specification. Unfortunately, inspection of the curing operation is neglected because there has not been a direct means of quantitatively measuring the uniformity or effectiveness of the coverage. This situation has been partially improved by several changes made to Mn/DOT curing specifications in March 1999 to improve the quality of the curing compounds used. The two primary changes included requiring the resin consist of 100 percent poly-alpha-methylstyrene and increasing the restrictions on maximum allowable water loss.

The effort put forth to insure the use of a quality curing compound is futile unless a uniform coverage of adequate thickness over the surface of the pavement is achieved. Using a nozzle suitable for broadcast spraying that is not excessively worn or damaged will help provide a uniform coverage provided the orientation, spacing and height of the nozzle has been appropriately adjusted. The cart speed and pump pressure controls the coverage rate. A pump pressure that produces droplets large enough to limit drift yet small enough to uniformly cover the pavement surface should be used. Manufacturers provide guidelines regarding appropriate pump pressures for each nozzle. Cart speed can then be calculated using equation 1 based on the pump pressure, nozzle spacing and desired coverage. This is a considerably more accurate method of monitoring the coverage rate then counting the number of empty barrels along the side of the pavement. Of course, it is also important that an effective wind shield is used so that the majority of the cure coming out of the sprayer is making it onto the pavement surface. To address these issues, the following recommendations are proposed:

1. The required application rate for the curing compound must be calculated for each job based on the type of surface texture used and the specified minimum coverage rate of 4 m^2/L.

2. Inspectors must calculate the spray overlap for the nozzle setup on the curing cart being used on each project to insure a 30 percent overlap is obtained.
3. Mn/DOT's 1995 Specification 2301.3, which describes nozzle orientation requirements, must be more strictly enforced.
4. A pump with adjustable pressure and a pressure gage must be required on each cure cart so that the coverage rate can be accurately monitored.
5. The coverage rate must be controlled by the cart speed, not the pump pressure, since changing the pump pressure changes the droplet size and changes in the droplet size will effect the uniformity of the coverage.
6. Inspectors must calculate the required cart speed for each job using equation 1 to insure the minimum coverage requirements are being met.
7. Nozzle tips must be checked on a routine basis for wear damage.
8. More stringent specifications that give a more detailed description of the type of wind shield required for the cure cart must be written and enforced.

Applying a quality curing compound uniformly over the pavement surface, as described above, will protect the concrete during the critical period of early strength development, thereby contributing to a durable pavement capable of serving the public throughout its design life.

REFERENCES

1991 Annual Book of ASTM Standards, Sec. 4, Vol. 4.02, American Society for Testing and Materials, Philadelphia, PA.

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APPENDIX A: Mn/DOT 1999 Specifications, Test Methods and Approval Program

CURING OF CONCRETE PAVEMENT

Specification 3754 is hereby modified. This product shall be identified as 3754 AMS.

Surfaces of the concrete which are exposed to the air shall be sprayed uniformly with a curing compound meeting the following requirements:

> White pigmented curing compound conforming to the requirements of ASTM Designation: C309, Type 2, Class B.
> The resin shall be 100 percent poly-alpha-methylstyrene.
> The curing compound shall conform to all requirements according to table CC-1.
>
> The shelf life of the product shall be: (1) 6 months or,
> (2) the calendar year the product was produced, whichever is greater.

Table CC-1

Properties	**Minimum**	**Maximum**
Total Solids, % by weight of compound	42	
% Reflectance in 72 hours (ASTM E1347)	65	
Loss of Water, kg/m^2 in 24 hours (ASTM C156)		0.15
Loss of Water, kg/m^2 in 72 hours (ASTM C156)		0.40
Settling Test, ml/100 ml in 72 hours[1]		2
V.O.C. Content, g/L		350
Infrared Spectrum, Vehicle[2]	100% poly-alpha-methylstyrene	

[1] Test Method on file at the Mn/DOT Central Laboratory
[2] The infrared scan for the dried vehicle from the curing compound shall match the infrared scan on file at the Mn/DOT Central Laboratory.

Minnesota Department of Transportation
Test Methods for White Pigmented Styrene-Based Concrete Curing Compounds
(ASTM Designation C309 Type 2 Class B)
March 1999

1. Scope

These test methods cover the testing requirements of white pigmented styrene based concrete curing compounds.

2. Referenced Documents:

2.1 ASTM Standards:

C156 Standard Test Method for Water Retention by Concrete Curing Materials
C1315 Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete.
D1644 Test Method for Nonvolatile Content of Varnishes
D2371 Test Method for Pigment Content of Solvent Reducible Paints
D3723 Test Method for Pigment Content of Water Emulsion Paints by Low Temperature Ashing
D2621 Standard Test Method for Infrared Identification of Vehicle Solids From Solvent Reducible Paints
E1347 Standard Test Method for Color and Color Difference Measurement By Tristimulus (Filter) Colorimetry

3. Solvents

Extraction Mixture- Mix 10 volumes of ethyl ether, 6 volumes of toluene, 4 volumes of methyl alcohol and 1 volume of acetone. See hazard precautions in Section 6 of ASTM D2371.

4. Procedure

<u>4.1 Vehicle Solids and Pigment Content</u>
Total solids and % pigment shall be determined according to Section 8.6 of C1315. Percent pigment can be determined either by D3723 or by D2371. Use extraction mixture listed above when using D2371. Retain extracts from D2371 for Infrared identification of curing compound vehicle.

% Vehicle Solids = %Total Solids - % Pigment

The curing compound shall have a minimum of 42% total solids by weight and the vehicle shall be 100% poly-alpha-methylstyrene.

4.2 Infrared Identification of Vehicle Solids
Use ASTM D2621 to prepare vehicle solids for infrared identification with the exception that D2371 shall be used to separate vehicle from pigment. If D 3723 was used to determine % pigment then a separate sample shall be used to prepare vehicle solids for infrared identification. Infrared spectrum of the vehicle solids shall match the reference spectrum of poly-alpha-methylstyrene prepared at Mn/DOT Chemical Laboratory.

4.3 Water Retention

Use ASTM C156 to test for water retention efficiency with the exception that measurements shall be taken at 24 hours and 72 hours.

The loss of water shall not be more than 0.15 kg/ m^2 at 24 hours and no more than 0.40 kg/ m^2 at 72 hours.

4.4 Reflectance

Use ASTM E1347 when measuring reflectance.

45/0 geometry color spectrophotometer or colorimeter using CIE Illuminant C with 2^o Standard Observer shall be used to measure reflectance. Reflectance is Y in the CIE Y,x,y color measurement system.

The 3 day reflectance readings shall be greater than 65.

4.5 Three Day Settlement Test
Pour curing compound into a 100-ml graduated cylinder until bottom of meniscus reaches the 100-ml mark. The graduated cylinder shall have sub-divisions of 1 ml.

Using disposable pipet remove any air bubbles incorporated into curing compound upon pouring into graduated cylinder. At this time you may add or extract excess curing compound to reach 100-ml mark.

Secure a rubber stopper in the graduated cylinder to minimize evaporation and leave sample undisturbed for 3 days. At the end of the 3-day time period measure the amount of settling to the nearest ml. The degree of settling is the amount of clear, colorless supernatant liquid in the graduated cylinder.

The settling of the curing compound shall not exceed 2 ml after 3 days.

Minnesota Department of Transportation
Curing Compound Manufacturer Approval Program
March 1999

The Minnesota Department of Transportation will accept curing compounds only from approved sources. This applies to all curing compounds sold to contractors for use on Mn/DOT projects.

To be accepted as a Mn/DOT Approved Source, a Manufacturer must demonstrate an ability to manufacture a curing compound meeting the requirements of Mn/DOT Specifications and the Manufacturer must:

- Conduct a Mn/DOT approved Quality Control Program.
- Provide samples for verification for each lot supplied to Mn/DOT projects
- Provide manufacturer's QC test results
- Supply shipping information
- Certify that their product meets the requirements of Mn/DOT Specifications
- Submit written agreement to this program

Acceptance of curing compounds under this program is based on the manufacturer's certification and Quality Control testing as verified by Mn/DOT Materials Lab testing of ?verification samples and spot checks on samples obtained from contractors stock or from project sites. Mn/DOT testing is for verification of the manufacturers QC testing. Discrepancies in test results between manufaturer?s lab and the Mn/DOT Materials Lab that indicate significant deviation from Mn/DOT specifications, which cannot be resolved, may result in removal of a manufacturer from the Approved Source List.

A. Manufacturer Quality Control Program

A written Quality Control Program that monitors a manufacturers production shall be submitted for Mn/DOT approval. The written program shall detail the frequency and types of tests performed on each lot produced for Mn/DOT projects as well as raw materials where appropriate.

B. Verification Samples

Manufacturer shall submit samples of each batch or lot manufactured to the Mn/DOT Materials Lab along with a certification stating that the sample is representative of the batch manufactured will be sent with the sample. Samples shall be taken for testing by an Agency Representative. Samples shall be tested prior to shipping of materials. Also include a Materials Safety Data Sheet (MSDS) and a Technical Data Information Sheet.

C. Testing

Tests will be performed according to ASTM Standards, Federal Test Methods, or Mn/DOT Methods as detailed in the Mn/DOT product specification. Other test methods may be used upon approval by Mn/DOT. Testing frequency shall be according to manufacturers approved QC Plan. Test results on finished batches shall be submitted to the Mn/DOT Materials Lab along with name and address of purchaser.

D. Certification

Each shipment shall be accompanied by manufacturers written certification listing batch number quantity and certifying that the product meets the appropriate Mn/DOT specifications. A copy of the certification shall be submitted to the Mn/DOT Materials Lab.

Non-compliance to the provisions may result in removing a manufacturer from the approved list.

Samples, test data, certifications and shipping information shall be sent to:

Minnesota DOT
Attention: Cement and Soils Lab
1400 Gervais Ave.
Maplewood MN 55109

Tel. (651) 779-5556
Fax (651) 779-5616