Studded Tire Wear Resistance of PCC Pavements with Special Mix Designs

WA-RD 658.2

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WSDOT Research Report

Experimental Feature Report

Final Report
Experimental Features WA 03-04, 04-01, and 05-04

Studded Tire Wear Resistance of PCC Pavements with Special Mix Designs

Contract 6620
I-90
Argonne Road to Sullivan Road
MP 286.91 to 292.38




Washington State
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16. ABSTRACT

The performance of portland cement concrete mixes with higher flexural strength, higher cement content, and with Hard-Cem additive, carpet drag finish, and tined finish were evaluated over a period of five years to determine their resistance to studded tire wear.

None of the pavements with special mixes or, mixes with Hard-Cem additive were more resistant to studded tire wear than conventional pavement with a 650 psi flexural strength mix design.

The wear resistance of the pavement could not be correlated to either the method used to finish the concrete or the concrete's flexural strength.

Finally, the carpet drag finishing method produced a pavement with acceptable friction resistance.

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Introduction

Washington State Department of Transportation's portland cement concrete pavement (PCCP) construction program has been relatively small since the completion of the Interstate system in the 1960's and early 1970's. Many of these pavements are now reaching the end of their useful lives and are being programmed for reconstruction. It is essential that the best possible materials and construction practices be used in order to ensure pavement service lives of 50 years or longer. This has led to the development of a number of experimental features that have been incorporated into PCCP construction projects to evaluate various innovative materials or construction practices that may have better performance, especially pavements that are more resistant to studded tire wear. This report covers three experimental features that were incorporated into the construction of Contract 6620, Argonne Road to Sullivan Road on Interstate 90 in Spokane. The experimental feature numbers and titles incorporated into Contract 6620 are; (1) 03-04, PCCP Features (Carpet Drag, Flexural Strength, and Surface Smoothness), (2) 04-01, Use of Hard-Cem in Concrete Pavements, and (3) 05-04, Use of Higher Slag and Cement Content in Concrete Pavements.

Objectives

This report, because it includes three experimental features, has a multitude of objectives. The primary objectives are:

- to determine if pavements built with higher flexural strength mixes, higher cement content mixes, and mixes with the Hard-Cem concrete hardener additive are more resistance to the wear from studded tires than pavements built with standard 650 psi flexural strength mix,
- to determine if a carpet drag texturing process will provide a pavement with adequate initial and long-term friction resistance,
- to determine if a carpet drag finish provides a more studded tire wear resistant pavement surface. The Texas Department of Transportation (TxDOT) asserts that tining exposes more surface area of the pavement to rapid drying during curing then a carpet drag finish. Rapid curing usually results in a pavement with less strength, and thus less resistance to wear from studded tires.

Background

Wear on PCCP in the state of Washington is primarily due to studded tires except on our mountain passes where chains are also a factor. Studded tires are allowed between November 1 and March 31. The wear pattern from studded tires ranges from a gradual dishing of the wheel paths to distinct ruts. The transverse tined finish that is specified for PCCP is removed in as little as three years on heavily trafficked routes. Figure 1 shows a concrete pavement that was constructed in 1995 on state route (SR) 395 just south of Interstate 90 (Ritzville vicinity). At the time this photo was taken in 2003, this pavement had been in service for seven years. The average annual daily traffic (AADT) on this route is approximately 6,800 vehicles. The tining in the wheel paths has been completely removed due to studded tires (note that the tining is still visible at the lane edges and between the wheel paths).

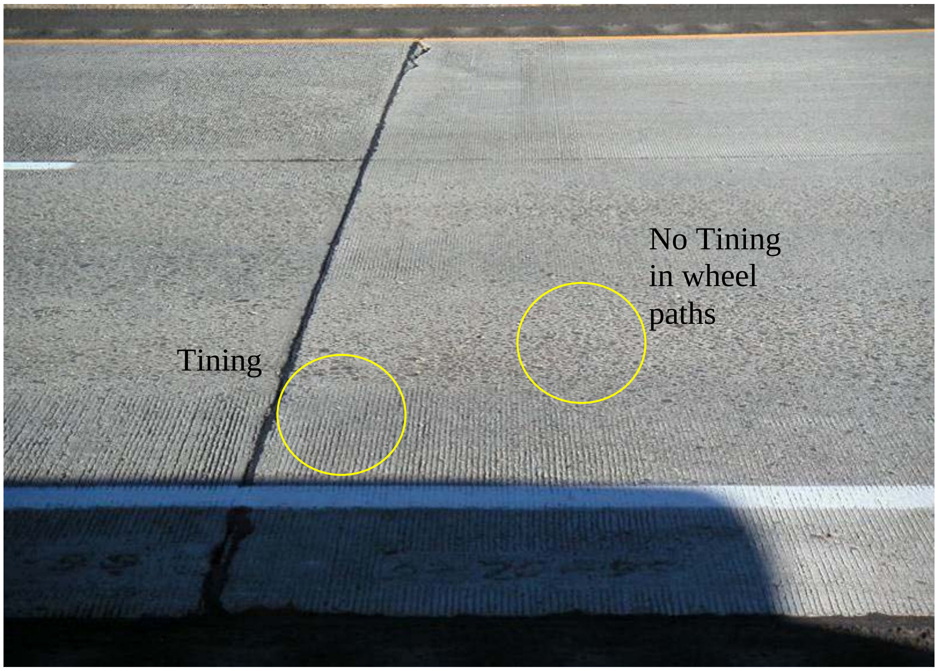

Figure 1. Concrete pavement on SR-395 south of the Interstate 90 interchange at Ritzville after seven years of traffic (ADT = 6,800).

In contrast to the studded tire wear on pavements in Washington, Figure 2 shows a thirteen year old concrete pavement located on Interstate 45 in Houston, Texas. Note the clear pattern of the tine marks across the entire width of the pavement lane. The AADT on this section is 178,000 vehicles per day. Although the state of Texas allows studded tires, in reality the climate in Texas does not typically warrant there use. The damaging effect of studded tires is clearly observable when comparing these two pavements. It is made even more dramatic when considering that the Texas pavement has received more than 26 times the daily traffic volume (6,800 versus 178,000) and has been in place for almost twice the number of years (seven years versus 13 years) as the pavement on SR 395.

Figure 2. Concrete pavement with tined finish on Interstate 45 in Houston, Texas after thirteen years of traffic (ADT = 178,000).

A more dramatic example of studded tire wear is shown in Figure 3 on I-90 in the Spokane area. The wear has formed ½ inch deep ruts in the PCCP. This rut formation from studded tire wear is especially prevalent in the Spokane area, which is reported to have the highest use of studded tires in the entire state.

Figure 3. Wear on PCCP on Interstate 90 near Spokane, Washington. Picture taken prior to pavement being diamond ground in 1995 (ADT = 52,000).

As mentioned previously, the challenge to reduce the excessive wear pavements receive from studded tires has prompted a series of experimental features to address this problem (Table 1). They include the use of combined aggregate gradation, ultra-thin and thin whitetopping, carpet drag texturing, experimental finishing methods such as longitudinal tining and carpet drag, higher flexural strength mix designs, high cement content mix designs, and special additives that are reported to make the concrete harder. The features reported in this document are in bold type.

Table 1. Experimental features for mitigating studded tire wear.		
Exp. Feature Number	**Experimental Feature Title**	**Location**
01-02	Combined Aggregate Gradation for PCCP	I-90, Sprague Ave I/C Phase III, Contract 6947
03-02	Ultra-Thin Whitetopping/Thin Whitetopping	I-90, Sullivan Road to Idaho State Line, Contract 6582
03-04	**PCCP Features (Carpet Drag, Flexural Strength, and Surface Smoothness)**	**I-90, Argonne Road to Sullivan Road, Contract 6620**
04-01	**Use of Hard-Cem in Concrete Pavements**	**I-90, Argonne Rd. to Sullivan Rd., Contract 6620**
05-02	PCCP Features (Carpet Drag and Noise Mitigation)	I-5, Federal Way to S. 317th Street HOV Direct Access, Contract 6757
05-04	**Use of Higher Slag and Cement Content in Concrete Pavements**	**I-90, Westbound, Argonne Rd. to Sullivan Rd., Contract 6620**
05-05	PCCP Features, (Carpet Drag and Noise Mitigation)	I-5, Pierce Co. Line to Tukwila I/C - Stage 4, Contract 6883

Project Description

The project is located on I-90 in the urban area of Spokane, Washington. Construction consisted of six lanes of PCCP, three lanes in each direction, between the limits of mileposts MP 287.98 and 292.08 a total of 24.6 lane miles. The average daily traffic on this section of I-90 is 75,519 with 10.4% trucks (2004 data). A vicinity map is provided in Figure 4.

Figure 4. Vicinity map of Contract 6620, Argonne Road to Sullivan Road.

Experimental Sections

The standard WSDOT mix design for PCC pavement calls for a flexural strength of 650 psi at 14 days and the standard finishing method is transverse tining. As a result of the problems with studded tire wear in the Spokane urban area the majority of this project was built using a mix design with 800 psi flexural strength and a carpet drag finish. Added to this were three additional sections of pavement with different mix designs, one with 650 psi flexural strength to match our current standard mix but with a carpet drag finish, one with 650 psi flexural strength but with a concrete hardener additive called Hard-Cem, and one with 925 pounds of cementitious material per cubic yard and carpet drag finish. One additional test section using 800 psi flexural strength and a transverse tined finish was also built as a comparison section to the control section of 650 psi flexural strength and tined finish. A test section with 30-35% slag cement content was in the original work plan but was not constructed due to the unavailability of the cement. It was also planned to have portions of the Hard-Cem and 925 lbs/cy cement content section built with a transverse tined finish, but this also did not take place due to an oversight by the Contractor. A plan view of the location of the special sections is shown in Figure 5. The test sections are summarized below.

Carpet Drag Test Sections

- 800 psi flexural strength mainline paving all lanes except as noted below
- 650 psi flexural strength MP 291.96 to 292.02 EB Lanes 2 and 3
- 650 psi flexural strength with Hard-Cem MP 291.85 to 291.96 EB Lanes 2 and 3
- 925 lbs. of cementitious material per cubic yard MP 288.46 to 288.58 WB Lanes 2 and 3

Tined Test Sections

- 800 psi flexural strength MP 287.98 to 288.03 EB Lanes 2 and 3

Control Section with Tined Finish

- 650 psi flexural strength MP 292.02 to 292.07 EB Lanes 2 and 3

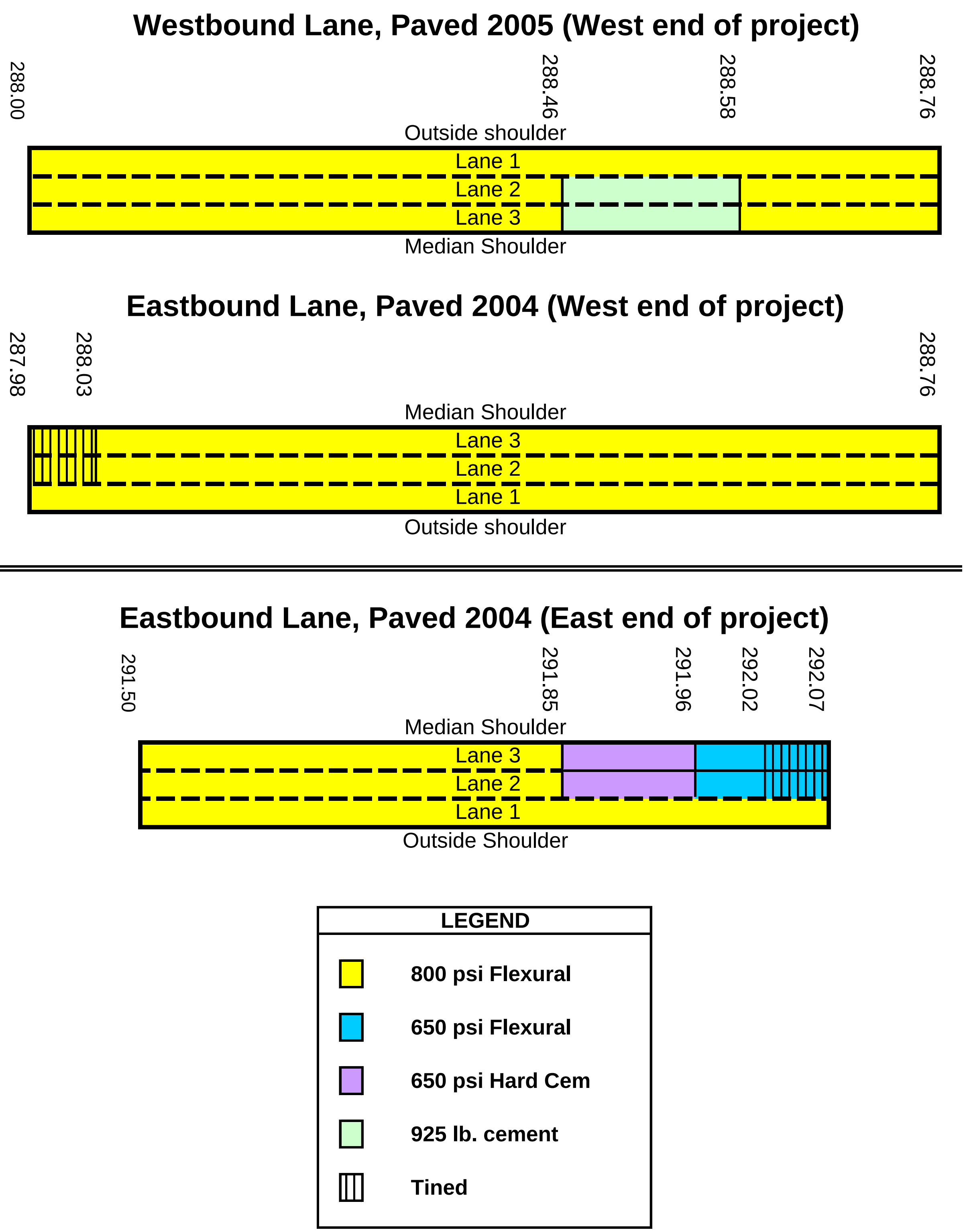

Figure 5. Location of special sections.

Mix Designs

Paving occurred over a two year period; the eastbound lanes paved in 2004 and the westbound lanes paved in 2005. Six mix designs were used over the period of the two years. In 2004 the standard mix design for the 800 psi flexural strength used throughout the project was 6620-02. A variation of 6620-02 with minor changes in aggregate gradation, 6620-02R, was also used in 2004. All of the mix designs used a combined gradation for the aggregates. All of the cement in 2004 was MaxCem which is a combination of 20-25% Ground Granulated Blast Furnace Slag (GGBFS) and portland cement. Table 3 and 4 provide details of the two 800 psi mix designs used in 2004.

Table 2. Mix design 6620-02 with 800 psi flexural strength.

Item	Source	Type	Lbs/cy	Specific Gravity
Cement	Lafarge	I-SM	660	3.15
Agg. Source 1	C-173	1 ½ - ¾	629	2.69
Agg. Source 2	C-173	3/4 - #4	599	2.68
Agg. Source 3	C-173	3/8	329	2.67
Agg. Source 4	C-173	5/8	421	2.69
Agg. Source 5	C-107	Coarse Sand	680	2.64
Agg. Source 6	C-297	Fine Sand	463	2.64
Water			217.8	1.00
W/C Ratio			0.33	
Water Reducer	Master Builders	Master Pave A&D	40-60 oz/cy	
Air Ent.	Master Builders	MBAE 90	6-12 oz/cy	

Table 3. Mix design 6620-02R with 800 psi flexural strength.

Item	Source	Type	Lbs/cy	Specific Gravity
Cement	Lafarge	I-SM	660	3.15
Agg. Source 1	C-173	1 ½ - ¾	470	2.69
Agg. Source 2	C-173	¾ - #4	1,314	2.68
Agg. Source 3	C-107	Coarse Sand	862	2.64
Agg. Source 4	C-297	Fine Sand	462	2.64
Water			212	1.00
W/C Ratio			0.33	
Water Reducer	Master Builders	Master Pave A&D	40-60 oz/cy	
Air Ent.	Master Builders	MBAE 90	6-12 oz/cy	

A 650 psi flexural strength mix was used in 2004 on a short section of pavement to act as a control section of WSDOT's standard specification mix and the mix design for it is shown in Table 4.

Table 4. Mix design 6620-03 with 650 psi flexural strength.

Item	Source	Type	Lbs/cy	Specific Gravity
Cement	Lafarge (MaxCem)	I-SM	565	3.15
Agg. Source 1	C-173	1 ½ - ¾	631	2.69
Agg. Source 2	C-173	¾ - #4	1,354	2.68
Agg. Source 3	C-107	Coarse Sand	682	2.64
Agg. Source 4	C-297	Fine Sand	464	2.64
Water			237	1.00
W/C Ratio			0.42	
Water Reducer	Master Builders	Master Pave A&D	40-60 oz/cy	
Air Ent.	Master Builders	MBAE 90	6-12 oz/cy	

The fourth mix design used in 2004 was a 650 psi flexural strength mix to which Hard-Cem was added. Hard-Cem is an integral concrete hardener manufactured by Cementec Industries, Inc. According to Cementec Industries, Hard-Cem is a functional filler additive and not a chemical admixture and claims it can be added to any concrete mix with no effect on the concrete qualities such as air-entrainment. Hard-Cem is a fine powder that is handled similar to cement, is added during the batching process, and affects the entire mix, not just the surface of the pavement. Hard-Cem is reported to improve the abrasion resistance of concrete by 35% as measured using ASTM C627, *Standard Test Method for Evaluating Ceramic Floor Tile Installation Systems Using the Robinson-Type Floor Tester*. The mix design for the 650 psi flexural strength mix with Hard-Cem is shown in Table 5. This mix design is identical to the 650 psi flexural strength design used for the control section except for the substitution of 67 lbs/cy of Hard-Cem for the same amount of Type I-SM cement. The addition of the Hard-Cem lowered the water cement ratio from 0.42 to 0.38.

Table 5. Mix design 6620-04 with 650 psi flexural strength and Hard-Cem additive.				
Item	**Source**	**Type**	**Lbs/cy**	**Specific Gravity**
Cement	Lafarge	I-SM	565	3.15
Slag	Lafarge	Hard-Cem	67	3.15
Agg. Source 1	C-173	1 1/2 - ¾	631	2.69
Agg. Source 2	C-173	¾ - #4	1,354	2.68
Agg. Source 3	C-107	Coarse Sand	670	2.64
Agg. Source 4	C-297	Fine Sand	428	2.64
Water			237	1.00
W/C Ratio			0.38	
Water Reducer	Master Builders	Master Pave A&D	20-30 oz/cy	
Air Ent.	Master Builders	MBAE 90	6-12 oz/cy	

A new mix design, 6620-05, was developed in 2005 for the 800 psi flexural strength concrete used on the 2005 paving. Details of the mix design are shown in Table 6. Mix design 6620-02R (see Table 3) was also used extensively in 2005 depending upon which source of cement was available at the time. When slag cement was not available they used 6620-02R, otherwise they use the new mix design 6620-05. Approximately 50% of the 2005 paving was constructed with each of the two mix designs.

Table 6. Mix design 6620-05 with 800 psi flexural strength.				
Item	**Source**	**Type**	**Lbs/cy**	**Specific Gravity**
Cement	Lafarge	I-SM	495	3.15
Slag	Lafarge	New Cem	165	2.83
Agg. Source 1	C-173	1 ½ - ¾	627	2.69
Agg. Source 2	C-173	¾ - #4	1,345	2.68
Agg. Source 3	C-107	Coarse Sand	688	2.64
Agg. Source 4	C-297	Fine Sand	459	2.64
Water			218	1.00
W/C Ratio			0.33	
Water Reducer	Master Builders	Master Pave A&D	40-60 oz/cy	
Air Ent.	Master Builders	MBAE 90	6-12 oz/cy	

The final mix design used on the project was the high cement content design (Table 7). This design was added to see what affect higher cement content would have on the studded tire wear. As a comparison the mix design for the 900 psi mix for the SHRP SPS-2 test sites on SR-395 paved in 1997 is shown in Table 8, along with a summary of the 925 lbs/cy design. Notice that the mix design for the SPS-2 900 psi flexural strength concrete is very similar to the mix design for the 925 lbs/cy design.

Table 7. Mix design 6620-08 with 925 lbs/cy of cementitious material.

Item	Source	Type	Lbs/cy	Specific Gravity
Cement	Lafarge	I-SM	925	3.15
Agg. Source 1	C-173	1 ½ - ¾	595	2.69
Agg. Source 2	C-173	¾ - #4	1,278	2.68
Agg. Source 3	C-107	Coarse Sand	475	2.64
Agg. Source 4	C-297	Fine Sand	317	2.64
Water			305	1.00
W/C			0.33	
Water Reducer	Master Builders	Master Pave A&D	40-60 oz/cy	
Air Ent.	Master Builders	MBAE 90	6-12 oz/cy	

Table 8. Comparison of mix design with 900 psi flexural strength with mix design with 925 lbs/cy of cementitious material.

Item	Type	SPS-2 900 psi flexural strength	6620-08 925 lbs/cy cement content
Cement	II (Holman)	925	925
Fine Aggregate	WSDOT Class II	948	792
Coarse Aggregate	WSDOT Type II	1,833	1,873
Water		285	305
W/C Ratio		0.33	0.29

In summary, the test sections include both carpet drag and tined 800 psi flexural strength mixes, both carpet drag and tined 650 psi flexural strength sections, and two special sections, one with 650 psi flexural strength mix and Hard-Cem concrete hardener and one with 925 pounds of cementitious material per cubic yard. The last two, the Hard-Cem and the 925 pound section were done exclusively with a carpet drag finish. No companion sections were included with a tined finish.

Paving

The prime contractor on the project was Scarsella Brothers, Inc. and the subcontractor for paving was Acme Concrete Paving, Inc. The roadway paving section used on the project was 1.00 feet of doweled PCCP over either the existing surfacing that was rotomilled or in areas were the existing pavement was completely removed the PCCP was placed on 0.20 ft ACP Class E PG 64-28 over 0.25 ft crushed surfacing base course. A total of 114,130 cubic yards of concrete was planned to be placed.

A sequence of photos, Figures 6 thru 16, show the paving operation beginning with the dump trucks unloading the wet concrete in front of the paving machine and ending with the joint sawing after the application of the astro turf carpet drag finish. Two paving machines were used for the lanes poured in 2004. The first machine, a Guntert & Zimmerman 150 two track paver, was used to spread the concrete in front of the second paver. The second paver, a Guntert & Zimmerman S-1500 four track, consolidated the concrete and inserted the dowel bars. The Contractor thought that this method would provide a smoother ride. The theory being that the first paver would spread the concrete so that there was a consistent amount of concrete in front of the second paver. This practice was abandoned after the 2004 paving season. The westbound lanes placed in 2005 were paved using only the Guntert & Zimmerman S-1500 four track paver. An analysis of the profilograph traces from the two phases did not reveal any substantial differences in ride between the two paver and single paver operations.

Figure 6. Dump trucks delivering the wet concrete to the Guntert & Zimmerman 150 two track paver. June 2004.

First paver used to spread the wet concrete is shown in Figure 6. The second paver (Figure 7) consolidated the concrete and placed the epoxy coated dowel bars at 15 foot intervals.

Figure 7. Guntert & Zimmerman S-1500 four track paver used to consolidate and insert dowel bars in the eastbound lanes. August 2004.

Figure 8. Dowel bar inserter on Guntert & Zimmerman S-1500 paver. June 2004.

Figure 8 shows the dowel bar inserter and Figure 9 the tie bar inserter mounted on the Guntert & Zimmerman S-1500 paver.

Figure 9. Inserter set-up on paving machine for epoxy coated tie bars. June 2004.

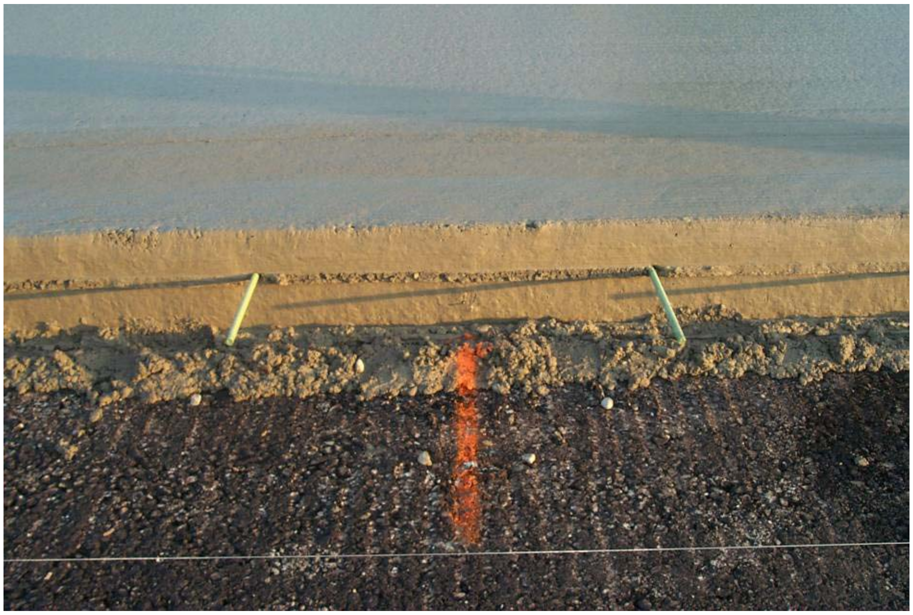

Figure 10. Tie bar inserted into edge of pavement. June 2004.

Figure 10 shows the tie bars that form the connection between the lanes and Figure 11 shows the consolidated concrete as it comes out of the paving machine.

Figure 11. Pavement surface directly behind the second paving machine. June 2004.

Figure 12. Pipe float used to smooth the surface of the wet concrete prior to the application of the astro turf carpet drag texture. June 2004.

Figure 12 shows the pipe float used to smooth the surface of the concrete prior to the astro turf carpet drag shown in Figure 13.

Figure 13. Astro turf carpet used to apply texture to the wet concrete.

June 2004.

The contract Special Provisions (Appendix A) describe the details concerning the special carpet drag finish as noted in the following excerpt from the contract:

> *"The pavement shall be given a final finish surface by drawing a carpet drag longitudinally along the pavement before the concrete has taken an initial set. The carpet drag shall be a single piece of carpet of sufficient length to span the full width of the pavement being placed and adjustable so as to have up to 4 feet longitudinal length in contact with the concrete being finished. The carpeting shall be artificial grass type having a molded polyethylene pile face with a blade length of 5/8" to 1" and a minimum mass of 70 ounces per square yard. The backing shall be a strong durable material not subject to rot and shall be adequately bonded to the facing to withstand use as specified."*

These provisions mimic those used by Texas Department of Transportation and do not include any provision for measuring the depth of texture provided by the method.

Figure 14. Bridge used for the pipe float and carpet drag operation. June 2004.

Figure 15. Final texture of the wet concrete with the astro turf carpet drag. June 2004.

A liquid curing compound (W.R. Meadows Sealtight 1600-White) was applied and the joints were saw cut at the prescribed 15 foot intervals using the machine shown in Figure 16.

Figure 16. Joint sawing equipment. June 2004.

Figure 17 shows the completed project. A total of 113,410 cubic yards of concrete were placed.

Figure 17. Project completion. May 2006.

Construction Test Results

The construction acceptance testing of interest to this study was the flexural strength of the hardened concrete. All of the mix designs were focused on achieving a certain level of flexural strength, flexural strength being thought of as a key measure of the pavement's resistance to wear from studded tires. The average and range for the compressive and flexural strength results for all of the mix designs are summarized in Table 9.

Table 9. Summary of compressive and flexural strength results from all of the mix designs.

Mix Design	6620-02	6620-02R	6620-05	6620-03	6620-04	6620-08
Special Identifier	800 psi Mainline Paving	800 psi Mainline Paving	800 psi Mainline Paving	650 psi Control Section	650 psi Hard-Cem Section	925 lbs/cy Cement Content Section
	Compressive Strength					
Average	5,976	6,027	5,732	5,020	5,745	5,930
Range	4,730-7,070	4,490-7,200	3,750-7,050	5,020	5,630-5,860	5,930
	Flexural Strength					
Average	971	975	923	791	846	N.A.
Range	865–1,057	842-1,067	717-1,012	791	838-855	N.A.

The flexural strength results for all of the mainline paving for both 2004 and 2005 (first three columns of Table 9) had an average flexural strength of 946 psi, with a range of 717 to 1,067 psi. This average exceeds the design requirements of 800 psi by over 18%. There were only three sets of cylinders that fell below the 800 psi specification. The flexural strengths for this project thus exceed even the 900 psi flexural strengths attained on the SHRP SPS-2 high strength test sections on SR-395 south of I-90. These are the sections that are showing more resistance to studded tire wear than the adjacent 550 and 650 psi flexural strength sections as detailed in the Background section of this report.

The last three columns of Tables 9 summarize the cylinder breaks from the special test sections. The 650 psi control section had a flexural strength of 791 for the one set of cylinders made for this mix design, which is 22% higher than the 650 psi flexural strength design. The two sets of cylinders made for the 650 psi Hard-Cem section averaged 846 psi which exceeds the 650 psi flexural strength design by 30%. The last column shows the compressive strength results for the 925 lbs/cy high cement content mix design. Since this is a recipe mix supplied by the State, there was no requirement to develop a compressive strength to beam strength comparison to provide a conversion factor. The cylinder breaks of 6,000 and 5,860 psi would probably translate into flexural strengths well in excess of 900 psi.

In summary, the compressive strengths from the cylinder breaks were all exceptionally high. It is somewhat of a concern that the average flexural strength test for the control section at 791 psi is not very close to the target design strength of 650 psi. However, this was the standard mix design used by this contractor on other major paving projects in the Spokane area.

Post Construction Testing

Texture

Sand patch tests were conducted on the finished concrete to measure the depth of texture using ASTM E-965, Measuring Pavement Microtexture Depth Using a Volumetric Technique. The tests were run for informational purposes, and only on the westbound lanes, to sample the degree of texture that had been achieved (Table 10). This was the first project that used the carpet drag finish and the special provisions included in the contract used the Texas DOT specification which did not require sand patch testing to measure the texture. In a subsequent project, Federal Way to 317th Street HOV Direct Access completed in 2005, the Minnesota DOT (Mn/DOT) specification was used which requires the use of the sand patch test to verify that the contractor is achieving the desire texture. The Mn/DOT specification has a minimum texture depth of 1.0 mm. None of the tests from the Argonne Road to Sullivan Road project would have met the Minnesota DOT specification.

Test Date	Milepost	Offset LT (ft)	Average Macro Texture Depth (mm)	Test Date	Milepost	Offset LT (ft)	Average Macro Texture Depth (mm)
6/29/05	289.31	42	**0.1797**	8/30/05	290.73	16	**0.1980**
6/29/05	289.28	20	**0.1096**	8/30/05	290.48	25	**0.1830**
6/29/05	289.25	49	**0.1348**	8/30/05	290.28	-	**0.2070**
6/29/05	289.99	43	**0.1250**	8/30/05	290.76	14	**0.2060**
6/30/05	289.85	63	**0.1783**	8/30/05	290.93	31	**0.2580**
6/30/05	289.70	44	**0.1263**	8/30/05	291.13	27	**0.2910**
6/30/05	291.99	19	**0.1817**	8/30/05	290.66	63	**0.3120**
6/30/05	291.91	33	**0.2978**	8/30/05	290.55	76	**0.2470**
6/30/05	291.81	18	**0.1553**	8/30/05	290.47	-	**0.2200**
6/30/05	291.56	58	**0.1828**	9/07/05	292.07	37	**0.3630**
6/30/05	291.47	43	**0.1544**	9/07/05	291.96	39	**0.2510**
6/30/05	291.43	54	**0.1250**	9/07/05	291.95	32	**0.2270**
6/30/05	291.42	17	**0.1523**	9/07/05	288.46	49	**0.1230**
6/30/05	291.31	27	**0.1581**	9/07/05	288.63	52	**0.1270**
6/30/05	291.22	29	**0.2291**	9/07/05	288.80	38	**0.1450**
7/05/05	290.28	56	**0.1629**	9/07/05	288.53	13	**0.1180**
7/05/05	290.38	49	**0.2118**	9/07/05	288.83	15	**0.2550**
7/05/05	290.63	40	**0.1246**	9/07/05	288.91	24	**0.2160**
8/30/05	291.16	42	**0.1200**	9/07/05	288.92	16	**0.3040**
8/30/05	291.01	47	**0.1360**	9/07/05	289.18	31	**0.2670**
8/30/05	290.75	39	**0.1330**	9/07/05	289.10	28	**0.3120**
						Project Average	**0.1954**

Table 10. Sand patch test results.

A sample of a data collection sheet and a sample calculation for the sand patch test are included in Appendix B.

Lane Numbering Convention

The lane numbering convention used throughout this report is that the lanes are numbered from the outside of the roadway toward the median. Lane 1 is the outside, driving/truck lane and Lane 3 is the inside, passing/median lane.

Friction

An initial set of friction resistance measurements was performed on August 30, 2005 using the WSDOT Locked Wheel Friction Tester meeting ASTM E274 specifications. At the time, the eastbound lanes were carrying both directions of I-90 traffic with two lanes operating in each direction. The results from these preliminary tests are summarized in Table 11. It should be noted that it was not always possible to obtain tests in the correct direction of travel and correct wheel path due to the odd lane configuration necessitated by the construction detour. The eastbound lanes had been open to traffic since October of 2004, but the westbound lanes were still under construction, however, it was possible to gain access to portions of these lanes and additional tests were performed. The values in Table 11 with the adjacent lanes label are from the Sprague Avenue to Argonne Road project that was opened to traffic in 2002. These results were included to provide an idea of the general range of friction values or PCC pavements with a transverse tined finish in the Spokane area.

Table 11. Preliminary friction test results (August 2005).

Location	Average	Range
Eastbound Lanes Carpet Drag Finish	32.8	27.9 – 42.4
Westbound Lanes Carpet Drag Finish	48.6	46.7 – 54.5
Adjacent PCCP MP 285-288 Transverse Tined Finish	30.9	27.1 – 33.6

The values for the eastbound lanes were what one might expect for a pavement that has been exposed to traffic for about a year. The values for the westbound lanes are equivalent to other PCC pavements prior to opening to traffic.

Additional friction testing was performed on May 3 and 4, 2006. All lanes in each direction were open to traffic and were tested in the correct direction and correct wheel paths. The average and range for each section is listed in Table 12. The numbers were on the low side for all sections; with average friction numbers ranging from a high of 36.7 for the 650 psi flexural strength section with tining to a low of 29.6 for the 925 lbs/cy cement content with carpet drag finish. The friction numbers for individual tests for all of the sections ranged from a low of 23.2 to a high of 54.3.

Table 12. FN test results for each section from May 3 and 4, 2006.

Section (Year Paved)	Year Paved	Lane	Dir.	Average FN	Range FN
650 psi Flexural Strength, Carpet Drag	2004	2&3	E	31.5*	29.8 – 33.9*
650 psi Flexural Strength, Hard-Cem Carpet Drag	2004	2&3	E	31.2*	30.2 – 33.5*
650 psi Flexural Strength, Tined	2004	2&3	E	36.7*	35.0 – 37.6*
800 psi Flexural Strength, Carpet Drag	2004	1,2&3	E	34.6*	23.2 – 44.6*
800 psi Flexural Strength, Tined	2004	2&3	E	36.3*	34.3 – 38.9*
800 psi Flexural Strength, Carpet Drag	2005	1,2&3	W	33.1*	24.4 – 54.3*
925 lbs/cy Cement Content, Carpet Drag	2005	2&3	W	29.6*	24.9 – 34.6*
All Sections				33.3*	23.2 – 54.3*

The occurrences of values in the 26-30 and below 26 categories are of concern to WSDOT. The WSDOT Directive for the Skid Accident Reduction Program requires that the Headquarters Materials Laboratory, operators of the friction tester, report any FN 30 or less to the appropriate offices in Headquarters and the affected Region. Locations with values between 26 and 30 are to be evaluated and those with numbers below 26 require that some solution be applied, which is at a minimum the installation of a Slippery When Wet sign.

In light of this directive, the values from the tests performed in May were tabulated for the two categories of 26-30 and below 26 (Table 13). The westbound lanes that were opened to traffic in November of 2005 had significantly more values in the 26-30 category then the eastbound lanes opened to traffic in a year earlier. The number of values less than 26 was equivalent in both the eastbound and westbound lanes, 2 in each direction.

Table 13. FN comparison between eastbound and westbound lanes.

Open to Traffic October 2004			Open to Traffic November 2005		
EB Lane	**FN26-30**	**FN<26**	**WB Lane**	**FN26-30**	**FN<26**
1	1	0	1	12	0
2	7	1	2	18	1
3	2	1	3	12	1
Totals	**10**	**2**	**Totals**	**42**	**2**

The project was tested again on October 17, 2006. The results are shown in Table 14 along with the May 2006 results. The values for each section have improved since the May measurement with the average improvement for all of the sections being 2.7. The greatest improvement was observed on the 800 psi flexural strength tined section (5.3) and the least improvement on the 925 lbs/cy cement content carpet drag section (0.6). There were no friction numbers below 30 in the eastbound lanes and only five below 30 in the westbound lanes. There were no readings below 26 in either direction. This is in contrast to the numerous readings below 30 and below 26 from the May 2006 testing as noted in Table 13.

Table 14. FN results for all sections for spring and fall of 2006.							
Section (Year Paved)	Year Paved	Lane	Dir.	Tested May 3&4, 2006		Tested Oct. 17, 2006	
				Average FN	Range FN	Average FN	Range FN
650 psi Flexural Strength, Carpet Drag	2004	2&3	E	31.5*	29.8 – 33.9*	35.1*	33.8 – 36.3*
650 psi Flexural Strength, Hard-Cem Carpet Drag	2004	2&3	E	31.2*	30.2 – 33.5*	33.4*	32.3 – 35.0*
650 psi Flexural Strength, Tined	2004	2&3	E	36.7*	35.0 – 37.6*	39.1*	38.1 – 40.5*
800 psi Flexural Strength, Carpet Drag	2004	1,2&3	E	34.6*	23.2 – 44.6*	37.3*	31.5 – 46.9*
800 psi Flexural Strength, Tined	2004	2&3	E	36.3*	34.3 – 38.9*	41.6	41.1 – 42.0*
800 psi Flexural Strength, Carpet Drag	2005	1,2&3	W	33.1*	24.4 – 54.3*	35.3	27.3 – 53.4*
925 lbs/cy Cement Content, Carpet Drag	2005	2&3	W	29.6*	24.9 – 34.6*	30.2	27.9 – 32.1*

Ride

Ride measurements were taken on April 26, 2006 and again on October 7, 2006 using the WSDOT Pavement Condition Collection Van. The ride readings for each section, expressed in IRI (International Roughness Index), are summarized in Table 15.

There was a slight difference in the spring and fall ride readings between the eastbound lanes which were paved using two paving machines and the westbound lanes that used only one paver. The average ride for all section in the eastbound direction was 97 inches/mile whereas in the westbound direction the average was 106 inches/mile. The fall 2006 measurements are showing only a slight difference between the averages for the two directions with the eastbound being 95 inches/mile and the westbound 97 inches/mile. It appears that the initial texture of the pavement influenced the ride measurements on the newest pavement (the westbound lanes) and as the texture has been worn off by traffic the differences between the lanes is insignificant.

Table 15. Ride measurement for each section from spring and fall 2006.

Test Section	Lane	Direction	April 2006 IRI Ave. (in/mile)	Oct. 2006 IRI Ave. (in/mile)
800 psi flexural strength, carpet drag	1	E	86	87
800 psi flexural strength, carpet drag	2	E	106	103
800 psi flexural strength, carpet drag	3	E	91	89
650 psi flexural strength, carpet drag	2	E	100	95
650 psi flexural strength, carpet drag	3	E	84	79
650 psi flexural strength, Hard-Cem, carpet drag	2	E	99	102
650 psi flexural strength, Hard-Cem, carpet drag	3	E	81	83
650 psi flexural strength, tined	2	E	81	78
650 psi flexural strength, tined	3	E	83	84
800 psi flexural strength, tined	2	E	151	143
800 psi flexural strength, tined	3	E	105	101
800 psi flexural strength, carpet drag	1	W	108	93
800 psi flexural strength, carpet drag	2	W	105	101
800 psi flexural strength, carpet drag	3	W	109	103
925 lbs/cy cement content, carpet drag	2	W	103	95
925 lbs/cy cement content, carpet drag	3	W	105	94
Average EB Lanes			**97**	**95**
Average WB Lanes			**106**	**97**

Wear

Wear measurements were made on April 26, 2006 and again on October 7, 2006, using the WSDOT Pavement Condition Data Collection Van. The wear measurements for all sections are summarized in Table 16. These are the first wear measurements on this project and they came after the eastbound lanes had experienced two winters of studded tire wear and the westbound lanes one winter. It was unfortunate that it was impossible to get initial wear measurements in 2005 prior to the start of the studded tire season (November 1- March 31), but one might assume that the transverse profile is essentially flat for a new PCC pavement.

The wear measurements for all of the sections for the most recent readings taken in October ranged from a high of 4.5 mm for the 650 psi flexural strength section with tined finish to a low of 2.0 for the 650 flexural strength section with Hard-Cem additive. Comparing the spring with the fall readings it is interesting to note that all of the tined sections showed an increase in wear. In contrast, all of the sections in the westbound direction paved in 2005 stayed the same or showed a decrease in wear as compared to the spring readings. This may indicate that the surface texture is still in the process of being removed by traffic. The sections on the eastbound lanes paved in 2004 are a mixture of more wear, less wear and no change.

Table 16. Wear measurements for spring and fall 2006.				
Test Section	Lane	Direction	April 2006	Oct. 2006
			Average (mm)	Average (mm)
800 psi flexural strength, carpet drag	1	E	2.5	2.4
800 psi flexural strength, carpet drag	2	E	2.6	2.6
800 psi flexural strength, carpet drag	3	E	2.5	2.5
650 psi flexural strength, carpet drag	2	E	2.0	2.1
650 psi flexural strength, carpet drag	3	E	2.7	3.4
650 psi flexural strength, Hard-Cem, carpet drag	2	E	2.1	2.0
650 psi flexural strength, Hard-Cem, carpet drag	3	E	2.7	3.0
650 psi flexural strength, tined	2	E	2.4	2.8
650 psi flexural strength, tined	3	E	3.7	4.5
800 psi flexural strength, tined	2	E	2.9	2.6
800 psi flexural strength, tined	3	E	4.0	3.2
800 psi flexural strength, carpet drag	1	W	3.0	3.0
800 psi flexural strength, carpet drag	2	W	2.8	2.7
800 psi flexural strength, carpet drag	3	W	3.7	3.5
925 lbs/cy cement content, carpet drag	2	W	2.7	2.5
925 lbs/cy cement content, carpet drag	3	W	2.6	2.6

Discussion of Post-Construction Testing Results

It is difficult to discuss the results if all of the mix designs and all of the lanes are treated as separate items, therefore, for discussion purposes the results been pared down according to the mix design. The results for the eastbound and westbound 800 psi flexural strength mix designs were kept separate because they are of different ages (the eastbound was paved in 2004 and the westbound in 2005). The results are listed in tables and displayed in bar charts for friction, ride and wear to show how each mix design is performing relative to the others.

On all of the bar charts the 650 psi flexural strength sections are shown in green, the 800 psi flexural strength sections in blue and the 925 lbs/cu cement content section in yellow. The darker colored bar in the pair represents the May measurement and the lighter colored the October reading. The sections paved in 2005 are shown with a stippled pattern which distinguishes them from the sections paved in 2004. On the bar charts the average actual flexural strength from the cylinder breaks is also shown in parentheses for each mix design category.

Friction

The average friction numbers for all of the sections for both spring and fall measurements are summarized in Table 17 and plotted in a bar chart in Figure 18. A slight increase in friction number is observed between the spring and the fall readings for all of the sections. The values for the latest set of readings are tightly grouping between a low of 30.2 and a high of 41.6. The slight increase in friction resistance for all of the sections is an encouraging sign given the initial set of low readings on the eastbound lanes. For the most recent set of readings there were no values less than 26 and only 5 values between 26-30, all in the westbound lanes 1 and 2. This is a vast improvement over the May 2006 results that showed 42 readings in the 26-30 range for the westbound lanes.

Table 17. Friction resistance measurements for each section from spring and fall 2006.

Section	Year Paved	April 2006 FN	Oct. 2006 FN
650 psi flexural strength, carpet drag	2004	31.5*	35.1*
650 psi flexural strength, Hard-Cem, carpet drag	2004	31.2*	33.4*
650 psi flexural strength, tined	2004	36.7*	39.1*
800 psi flexural strength, carpet drag	2004	34.6*	37.3*
800 psi flexural strength, tined	2004	36.3*	41.6*
800 psi flexural strength, carpet drag	2005	33.1*	35.3*
925 lbs/cy cement content carpet drag	2005	29.6*	30.2*

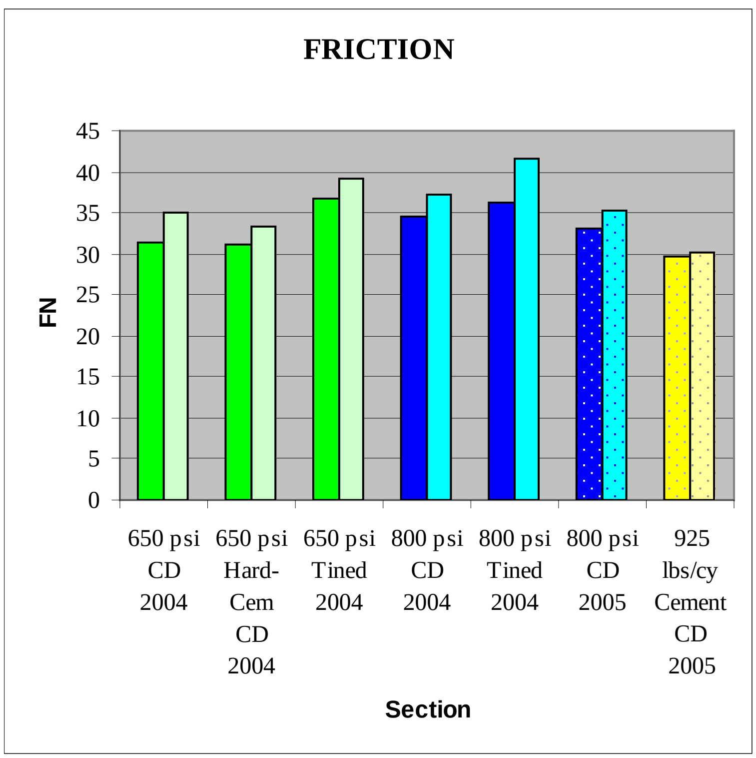

Figure 18. Average friction numbers for the various mix design/finishing methods. Dark colored bars are April 2006 readings and light colored bars are October 2006 readings.

There does not seem to be any correlation between high flexural strength and friction number. It is interesting to note, however, that the lowest friction numbers are for the 925 lbs/cy cement content section.

Ride

The ride measurements for all of the sections are summarized in Table 18 and plotted in Figure 19. The ride measurements have a general trend toward a smoother ride with age, although the changes in IRI values are very small. The only exception to this trend was for the 650 psi flexural strength section with the Hard-Cem additive which actually showed an increase in IRI between the spring and fall measurements. The decrease IRI in the other 6 sections ranged from as little as one inch per mile for two of the sections (650 psi tined and 800 psi flexural 2004) to as much as nine for the section with the 925 lbs/cy cement content mix. It is interesting to note that the sections paved in 2005 showed the largest change in IRI. This would seem to indicate that the IRI readings are being influenced by the texture on the pavement when the pavements are just opened to traffic and that this effect diminishes with more traffic exposure.

Table 18. Ride measurements for each section for spring and fall of 2006.

Section	Year Paved	April 2006	Oct. 2006
		IRI (inch./mile)	IRI (inch./mile)
650 flexural strength, carpet drag	2004	92	87
650 psi flexural strength, Hard-Cem, carpet drag	2004	90	93
650 psi flexural strength, tined	2004	82	81
800 psi flexural strength, carpet drag	2004	94	93
800 psi flexural strength, tined	2004	128	122
800 psi flexural strength, carpet drag	2005	107	99
925 lbs/cy cement content, carpet drag	2005	104	95

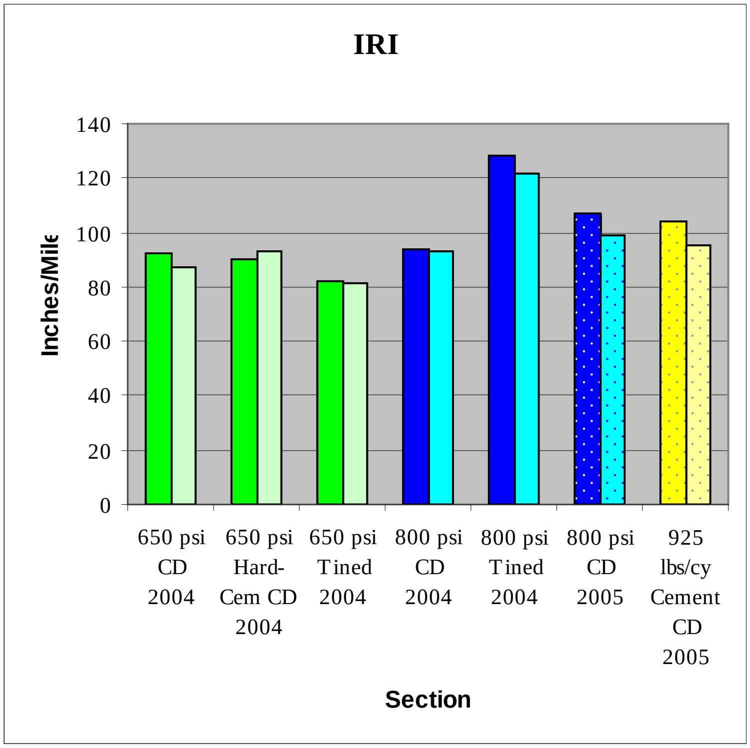

Figure 19. Average IRI values for the various mix design/finishing methods. Dark colored bars are April 2006 readings and light colored bars are October 2006 readings.

Wear

The wear data for all of the sections is summarized in Table 19 and plotted in Figure 20. It is difficult to draw any conclusions regarding the wear for any of the sections. If anything the wear pattern is opposite of what one would expect. The higher flexural strength sections are in general showing more total wear than the lower strength sections, the only exception being the 650 psi tined section.

Table 19. Wear measurements for each section from spring and fall 2006.			
Section	Year Paved	April 2006 Wear (mm)	Oct. 2006 Wear (mm)
650 psi flexural strength, carpet drag	2004	2.4	2.8
650 psi flexural strength, Hard-Cem, carpet drag	2004	2.4	2.5
650 psi flexural strength, tined	2004	3.1	3.7
800 psi flexural strength, carpet drag	2004	2.6	2.5
800 psi flexural strength, tined	2004	3.5	2.9
800 psi flexural strength, carpet drag	2005	3.2	3.1
925 lbs/cy cement content carpet drag	2005	2.7	2.6

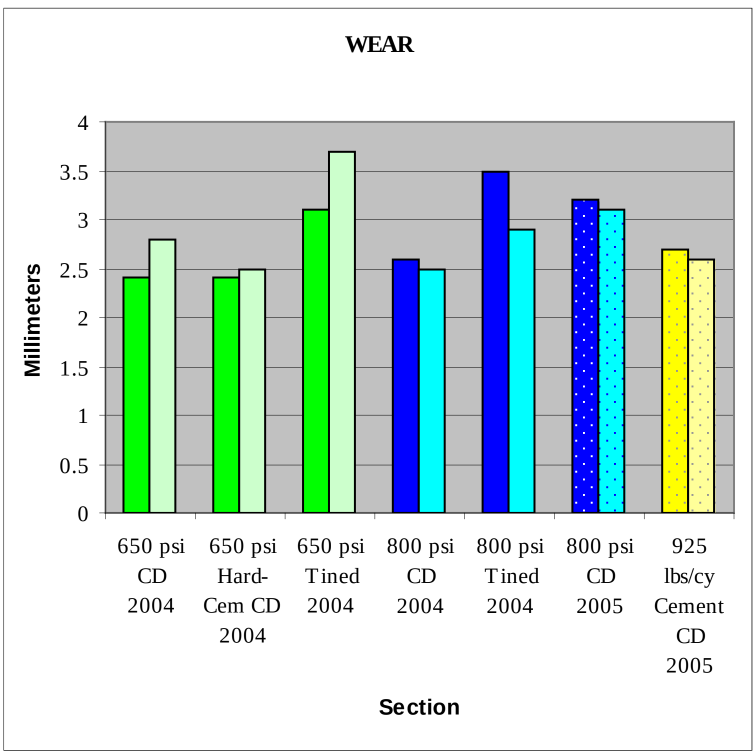

Figure 20. Average wear values for the various mix design/finishing methods. Dark colored bars are April 2006 readings and light colored bars are October 2006 readings.

Rate of Wear

In addition to the total wear, the rates of wear are also a primary concern. Table 20 lists of the wear rates (total wear divided by the years open to traffic) for each of the sections. Figure 21 shows the wear rates on a bar chart.

Table 20. Rates of wear for the various sections using the October 2006 measurements.

Section	Wear Rate (mm/year)
650 psi Flexural Strength Carpet Drag 2004	1.4
650 psi Flexural Strength Hard-Cem Carpet Drag 2004	1.3
650 psi Flexural Strength Tined 2004	1.9
800 psi Flexural Strength Carpet Drag 2004	1.3
800 psi Flexural Strength Tined 2004	1.5
800 psi Flexural Strength Carpet Drag 2005	3.1
925 lbs/cy Cement Content 2005	2.6

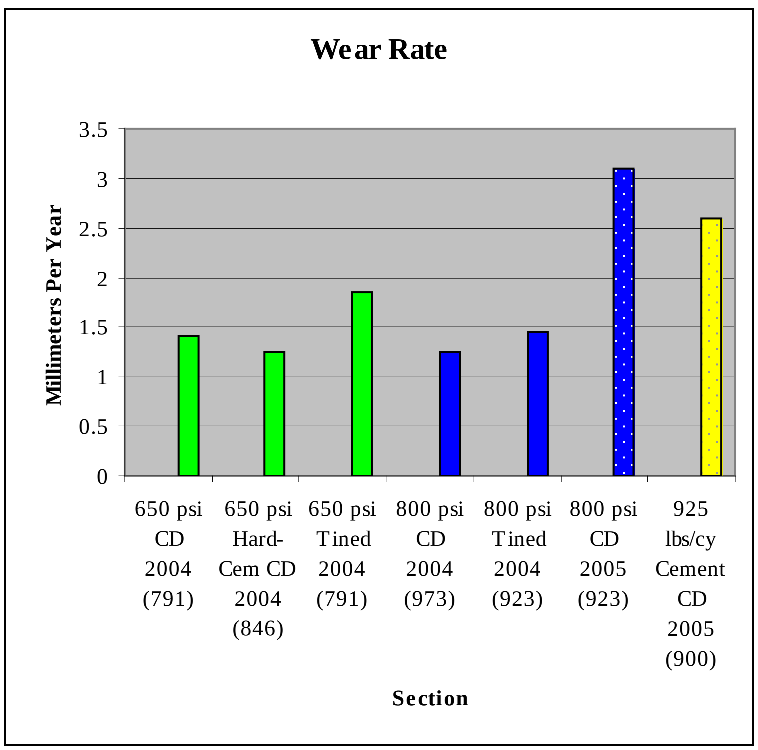

Figure 21. Rates of wear for each section.

The sections built in 2005 have much higher wear rates then the section built in 2004. This does not seem to be reasonable given that the flexural strengths of the 2005 sections are equal to the flexural strengths of the sections built in 2004. Another variable seems to be influencing the wear rates other than flexural strength. The data indicates that there is an initial high rate of wear when the pavement is first exposed to studded tires and then a stabilization of the rate with time. This could be attributed to a wearing off of the paste on the surface of the new concrete and once the paste is gone the aggregate wears at a much slower rate. With regard to the highest rates of wear being shown by the tined sections, perhaps the TxDOT's hypothesis that tining weakens the surface of the pavement by exposing more surface area to rapid drying has some validity. Or it could be that there is more paste to wear away on the tined surface before the aggregate is exposed. It is impossible to prove which is the case, but the bottom line is that the tined sections of the pavements built with equivalent mix designs are showing the **m**ost total wear and the highest rates of wear.

Final Performance Results

Introduction

Wear, ride and friction measurements were made every spring and fall to monitor the performance of each of the sections with the special mix designs or additives. These measurements bracket the season when studded tires are legal. One would expect large changes in these measurements for the spring readings if studded tire usage is a factor, however, as will be shown later in this report, the amount of wear in winter and summer is relatively constant.

Wear

The pavement wear for each section at each time of measurement is listed in Table 21 and plotted in Figure 22. Measurements were taken in the Fall before studded tires are legal and in the Spring after the studded tire season is over. The amount of wear for a section is usually greater as time progresses, however some reversals are evident. These reversals may be due to slight variations in the operation of the van that takes the wear measurements. The fact that some section are only 600 feet in length means that the number of data points is small and any variation in the starting or ending point of the measurements can have a significant difference in the average wear for that section.

Table 21. Historical wear measurements in millimeters from post-construction to present.

Section	2006		2007		2008		2009		2010	
	S	F	S	F	S	F	S	F	S	F
650 psi CD 2004 (791)	2.4	2.8	4.6	2.5	2.7	3.2	3.9	3.6	4.4	3.8
650 psi Hard-Cem CD 2004 (846)	2.4	2.5	4.9	2.1	2.6	3.2	3.8	3.6	4.4	4.1
650 psi Tined 2004 (791)	3.1	3.7	4.9	2.3	2.9	3.2	3.4	3.8	4.2	3.2
800 psi CD 2004 (973)	2.6	2.5	3.9	2.3	2.9	3.3	3.9	3.9	4.1	4.1
800 psi Tined 2004 (923)	3.5	2.9	4.1	-	5.0	6.0	7.4	7.0	8.0	6.5
800 psi CD 2005 (923)	3.2	3.1	3.2	2.9	3.4	3.9	4.4	4.5	5.0	5.0
925 lbs/cy CD 2005 (900)	2.7	2.6	3.4	3.2	3.5	4.2	4.6	5.0	5.1	5.5

Note: CD is carpet drag, (actual flexural strength), S is Spring, F is Fall.

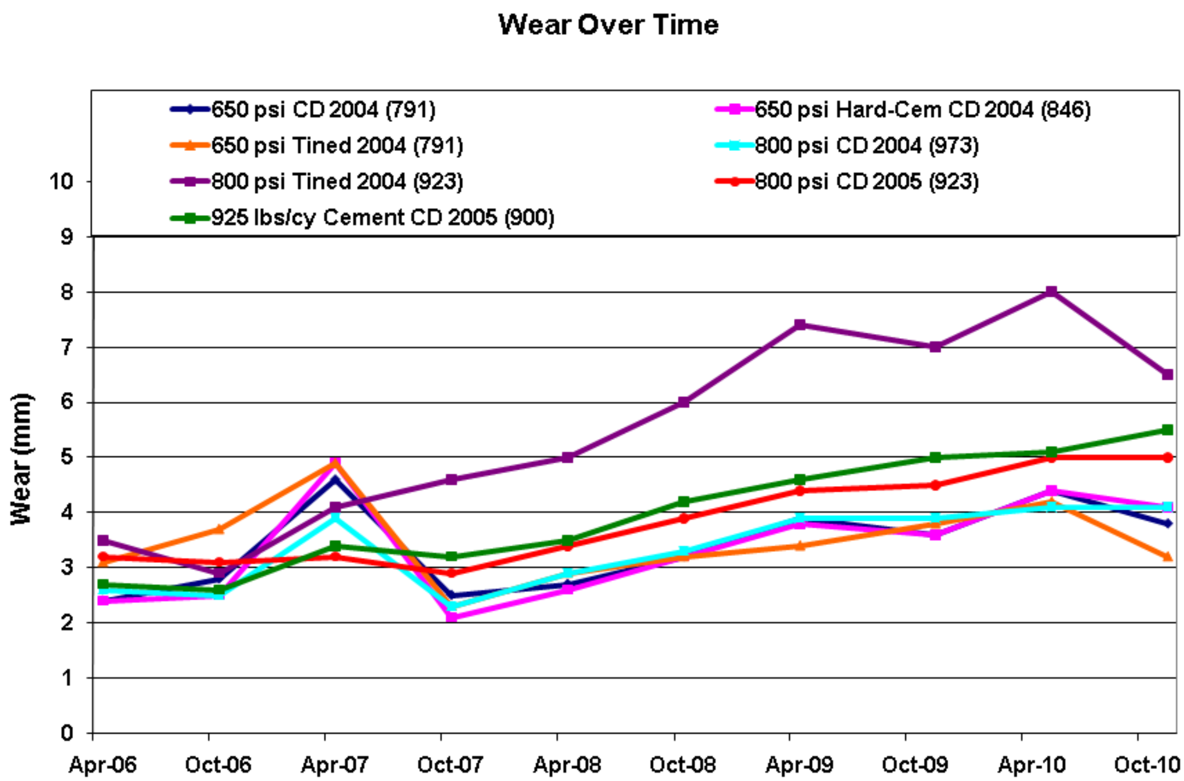

Figure 22. Amount of wear for each section from April 2006 to November 2010.

There does not seem to be a pattern in the amount of wear and its relationship to how the sections were designed or actually constructed, that is design strength, finishing method, or actual measured flexural strength. Observations concerning the wear are listed below:

- The 800 psi tined section built in 2004 had the greatest amount of wear of any of the sections.
- The two sections with carpet drag and tined 650 psi design flexural strength section had less wear than the sections with higher design flexural strength, Hard-Cem additive or higher cement content.
- The section with Hard-Cem additive was not more resistant to wear than other sections of equivalent design flexural strength (650 psi CD and Tined)..
- The sections constructed in 2005 experienced more wear than most of the sections built in 2004, with the exception of the 800 psi tined section.

- The sections with the higher measured flexural strength (650 psi Hard-Cem, 800 psi CD and Tined, and 925 lbs/cu) had greater amounts of wear than the sections with lower measured flexural strength (650 psi CD and Tined).

- The section with higher cement content was not more resistant to wear than sections with lower cement content.

- The sections with tined finish had the least amount of wear (650 psi) and the other had the greatest amount (800 psi).

The only general observation that can be made is that the amount of wear increases with the age of the pavement

Wear Rate

The wear rates for each of the sections based on the Fall 2010 measurements are shown in Figure 23. The wear rates mimic the trend of the yearly wear measurements with all the section with 650 psi design flexural strength and the section with 800 psi design flexural strength built in 2004 with the lowest values and the 800 psi tined section built in 2004 and both sections built in 2005 having the highest rates of wear.

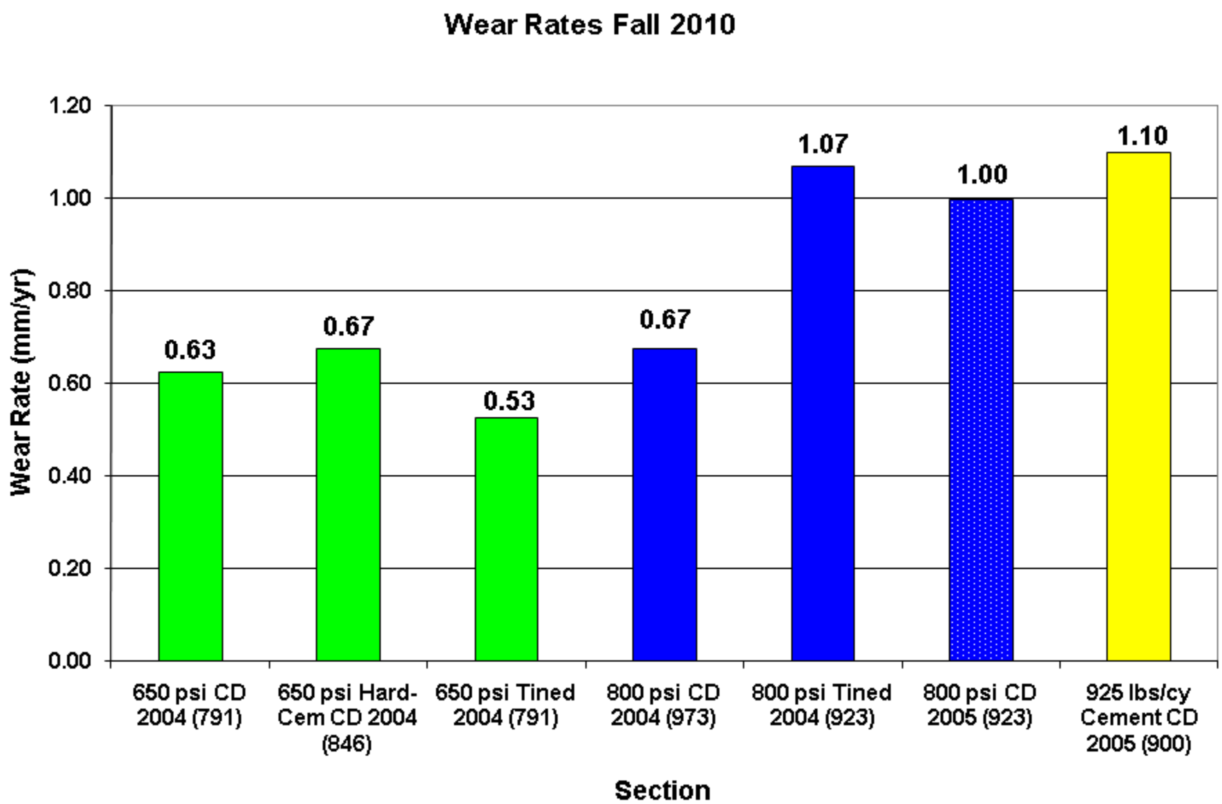

Figure 23. Wear rates for each section for the Fall 2010 measurements.

The wear rates for each measurement period are plotted in Figure 24 to show if there are variations in the rate of wear over time. These are calculated by dividing the amount of wear by the age of the pavement at the time of measurement. The number of months between all measurements is six months, so the time between measurements are identical. The first thing to notice is that there is a slight increases in the wear rates for the Spring 2007, Spring 2009 and Spring 2010 measurements.. This is the measurement that occurs after the winter studded tire season. It would seem to indicate that studded tires may be a factor in the wearing of the pavements. The wear rates over time for all of the sections show a similar trend with higher and more variable rates when the pavements were new and then a flatting out of the rates as the pavements age. The two sections built in 2005 (the 800 psi carpet drag and 925 lbs/cy cement content) and the 800 psi tined built in 2004 have the highest rates of wear with that are over one millimeter per year. The other sections are all in the 0.5 to 0.7 millimeters per year range.

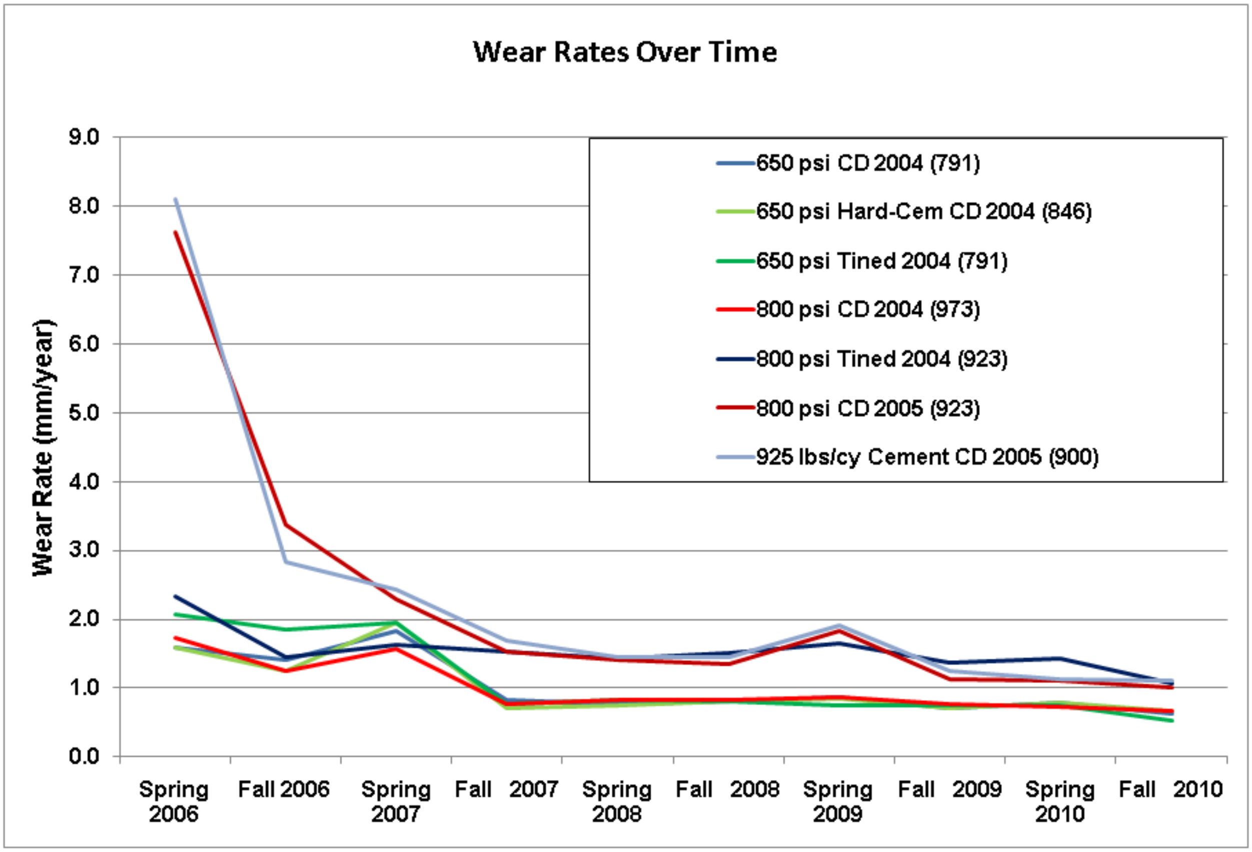

Figure 24. Wear rates over time for each pavement section.

Table 22 lists the wear rates and the time to 10 mm of wear, which is the depth that triggers rehabilitation of a pavement. This time period ranges from as little as 9.1 years for the 925 lbs/yd cement content section built in 2005 to a high of 18.9 years for the 650 psi tined section built in 2004.

Table 22. Time in years to reach the 10 mm target for scheduling a project for rehabilitation.		
Section	**Fall 2010 Wear Rate**	**Years to 10 mm Wear**
650 psi CD 2004	0.63	15.9
650 psi Hard-Cem CD 2004	0.67	14.9
650 psi Tined 2004	0.53	18.9
800 psi CD 2004	0.67	14.9
800 psi Tined 2004	1.07	9.3
800 psi CD 2005	1.00	10.0
925 lbs/cy CD 2005	1.10	9.1

Ride

The ride measurements for each section are listed in Table 23. The measurements did not vary much over the five year evaluation period for any of the sections. The average change, either rougher or smoother, was 2.7 inches per mile with a maximum increase in roughness of eight inches per mile and a maximum decrease of two inches per mile when comparing the initial Spring 2006 readings with the Fall 2010 readings. These very slight variations are not unexpected given that these are concrete pavements. More variation with time would be expected for asphalt pavements.

Table 23. Historical ride measurements. Measurements are in IRI, inches/mile.

Section	2006		2007		2008		2009		2010	
	S	F	S	F	S	F	S	F	S	F
650 psi CD 2004 (791)	92	87	82	85	89	84	84	81	88	91
650 psi Hard-Cem CD 2004 (846)	90	93	90	91	98	87	96	90	96	98
650 psi Tined 2004 (791)	82	81	82	83	92	82	88	78	85	81
800 psi CD 2004 (973)	94	93	91	93	97	90	93	90	93	93
800 psi Tined 2004 (923)	128	122	125	111	132	121	129	125	132	128
800 psi CD 2005 (923)	107	99	98	99	109	97	93	98	99	101
925 lbs/cy CD 2005 (900)	104	95	100	87	112	100	101	95	97	102

Note: CD is carpet drag, (actual flexural strength), S is Spring, F is Fall.

Friction

Friction measurements were also made each spring and fall as summarized in Table 24. Initial low readings on some of the sections appear to have corrected themselves, possibly due to the roughening of the surface from studded tire wear. The final average friction numbers from all sections were well above the initial readings which were of some concern because of the numerous readings below 30. Pavements with friction numbers less than 30 warrant additional evaluation, and if less than 26, require the installation of Slippery When Wet signs. This project showed that concerns over the frictional properties of pavements with carpet drag texture are not warranted, at least in Washington State. This is primarily because studded tires remove any type of texture within a short time after construction. The initial problems with low readings are attributed to the lack of depth of the texture achieved on the carpet drag finish as evidenced by the poor sand patch test results (Table 10, page 26).

Table 24. Historical friction measurements.

Section	2006		2007		2008		2009		2010	
	S	F	S	F	S	F	S	F	S	F
650 psi CD 2004 (791)	32	35	40	33	36	35	49	38	39	40
650 psi Hard-Cem CD 2004 (846)	31	33	35	32	37	33	43	37	38	39
650 psi Tined 2004 (791)	37	39	36	36	39	35	49	39	41	42
800 psi CD 2004 (973)	35	37	40	35	40	35	42	39	39	40
800 psi Tined 2004 (923)	36	42	46	38	41	38	43	40	42	41
800 psi CD 2005 (923)	33	35	39	34	39	35	40	39	37	38
925 lbs/cy CD 2005 (900)	30	30	33	30	35	31	35	35	34	37
Average	**33**	**36**	**38**	**34**	**38**	**35**	**43**	**38**	**38**	**40**

Note: CD is carpet drag, (actual flexural strength), S is Spring, F is Fall.

Discussion of Final Performance Results

The wear measurements and the wear rates are not similar for each of the sections as noted previously. However, the reasons for the differences in wear and the wear rates do not follow the pattern that was expected in the design of the study. The sections with higher flexural strengths and higher cement contents had which were expected to be resistant to wear had, in general, the higher rates of wear. The sections with the lower designed flexural strengths (which are our standard design) had the lowest rates of wear. Flexural strength does not seem to be a predictor of a pavements ability to resist wear from studded tires. Similarly, putting more cement in the mix does not seem to result in greater resistance to studded tire wear.

The results for carpet drag and tining were mixed. The theory that tining causes the surface of a pavement to dry more rapidly than one receiving a carpet drag finish, did not match with the rates of wear on the carpet drag sections as compared to those with the tined finish. The carpet drag sections have some of the lowest and some of the highest rates of wear. Similarly, the sections with tined finish had both a very low rate of wear and the highest rate of wear.

The final measurements of friction and ride indicate that the various sections with either special mixes or additives are all performing in a similar manner and the values are relatively consistent over the five year evaluation period. This is what would be expected of a portland cement concrete pavement built to last 50 years.

Conclusions

The following conclusions can be drawn concerning the use of various mix designs and additives to produce a pavement with a greater resistance to studded tire wear:

- Mixes with higher flexural strength, higher cement content, or the additive Hard-Cem did not produce a pavement more resistant to studded tire wear than the WSDOT conventional 650 psi flexural strength mix design.
- No correlation was found between the amount of wear and the method used to finish the concrete.

- No correlation was found between the amount of wear and the design or measured flexural strength of the pavement.
- There is some evidence that the rate of wear increases during the winter studded tire season although the indications are very weak.
- The results from this study do not support the use of special mix designs or concrete additives to make a pavement more resistant to studded tire wear.

Recommendations

The use of our standard 650 psi flexural strength mix designs is recommended as the design that has equal or better resistant to studded tire wear than any of the mix designs evaluated in this study.

Appendix A

Contract Special Provisions

CEMENT CONCRETE PAVEMENT

Construction Requirements

Concrete Mix Design for Paving
The second sentence of item 2 in Section 5-05.3(1) is revised to read as follows:

(******)
The mix shall be capable of providing a minimum flexural strength of 800 psi at 14 days.

When combined aggregate concrete gradation is used, item 3 in Section 5-05.3(1) is revised to read as follows:

(August 5, 2002)
3. Mix Design Modifications. The Contractor may initiate minor adjustments to the approved mix proportions. The combined aggregate gradation may be adjusted provided it remains with the specifications limits detailed above. The mix design will not be required to be resubmitted as long as the water cementitious ratio does not change.

   Only non-chloride accelerating admixtures that meet the requirements of Section 9-23.6 Admixture for Concrete, shall be used.

   The Contractor shall notify the Engineer in writing of any proposed modification. A new mix design will designate a new lot.

Consistency
The first sentence of the second paragraph of Section 5-05.3(2) is revised to read as follows:

(******)
The water/cementitious material ratio, by weight, shall not exceed 0.33.

Equipment

Finishing Equipment
Section 5-05.3(3)C is supplemented with the following:

(******)
The slip-form paver shall be equipped with an approved automated dowel bar inserter.

Sign structures within four feet of the outside finished paved shoulder will be encountered during paving operations. The Contractor will need to come up with an optional paving plan within these areas so as not to damage the sign structure foundation or compromise the integrity of the Portland cement concrete pavement.

Smoothness Testing Equipment
Section 5-05.3(3)E is supplemented with the following:

(******)
WSDOT Test Method No. 807 is revised to reflect a zero blanking band.

Tie Bars and Dowel Bars
The first paragraph of Section 5-05.3(10) is supplemented with the following:

(******)
Dowel bars are required for the 12' wide outside mainline shoulders.

(******)
The sixth paragraph of Section 5-05.3(10) is deleted.

Finishing
The third paragraph of Section 5-05.3(11) is revised to read as follows:

(******)
The pavement shall be given a final finish surface by drawing a carpet drag longitudinally along the pavement before the concrete has taken an initial set. The carpet drag shall be a single piece of carpet of sufficient length to span the full width of the pavement being placed and adjustable so as to have up to 4 feet longitudinal length in contact with the concrete being finished. The carpeting shall be artificial grass type having a molded polyethylene pile face with a blade length of 5/8" to 1" and a minimum mass of 70 ounces per square yard. The backing shall be a strong durable material not subject to rot and shall be adequately bonded to the facing to withstand use as specified.

Surface Smoothness
The second sentence of the first paragraph of Section 5-05.3(12) is revised to read as follows:

(******)
Smoothness of all pavement placed except ramp tapers and small or irregular areas as defined by Section 5-05.3(3) unless specified otherwise, shall be measured with a recording profilograph, as specified in Section 5-05.3(3), parallel to centerline, from which the profile index shall be determined in accordance with WSDOT Test Method 807. WSDOT Test Method No. 807 is revised to reflect a zero blanking band. The 12' wide outside mainline shoulders are not excepted and shall be measured with a recording profilograph.

The Contractor shall provide copies of the recordings and daily profile indexes to the Contracting Agency no later than 9:00 a.m. the following day.

The third, fourth, and fifth paragraphs of Section 5-05.3(12) are revised as follows:

(******)
All reference to 7 inches per mile are revised to read 25 inches per mile.
All references to 0.7 inch are revised to read 2.5 inch.

Measurement

The fourth paragraph of Section 5-05.4 is revised to read as follows:

(******)
Epoxy-coated tie bars with drill hole will be considered part of the contract bid item "Cement Conc. Pavement – Including Dowels", and no measurement will be made.

Payment

The fifth paragraph of Section 5-05.5 is revised to read as follows:

(******)
The unit contract price per cubic yard for "Cement Conc. Pavement – Including Dowels" shall include furnishing and installing epoxy coated dowel bars and tie bars, including tie bars drilled into cement concrete pavement.

Point No. 2 of the eleventh paragraph is revised to read as follows:

(******)
2. "Ride Smoothness Compliance Adjustment" will be calculated for each 0.1 mile section represented by profilogram using the following schedule:

Ride Smoothness Profile Index (Inches per mile)	Compliance Adjustment (Percent adjustment)
5.0 or less	+4
over 5.0 to 9.0	+3
over 9.0 to 13.0	+2
over 13.0 to 18.0	+1
over 18.0 to 25.0	0
over 25.0 to 35.0	-2*
over 35.0	-4*

*Also requires correction to 25 inches per mile.

Appendix B

Sand Patch Data Collection and Texture Calculations

Sand Patch Data Collection Sheet

ASTM E 965- SAND PATCH TEST

$MATX_d = 4V/\pi D_{avg.}^2$

Date: _____________
Location: _____________
Operator: ______________
Texture type: _________________________

Trial 1

Volume of glass spheres, V: ____________mm^3

Dia. 1: ________mm Dia. 2: ________mm Dia. 3: ________mm Dia. 4: ________mm

Average Diameter, $D_{avg.}$: [   ] mm

Avg. Macro Texture Depth, $MATX_d$: _____________mm

Trial 2

Volume of glass spheres, V: ____________mm^3

Dia. 1: ________mm Dia. 2: ________mm Dia. 3: ________mm Dia. 4: ________mm

Average Diameter, $D_{avg.}$: [   ] mm

Avg. Macro Texture Depth, $MATX_d$: _____________mm

Trial 3

Volume of glass spheres, V: ____________mm^3

Dia. 1: ________mm Dia. 2: ________mm Dia. 3: ________mm Dia. 4: ________mm

Average Diameter, $D_{avg.}$: [   ] mm

Avg. Macro Texture Depth, $MATX_d$: _____________mm

Trial 4

Volume of glass spheres, V: ____________mm^3

Dia. 1: _______mm Dia. 2: _______mm Dia. 3: _______mm Dia. 4: _______mm

Average Diameter, $D_{avg.}$: [   ] mm

Avg. Macro Texture Depth, $MATX_d$: ____________mm

Texture Calculations

The volume of the canister was calculated to be:

V = 34.1 and when converted to mm^3 and equals <u>34,100.</u>

$MATX_d = 4V/\pi D_{avg.}^2$

Example

<u>Trial 1</u>

Volume of glass spheres, V: **<u>34,100</u>** mm^3

Dia. 1: **<u>201</u>** mm Dia. 2: **<u>198</u>** mm Dia. 3: **<u>210</u>** mm Dia. 4: **<u>195</u>** mm

Average Diameter, $D_{avg.}$: **[201]** mm

$$MATX_d = 4V/\pi D_{avg.}^2$$

(4 x 34,100) / (3.14159) x (201 x201)

136,400 / (3.14159 x 40,401)

136,400 / 126,923.49 = 1.07

Appendix C

Experimental Feature Work Plan

Washington State Department of Transportation

WORK PLAN

PCCP Features

(Carpet Drag, Flexural Strength, and Surface Smoothness)

I-90, Argonne Road to Sullivan Road
Milepost 287.98 to Milepost 292.16

Prepared by

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June 2003

Introduction

Washington State Department of Transportation's (WSDOT) Portland Cement Concrete Pavement (PCCP) construction program has been relatively small since the construction of the Interstate system in the 1960's and early 70's. As many of these early pavements deteriorate and require reconstruction, the best possible construction practices will be essential in order to provide pavements that will last 40 years or longer.

One of the challenges facing WSDOT is to reduce the excessive wear concrete pavements received from studded tires. An Experimental Feature "Combined Aggregate Gradation for Concrete Pavements" is under study and is investigating the use of a combined aggregate gradation to curb the effects of studded tire wear. An additional WSDOT study involves the rates of stud wear on the Specific Pavement Studies (SPS) located on SR 395 south of Ritzville. To date there is definitely less wear due to studded tires in the 900-psi section as compared to the lower strength sections. Further, the tine grooves are still apparent in the high strength sections and are, in essence, gone from the lower strength ones. While these observations are far from conclusive, WSDOT wishes to explore the effects of higher strength PCCP mixes.

Another challenge observed with WSDOT PCCP construction has been with providing smooth riding surfaces, particularly in urban areas. WSDOT has built several pavements in recent years where bonuses have been paid to contractors for satisfying for ride smoothness profile indexes, however, the roadway is still perceived rough. WSDOT's current smoothness requirement is based on a 0.20 inch blanking band with an allowable daily profile index of 7.0 inches per mile or less.

Plan of Study

Under this proposal the existing ACP structure will be replaced with 12 inches of PCCP. Specific features beyond the 2002 WSDOT Standard Specifications include the use of a carpet drag finish, increasing the flexural strength of the PCCP, and providing a zero blanking band for measuring surface smoothness. Following construction of the PCCP, the influences from the carpet drag finish and increased flexural strength specification on the pavement will be monitored to determine its ability to resist surface abrasion. Additionally, the results of using a zero blanking band to determine smoothness will be analyzed and compared with profilograph results using a 0.20-inch blanking band.

Scope

This project involves the reconstruction of 4.18 miles of I-90 by placing 12 inches (1.0’) of PCCP over 2.4 inches (0.20’) of asphalt concrete over 3.0 inches (0.25’) of crushed surfacing. The total 40-year design ESALs in the design lane are about 100,000,000 million. The experimental features will be incorporated over the total project length.

Carpet Drag

The final pavement surface will be obtained by drawing a carpet drag longitudinally along the pavement before the concrete has taken its initial set. The carpet drag will be a single piece of carpet of sufficient length to span the full width of the pavement being placed and adjustable to allow up to 4 feet longitudinal length in contact with the concrete being finished. Initial WSDOT analysis shows that the carpet drag finish provides an equal or better skid resistance than normal WSDOT transverse tined pavements. This is significant considering studded tire wear normally removes transverse tining within 5 years after placing PCCP.

Mix Design

The mix design requirements will be modified to target a higher strength pavement than traditional PCCP mixes to possibly reduce or resist the abrasive wear from studded tires. The target flexural strength for this project will be 800 psi.

Test Sections

The project will include test sections that provide a measure of the possible differences in studded tire wear on a carpet drag finish surface versus a tined finish surface for both the pavements built with 800 psi strength concrete and a special section built with 650 psi strength concrete:

A summary of the test sections is noted below:

- A 300 foot section of the 800 psi section will be tined to provide a comparison between the tined and carpet drag finishes with the higher strength mix.
- A special 600 foot section of 650 psi mix will be split into two 300 foot test sections, one with carpet drag and one with tining to again provide a comparison of the two finishing techniques using the lower strength mix.

Surface Smoothness

WSDOT Test Method No. 807 (Method of Operation of California Profilograph) will be revised to reflect a zero blanking band. The daily profile index of the finished pavement shall be set to 25 inches per mile or less. Payment for “Ride Smoothness Compliance Adjustment” is as follows:

Ride Smoothness Profile Index (Inches per mile)	Compliance Adjustment (Percent adjustment)
5.0 or less	+4
Over 5.0 to 9.0	+3
Over 9.0 to 13.0	+2
Over 13.0 to 18.0	+1
Over 18.0 to 25.0	0
Over 25.0 to 35.0	-2
Over 35.0	-4

Construction

Concrete will be placed by a slip form paver. Except as indicated, 2002 WSDOT Standard Specifications will apply.

Staffing

The Region Project office will coordinate and manage all construction aspects. Representatives from WSDOT Materials Laboratory (1 or 2 persons) will also be involved with documenting the construction.

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Testing

The completed PCCP will be skid tested to determine friction values. The friction values will be measured yearly on each of the test sections for the duration of the experiment.

Reporting

An "End of Construction" report will be written following completion of the project. This report will include construction details, material test results, and other details concerning the overall process. Annual summaries will also be conducted over the next 5 years. At the end of the 5-year period, a final report will be written which summarizes performance characteristics and future recommendations for use of this process.

Cost Estimate

Construction Costs

Description	Quantity	Unit Cost	Total Price
Carpet Drag			-45,000(credit)
Increased Flexural Strength	115,000cy	$7.00/cy	805,000
Surface Smoothness (added grinding)			50,000
Total			$810,000

Testing Costs

Condition Survey – will be conducted as part of statewide annual survey, no cost.

Rut Measurements – 6 surveys (2 hours each) requires traffic control = $12,000

Friction Measurements – 6 surveys done in conjunction with annual new pavement friction testing, no cost.

Skid test = $1,500

Report Writing Costs

Initial Report – 20 hours = $1,500
Annual Report – 5 hours (1 hour each) = $500
Final Report – 10 hours = $1,000

Total Cost = $826,500

Schedule

Construction Date: Westbound lanes – November 2004

Date	Condition Survey (Annual)	Rut & Friction Measurements (Annual)	End of Construction Report	Annual Report	Final Report
January 2005		X	X		
January 2006	X	X		X	
January 2007	X	X		X	
January 2008	X	X		X	
January 2009	X	X		X	
January 2010	X	X		X	X