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16. Abstract

The main purpose of this project was to implement previous research performed on concrete utilizing micro-fines in a field test. The project can be divided into three main parts: First, predetermined materials that were local to the field trial site, were characterized and used to design three concrete mixtures with increasing percentages of micro-fines; Next, the mixtures were placed on Business 287 in Saginaw, Texas to monitor their workability during construction and their short and long-term behavior; Lastly, a procedure was developed to design pavement mixtures with higher percentages of micro-fines.

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Implementation of the Use of Higher Micro-Fines in Concrete Pavements Final Report

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Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

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Products

The most recent draft of Product 5-9029-01-P1, Training Manual for Pavement Concrete Proportioning Method, is included as Appendix C.

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Chapter 1. Mixture Design

In Phase I, researchers used predetermined materials to design three concrete mixtures. The aggregates, including two fine- and two coarse-aggregate gradations (all from the same source) were initially characterized in the laboratory. The fine aggregates, including the micro-fine aggregates, were the most important part of the mixture design. Their gradation from the aggregate plant crushing operation falls outside of ASTM C33 guidelines as shown in Figure A1, Appendix A. This project and final report will show that ASTM C33, though a valid and useful gradation tool, is not the only valid proportioning method for making good concrete mixtures.

A TxDOT-optimized gradation mixture was used as a basis for the mixture design. This was the mixture determined to be used as the control in the implementation project. For comparison, and due to time and material supply constraints, it was decided to change as few variables as possible from the optimized "control" mixture. Each of the three test mixtures began with the optimized coarse aggregate gradation, but the fine aggregate was replaced with a fine aggregate mixture containing the specified percentage of micro-fines. Admixtures were modified after test mixing to achieve necessary workability. The three mixture designs for the 5%, 10%, and 15% micro-fines as a percent of the fine aggregate are included in Appendix A, Figures A1, A2, and A3 for the 5%, 10%, and 15% mixtures, respectively.

To keep dust pollution minimal, EPA regulations allow only wet processing in crushing operations in Texas, so most of the micro-fines generated are washed out into large collecting ponds. The aggregate supplier, however, was able to provide two fines-of-fracture sand products for this project that had appreciable amounts of micro-fines. One product was called manufactured sand, and it contained about 5% micro-fines. The second product, labeled dry screenings, had about 15% micro-fines. No attempt to regrade these products was made. The manufactured sand product was used for the total sand requirement in the 5% concrete mixture, the dry screenings product alone was used for the sand in the 15% mixture, and a 50:50 blend of the two was used for the sand in the 10% mixture.

Full laboratory testing for slump, comprehensive strength, and flexural strength was conducted on each of the three mixtures.

Chapter 2. Implementation

Phase II accomplished two main goals: (1) Determine the performance of fresh concrete paving mixtures with varying percentages of micro-fines during placement in the field (and verify the mixtures' required strength development) and (2) Performance of the mixtures in terms of internal stresses and strains, long-term performance for skid or abrasion resistance. To monitor their fresh properties during placement, the research team was present during much of the paving and conducted interviews with the paving crew and construction and project managers on the jobsite. To monitor internal stresses, vibrating wire gages were installed in the pavement sections. Surface friction losses will be monitored over time. This aspect of long-term field performance will be evaluated with the TxDOT skid trailer.

2.1 Gage Installation

Prior to paving each section, the research team installed vibrating wire gages in a regular configuration. Figure B1 (a) in Appendix B illustrates the four pavement sections within the large-scale project. There were four sections and a shoulder with the northern corner of Lane 1 at station 162+42. Figure B1 (b) is a representative illustration of the placement of six gages within each section. Three gages were placed longitudinally and three were placed transverse to the axis of the roadway. Among the three gages in each direction, one was placed 2 in. from the ground, another was placed at 4 in. and the third was placed at 6 in. in the 8 in. thick pavement slab. From the diagram, it may be noted that in both directions each of the gages is located 4 ft. from a slab edge or header. This was for two reasons. First, logistically for the installation and data cable access, the gages had to be placed close together. But, also, this was the distance thought to be approximately halfway between the construction joint and the first normal transverse cracking that will occur, avoiding any influence from edge boundary conditions to provide valuable information for how the mixtures behave over the long-term in relation to one another. Each of the gages was attached with wire according to manufacturer specifications as shown in Figure B2 (a) from Roctest Industries. Steel stakes were hammered into the road base material to allow an anchor for the wires to be attached as shown in Figure B2 (b). The final configuration is shown in Figure B3. The leads from each gage were run through conduit that was installed beneath the road base to a location beyond the shoulder of the roadway where a data logging device was installed. A Campbell Scientific CR10X Data logger, a solar-powered battery, two multiplexers, and two vibrating wire interfaces were installed in an electrical conduit box (Data Box). A laptop was used to retrieve the data.

In addition to the gages, a weather station was erected during concrete placement to record evaporation rate effects data during initial curing of the concrete. It was dismantled two weeks after the first concrete pour.

2.2 Concrete Placement

Paving began on the 5% micro-fines mixture in section 1 on Business 287 in Saginaw, Texas on Tuesday, July 15. With the delivery of the first truck it was discovered that the temperature of the concrete was too high. Concrete temperatures of 90 to 95 °F were observed. This was attributed to the distance of the ready mix plant from the site, the possibility of under-soaking the aggregate piles at the plant, and using water that was not properly circulated in order to cool it down. The first truck was rejected, but the high temperatures remained a problem in subsequent trucks.

Because of the low slumps, more water was added. Subsequent mixtures became much too wet. Though slump measurements were not taken on every truck, the slumps that were taken were on the upper limit of acceptance by the contractor. These slumps, though acceptable by contract standards, were too high for this mixture design. Resulting concrete was poor, because it showed segregation at the beginning and end of some loads, and it allowed the slip-formed shoulders to sag behind the paver.

Because of the high temperatures and the inability of the ready mix supplier to add ice to the mixture, paving was shut down at approximately 7:00 a.m. after 12 truckloads of concrete. Overall, concrete quality on this day was poor, due to improper quality control, poor planning for batching, and the ready-mix plant's initial unfamiliarity with the mixture design. Approximately 200 feet of paving was completed.

On Wednesday, July 16, paving began much more smoothly. The high temperatures were corrected with ice, and the air temperature was around 75 °F with a light rain at 4:00 a.m. Most of the trucks throughout the morning were satisfactory, and although some of them were too wet, all seemed to be within contract guidelines for slump. Some segregation was visible off the conveyor belt, but this seemed a function of high water content of the mixtures. Paving was shut down around 7:00 a.m. because of expected rainfall in the area. Approximately 500 feet of paving was completed.

On Thursday, July 17, the first truck of the day was the best mixture the team had seen. The slump was a little low for the contractor at 1 ½ inches, but the mixture was extremely homogenous. The concrete from this mixture directly after the paver required little external finishing. Once the sun began to rise, the ready mix supplier increased the water content in anticipation of higher temperatures. Trucks began to arrive that had to be rejected due to very high slumps. Those that were accepted were at the upper limit of slump for the contractor. These high slump mixtures demonstrated qualities that were expected: segregation and sagging behind the paver. The contractor quickly lowered the allowable slump and mixtures began to arrive with more desirable qualities. Section 1 was completed on this date. Photos of mixtures are shown in Appendix B (Figures B4 through B13).

Due to time and budget constraints, the researchers were not present during the placement of section 2 for the 10% mixture. It was reported that this section was placed much more smoothly as the ready-mix supplier and contractor were more prepared and familiar with the mixtures. For the 15% mixture placement—the highest percentage of micro-fines—the researchers returned to Saginaw. Though there were questions about the feasibility of this mixture—after the problems with low slumps in the lower micro-fines mixtures—the mix was placed with little problem. The same problems with quality control were witnessed and the same mixture reactions were observed (too little water led to low slumps, too much water led to high slumps and segregation). Overall, the mixture was placed successfully. Once again, the team was not present for the placement of section 4, the optimized aggregate control design.

2.3 Results

2.3.1 First Month Results

Overall, the mixtures performed well. As expected, they were stickier and, due to higher micro-fines contents, slightly pastier than a standard design, so more work was required to finish them. Also, as expected, the unfamiliarity of the contractor and the ready mix supplier with the behavior of these mixture designs introduced a learning curve for attaining success. However, when specifications for target slump and water content were met, the concrete behaved well. The contractor confirmed that the mixtures were viable.

Specimens were taken in the field from each section for quality control testing. Most specimen strengths were within desirable ranges as specified by TxDOT. Results of laboratory and field specimen strengths are shown in Appendix B (Table B1 and Figure B14). Further analysis will be performed with this data.

The gage data acquisition system performed well in test runs, and one early data acquisition contained approximately six days of data for sections 1 and 2. From these data, it could be observed that the monitored slabs from each batch design were performing similarly at early ages, as was expected. Data from the transverse and longitudinal gages are shown in Appendix B (Figure B15). Monitoring will continue for long-term durability implications. In addition, long-term traffic-induced skid resistance will be tested at the site.

2.3.2 One Year Results

Data was downloaded for all four test sections at approximately one year. A two month "snapshot" was evaluated. The naming convention for the gages was updated and simplified. Table 2.1 shows the gage name conversions. The gages that are 2-inches from the surface are now listed as top (T), 4-inches as middle (M), and 6-inches as bottom (B). The data acquisition program was reworked with the number of readings per day reduced to two. The readings are taken at 4:00 a.m. and 4:00 p.m. in an attempt to capture the coolest and hottest part of the day.

Graphs of the gage data from this time period are shown in Appendix B (Figures B16 through B21). Each graph compares gages with similar orientation and depth from all four mixtures. Figure B22 Shows a portion of the data set used to generate the graphs.

At this early date, the strains seem to be primarily driven by thermal expansion and contraction. The mixture with 15% replacement shows the least strain of all the mixtures. This can be attributed to the proportioning method used for the replacement. This method not only replaces a percentage of the fine aggregate, but also replaces a percentage of the cementitious material. This results in a lower overall coefficient of thermal expansion for this mixture. The gages located in the 10% replacement section showed the most strain. The researchers do not have a satisfactory explanation for why this occurred at this time. The TxDOT optimized mixture with no replacement showed the second most strain. This is what would be expected because, as stated earlier, as the percent replacement increases the coefficient of thermal expansion decreases.

Table 2.1: Gage Naming Convention Update

Original Name	Updated Name	Original Name	Updated Name
5% T2 1750	5% T-B	15% T2 1750	15% T-B
5% T6 2500	5% T-T	15% T6 2500	15% T-T
5% T4 1750	5% T-M	15% T4 1750	15% T-M
5% L2 2500	5% L-B	15% L2 2500	15% L-B
5% L6 2500	5% L-T	15% L6 2500	15% L-T
5% L4 3250	5% L-M	15% L4 3250	15% L-M
10% T2 1750	10% T-B	OPT T2 1750	OPT T-B
10% T6 1750	10% T-T	OPT T6 1750	OPT T-T
10% T4 1750	10% T-M	OPT T4 1750	OPT T-M
10% L2 1750	10% L-B	OPT L2 1750	OPT L-B
10% L6 1750	10% L-T	OPT L6 1750	OPT L-T
10% L4 2500	10% L-M	OPT L4 2500	OPT L-M

Chapter 3. Proportioning Procedure

The final phase was the development of a proportioning procedure for using aggregates with higher percentages of micro-fines in mixture designs. This is required because the proportioning methods presently used by TxDOT assume that the aggregates, both coarse and fine, meet ASTM C 33 requirements for grading. Quality (non-deleterious) micro-fines with manufactured sands (fines of fracture from normal crushing operations) typically do not initially meet the grading requirements for ASTM C 33. Simply regrading them not only does not usually improve the concrete properties, but it generates more waste material at the pit.

Additional materials and many test mixtures were performed to observe fresh concrete properties. Full hardened property testing was performed on five mixture designs. These test results allowed the researchers to apply formulas from self-consolidating concrete proportioning guidelines from Koehler (2000) to pavement concrete. A manual (Appendix C) was developed that presents a method to proportion concrete paving mixtures made with manufactured sands and increased micro-fines percentages in a step-by-step manner. An interactive spreadsheet that performs the calculations was developed and submitted to the Research, Technology and Implementation (RTI) offices as TxDOT 5-9029-01-P1 in November 2008.

Chapter 4. Conclusions

The primary purpose of implementation projects is to formally attempt to apply the results from research in an effective manner so as to improve the previous standards of performance. This project was aimed at making roadway pavement using concrete made from all of the fines of fracture that are naturally produced in normal aggregate crushing operations. By its very nature this is a different way of doing business. The fractured fines, called manufactured sand (MF), are flatter and often more angular. This often creates a much higher water demand to achieve the same workability. Increasing the fluid content of the matrix improves the workability, but if that extra fluid is merely extra water, reduced strength is the expected result. Water reducing admixtures and supplemental cementitious materials may help increase the fluid paste content, resulting in better workability with little or no loss in strength.

The strategy employed in this implementation requires an evaluation of the MF for critical properties from each source proposed before calculating a proper batch design without the use of ACI Committee 211 batch design method. These irregularly shaped MFs achieve optimal packing densities in grading that fall outside the ASTM C 33 specifications for fine aggregates, so designs using fineness moduli don't match up well for these materials. A batch design method based on the Power 45 curve is provided for more effective use of MFs by TxDOT materials engineers and district laboratories.

During this implementation project several problems occurred that could be avoided on the next construction job using higher micro-fines contents and MFs.

1. Confusion between the district/area office lab managers arose after the project was awarded and before the construction began. Implementation is a team effort, and key issues that cause variation from the normal practices, as well as the strict enforcement of pertinent normal practices, should be discussed before the job specifications go out for bid. This pre-bid discussion should include meetings between the implementation researchers and the area office lab manager and inspectors. Who is responsible for what must be established at this time. This includes novel batch design methods, but also enforcement methods for slump, air, temperature, strength development, finishing and curing practices.
2. Confusion at the jobsite meant that the first loads of paving concrete did not meet TxDOT standards for slump, air, but were allowed to be dumped in front of the paving train anyway. Some loads exceeded six inches of slump, while others were one inch or no slump. Until truckloads are consistently in compliance, each truck should be checked for critical properties and the loads sent back whenever they do not meet specifications.
3. Finishing problems of this stickier mix design were an important issue. There were such long delays between truckloads that, in an effort to stay busy, finishers continued to bless and float the surface long after they should have left it alone, allowed it to finish bleeding, and applied the curing compound. This resulted in a weakened wearing surface that lead to surface polishing due to micro-cracking in the over-watered, paste-rich surface and related surface erosion. This concept should be explained by the inspector or lab manager to the finishing crew, so they'll know this will not be allowed. Also, the ready mix supplier must be experienced enough to understand standard water reducing technology and to be able to ensure that trucks arrive on a reasonable schedule throughout the job.

Instrumentation was installed in the pavement to monitor and compare strain performance of the four trial sections and their unique concrete batch designs. The differences in strain in the first month and even after one year were small enough to preclude any great insights at this time. The gages do show general trends, such as expansions during the warmer part of the day and contractions in the cooler night temperatures, and the 15% micro-fines concrete seems to have strained the least, as would be expected. The gages were, however, placed for the purpose of longer term studies, and a more extensive analysis and discussion will be performed as a part of the related follow-up research project 0-6255, Use of Manufactured Sands for Concrete Paving.

References

Koehler, E. “Aggregates in Self-Consolidating Concrete” Ph.D. Dissertation, University of Texas at Austin, 2000.

Appendix A

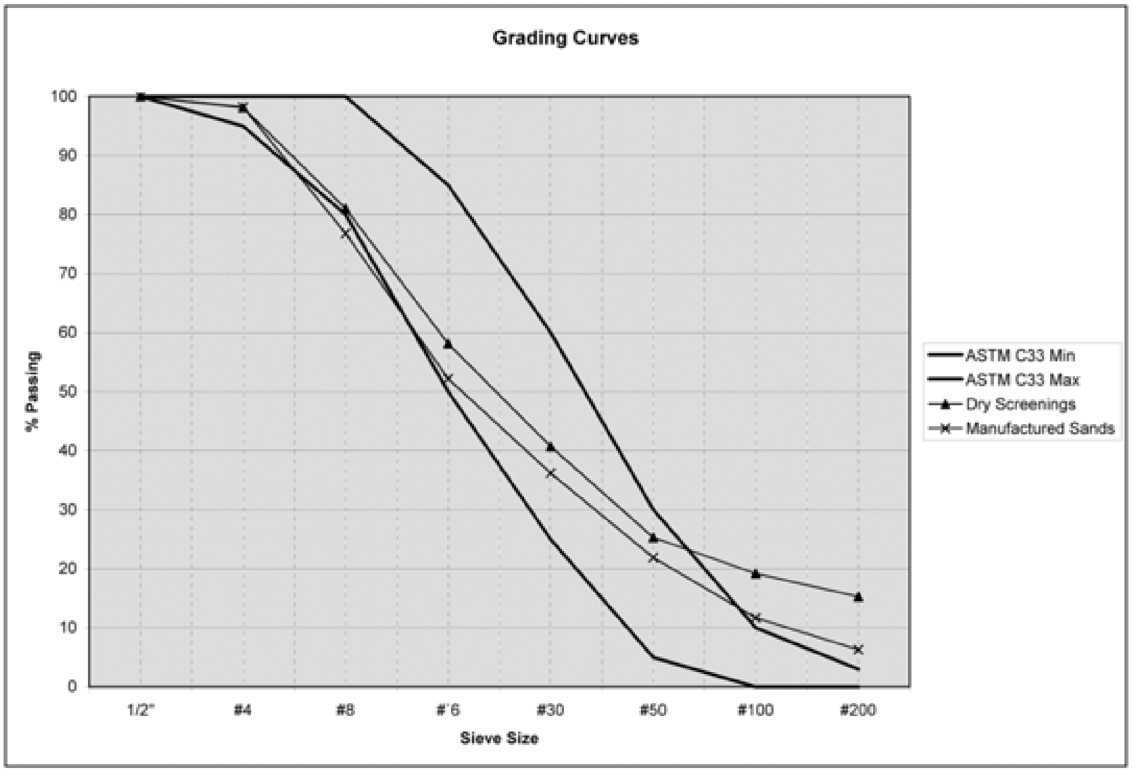
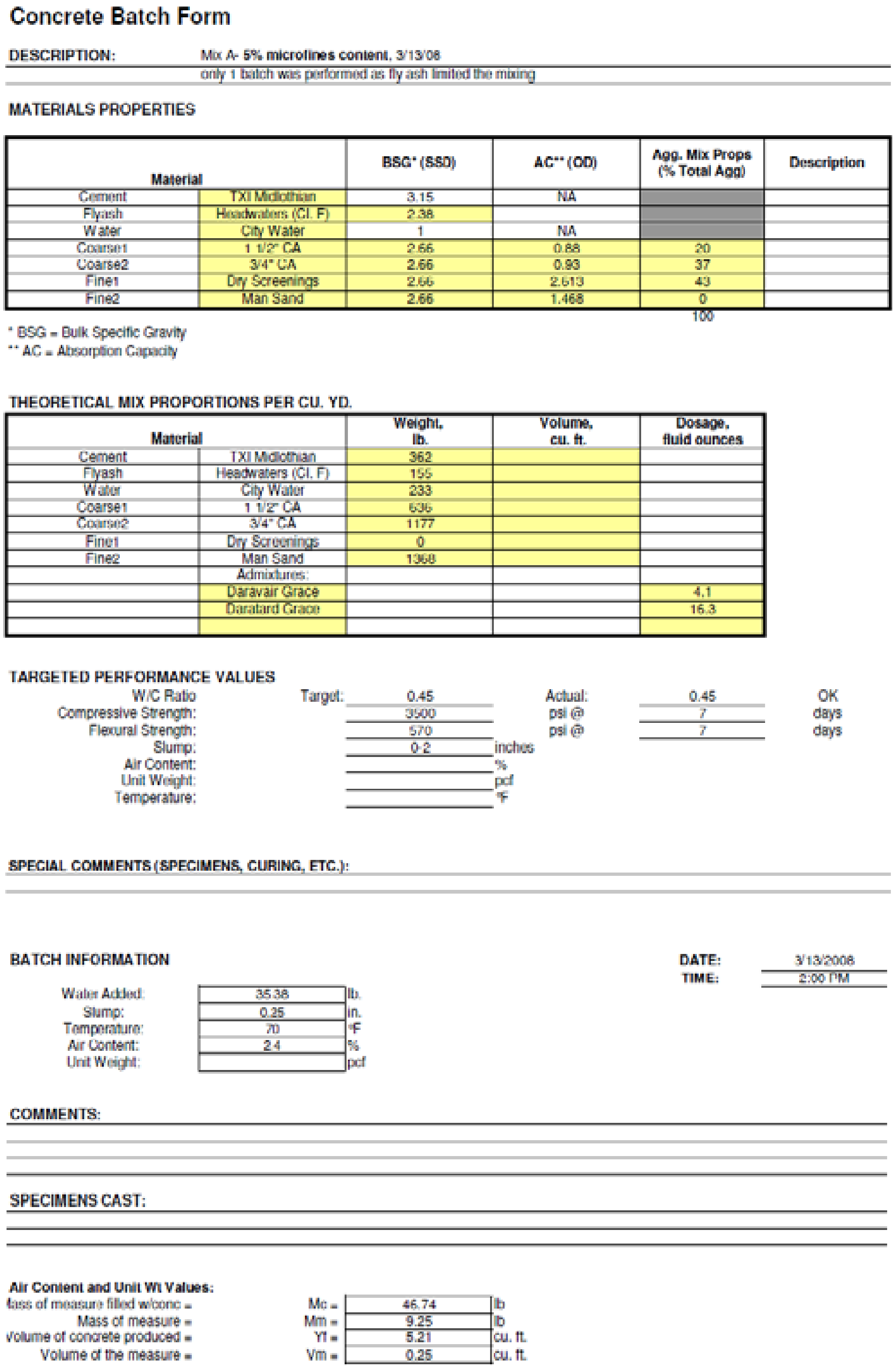


Figure A1. Gradation Curves for Fine Aggregate



Concrete Batch Form

DESCRIPTION: Mix A- **5% microfines content**, 3/13/08
only 1 batch was performed as fly ash limited the mixing

MATERIALS PROPERTIES

Material		BSG* (SSD)	AC** (OD)	Agg. Mix Props (% Total Agg)	Description
Cement	TXI Midlothian	3.15	NA	▨	
Flyash	Headwaters (Cl. F)	2.38		▨	
Water	City Water	1	NA	▨	
Coarse1	1 1/2" CA	2.66	0.88	20	
Coarse2	3/4" CA	2.66	0.93	37	
Fine1	Dry Screenings	2.66	2.613	43	
Fine2	Man Sand	2.66	1.468	0	
				100	

* BSG = Bulk Specific Gravity
** AC = Absorption Capacity

THEORETICAL MIX PROPORTIONS PER CU. YD.

Material		Weight, lb.	Volume, cu. ft.	Dosage, fluid ounces
Cement	TXI Midlothian	362		
Flyash	Headwaters (Cl. F)	155		
Water	City Water	233		
Coarse1	1 1/2" CA	636		
Coarse2	3/4" CA	1177		
Fine1	Dry Screenings	0		
Fine2	Man Sand	1368		
	Admixtures:			
	Daravair Grace			4.1
	Daratard Grace			16.3

TARGETED PERFORMANCE VALUES

W/C Ratio	Target:	0.45	Actual:	0.45	OK
Compressive Strength:		3500	psi @	7	days
Flexural Strength:		570	psi @	7	days
Slump:		0-2	inches		
Air Content:			%		
Unit Weight:			pcf		
Temperature:			°F		

SPECIAL COMMENTS (SPECIMENS, CURING, ETC.):

BATCH INFORMATION

DATE: 3/13/2008
TIME: 2:00 PM

Water Added:	35.38	lb.
Slump:	0.25	in.
Temperature:	70	°F
Air Content:	2.4	%
Unit Weight:		pcf

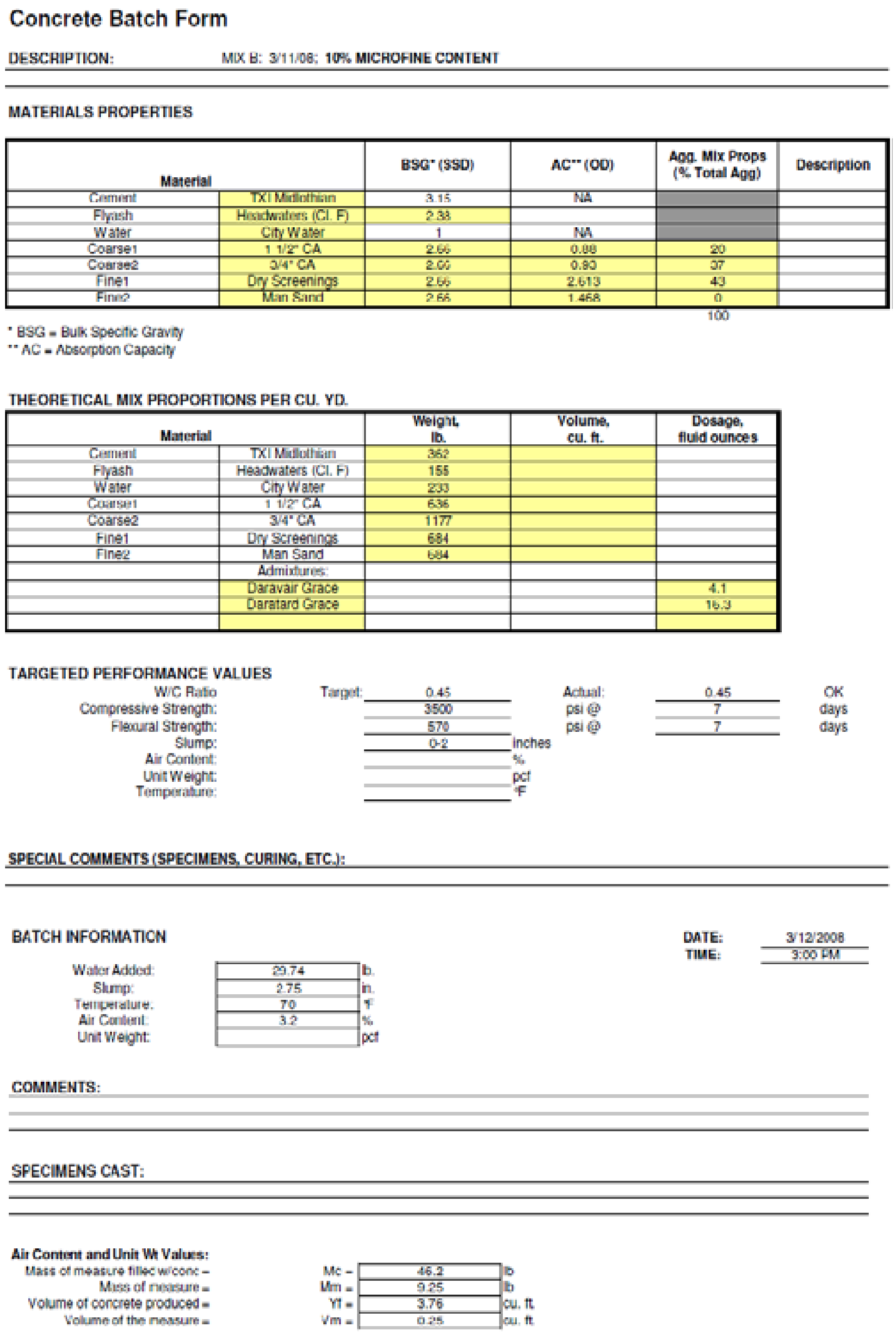
COMMENTS:

SPECIMENS CAST:

Air Content and Unit Wt Values:

lass of measure filled w/conc =	Mc =	46.74	lb
Mass of measure =	Mm =	9.25	lb
Volume of concrete produced =	Yf =	5.21	cu. ft.
Volume of the measure =	Vm =	0.25	cu. ft.

Figure A2. 5% Mixture Proportioning and Batch Information



Concrete Batch Form

DESCRIPTION: MIX B: 3/11/08: **10% MICROFINE CONTENT**

MATERIALS PROPERTIES

Material		BSG* (SSD)	AC** (OD)	Agg. Mix Props (% Total Agg)	Description
Cement	TXI Midlothian	3.15	NA		
Flyash	Headwaters (Cl. F)	2.38			
Water	City Water	1	NA		
Coarse1	1 1/2" CA	2.66	0.88	20	
Coarse2	3/4" CA	2.66	0.80	37	
Fine1	Dry Screenings	2.66	2.613	43	
Fine2	Man Sand	2.66	1.468	0	
				100	

* BSG = Bulk Specific Gravity
** AC = Absorption Capacity

THEORETICAL MIX PROPORTIONS PER CU. YD.

Material		Weight, lb.	Volume, cu. ft.	Dosage, fluid ounces
Cement	TXI Midlothian	362		
Flyash	Headwaters (Cl. F)	155		
Water	City Water	233		
Coarse1	1 1/2" CA	636		
Coarse2	3/4" CA	1177		
Fine1	Dry Screenings	684		
Fine2	Man Sand	684		
	Admixtures:			
	Daravair Grace			4.1
	Daratard Grace			16.3

TARGETED PERFORMANCE VALUES

W/C Ratio	Target:	0.45		Actual:	0.45	OK
Compressive Strength:		3500		psi @	7	days
Flexural Strength:		570		psi @	7	days
Slump:		0-2	inches			
Air Content:			%			
Unit Weight:			pcf			
Temperature:			°F			

SPECIAL COMMENTS (SPECIMENS, CURING, ETC.):

BATCH INFORMATION

DATE: 3/12/2008
TIME: 3:00 PM

Water Added:	29.74	lb.
Slump:	2.75	in.
Temperature:	70	°F
Air Content:	3.2	%
Unit Weight:		pcf

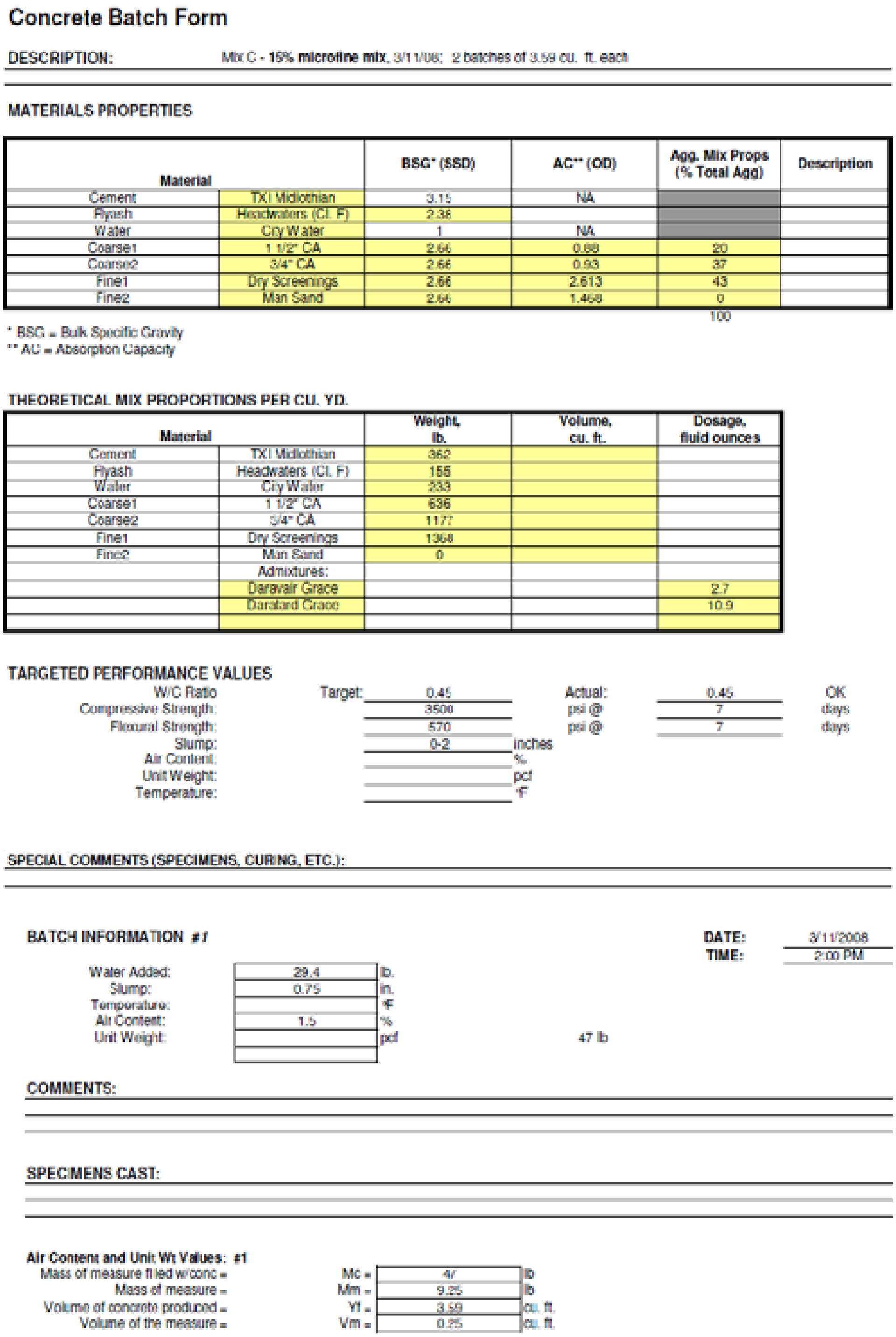
COMMENTS:

SPECIMENS CAST:

Air Content and Unit Wt Values:

Mass of measure filled w/conc =	Mc =	46.2	lb
Mass of measure =	Mm =	9.25	lb
Volume of concrete produced =	Yf =	3.76	cu. ft.
Volume of the measure =	Vm =	0.25	cu. ft.

Figure A3. 10% Mixture Proportioning and Batch Information



Concrete Batch Form

DESCRIPTION: Mix C - **15% microfine mix**, 3/11/08; 2 batches of 3.59 cu. ft. each

MATERIALS PROPERTIES

Material		BSG* (SSD)	AC** (OD)	Agg. Mix Props (% Total Agg)	Description
Cement	TXI Midlothian	3.15	NA		
Flyash	Headwaters (Cl. F)	2.38			
Water	City Water	1	NA		
Coarse1	1 1/2" CA	2.66	0.88	20	
Coarse2	3/4" CA	2.66	0.93	37	
Fine1	Dry Screenings	2.66	2.613	43	
Fine2	Man Sand	2.66	1.468	0	
				100	

* BSG = Bulk Specific Gravity
** AC = Absorption Capacity

THEORETICAL MIX PROPORTIONS PER CU. YD.

Material		Weight, lb.	Volume, cu. ft.	Dosage, fluid ounces
Cement	TXI Midlothian	362		
Flyash	Headwaters (Cl. F)	155		
Water	City Water	233		
Coarse1	1 1/2" CA	636		
Coarse2	3/4" CA	1177		
Fine1	Dry Screenings	1368		
Fine2	Man Sand	0		
	Admixtures:			
	Daravair Grace			2.7
	Daratard Grace			10.9

TARGETED PERFORMANCE VALUES

W/C Ratio	Target:	0.45	Actual:	0.45	OK
Compressive Strength:		3500	psi @	7	days
Flexural Strength:		570	psi @	7	days
Slump:		0-2	inches		
Air Content:			%		
Unit Weight:			pcf		
Temperature:			°F		

SPECIAL COMMENTS (SPECIMENS, CURING, ETC.):

BATCH INFORMATION #1

DATE: 3/11/2008
TIME: 2:00 PM

Water Added:	29.4	lb.
Slump:	0.75	in.
Temperature:		°F
Air Content:	1.5	%
Unit Weight:		pcf

47 lb

COMMENTS:

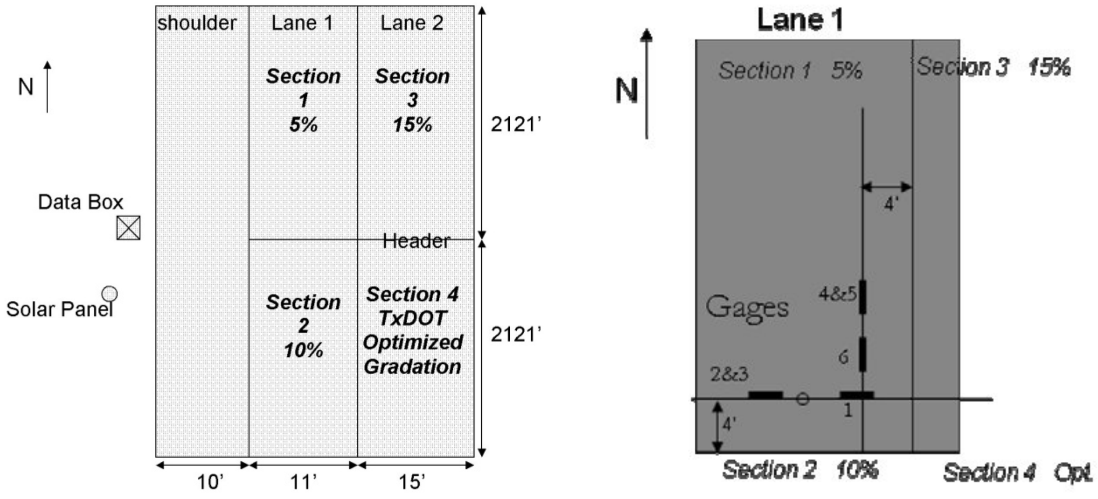
SPECIMENS CAST:

Air Content and Unit Wt Values: #1

Mass of measure filled w/conc =	Mc =	47	lb
Mass of measure =	Mm =	9.25	lb
Volume of concrete produced =	Yf =	3.59	cu. ft.
Volume of the measure =	Vm =	0.25	cu. ft.

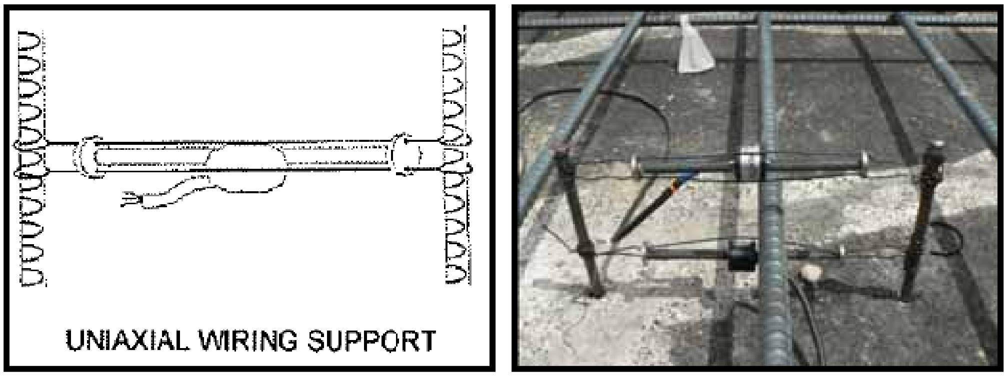
Figure A4. 15% Mixture Proportioning and Batch Information

Appendix B



(a) (b)

Figure B1. Construction and Gage Installation Layout



(a) (b)

Figure B2. Gage Configuration

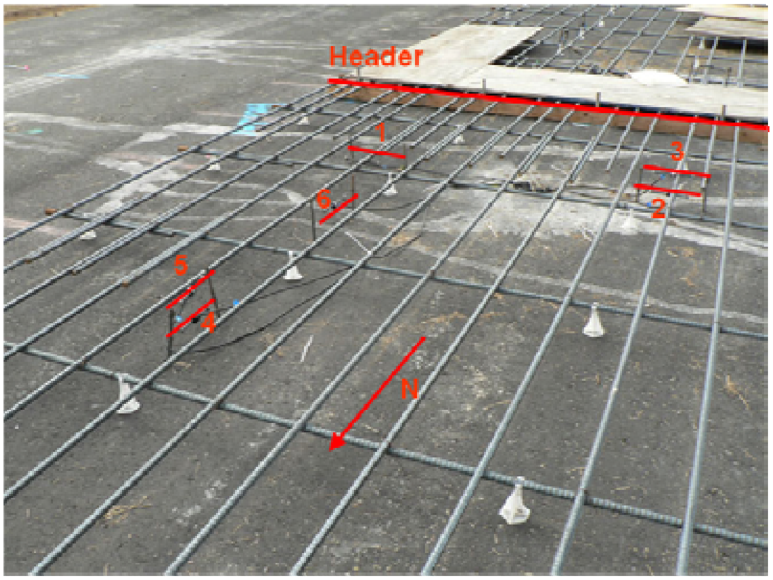


Figure B3. Complete Gage Set-up in Section 1

Figure B4. Extremely low slump on one of the first truck loads

Figure B5. Dry mixture is hardly compacted behind the paving machine

(a)
(b)

Figures B6. Additional work required to finish dry concrete

Figure B7. Concrete is eventually finished well

Figure B8. Concrete mixture with too much water

Figure B9. Poor concrete with visible segregation due to high water content

(a) (b)

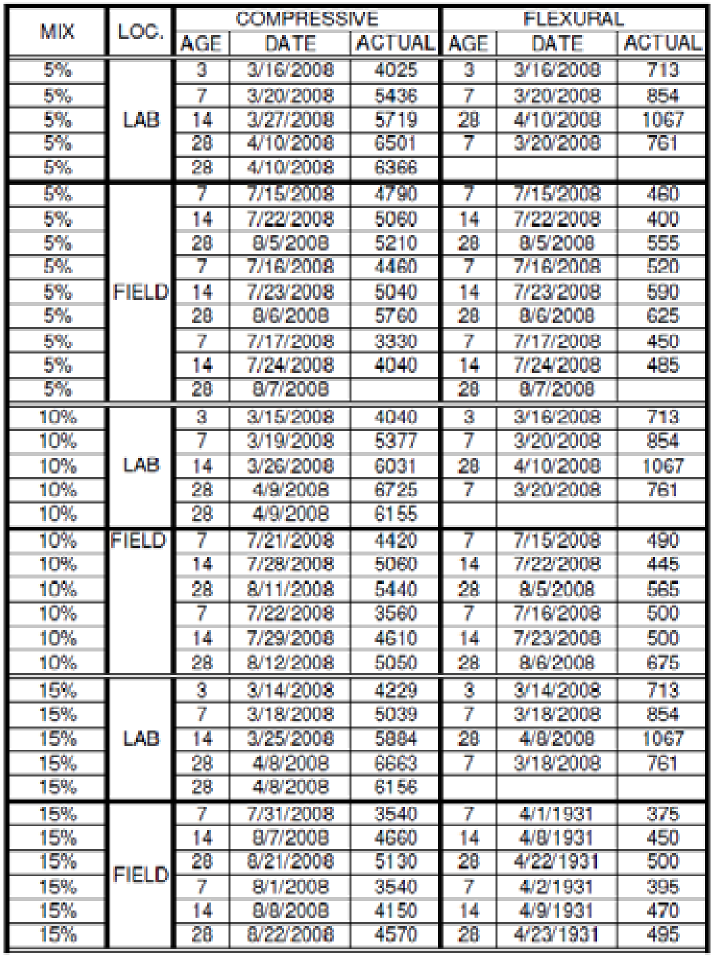
Figure B10. Texturing with carpet drag before transverse tining

Figure B11. Homogenous mixture with ideal slump

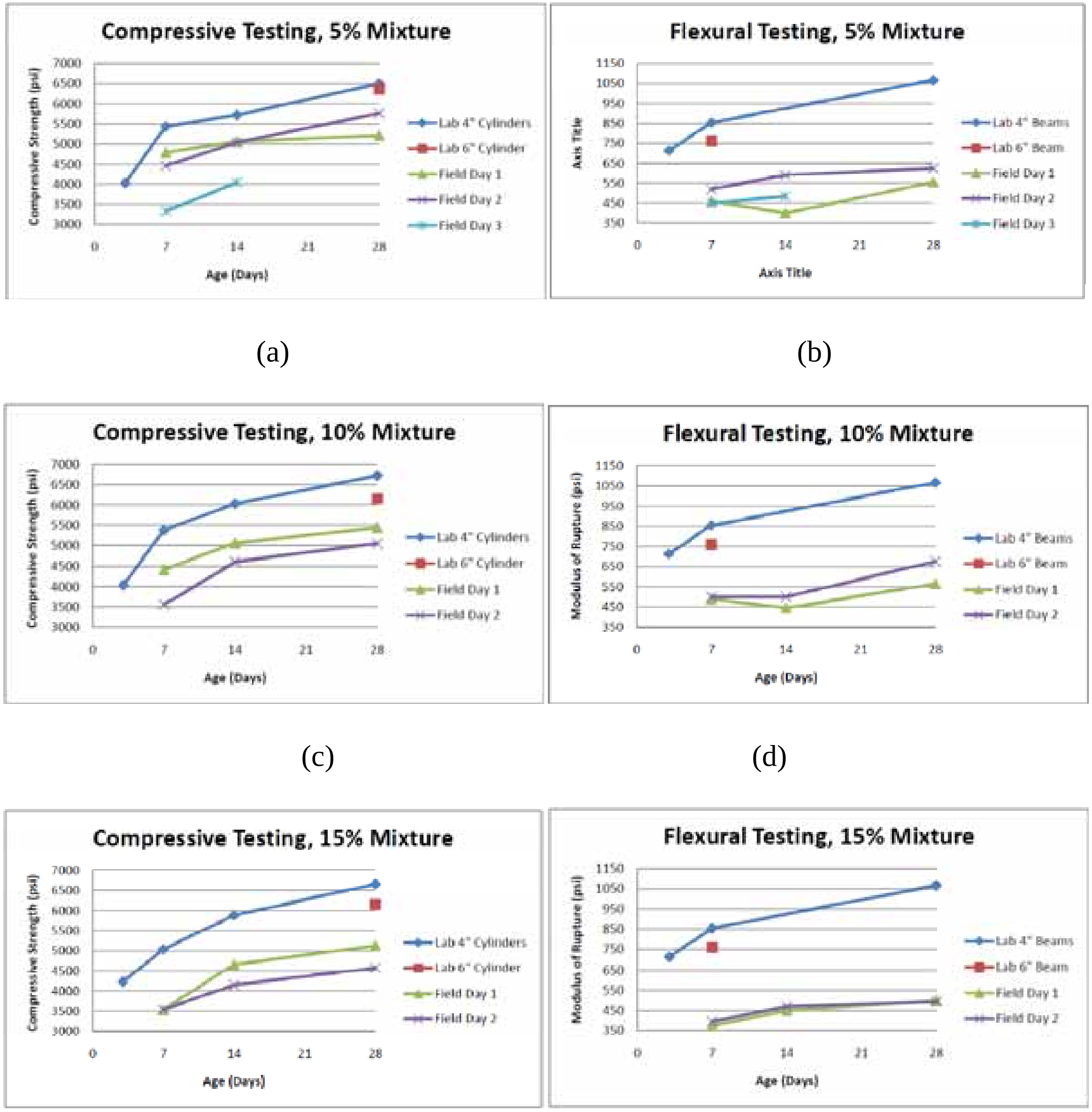
Figure B12. Concrete straight from the paver before workers began with final finishing

Figure B13. Segregation due to high water content

Table B1. Table of Compressive and Flexure Data for Field and Laboratory Specimens



MIX	LOC.	COMPRESSIVE			FLEXURAL		
		AGE	DATE	ACTUAL	AGE	DATE	ACTUAL
5%	LAB	3	3/16/2008	4025	3	3/16/2008	713
5%		7	3/20/2008	5436	7	3/20/2008	854
5%		14	3/27/2008	5719	28	4/10/2008	1067
5%		28	4/10/2008	6501	7	3/20/2008	761
5%		28	4/10/2008	6366			
5%	FIELD	7	7/15/2008	4790	7	7/15/2008	460
5%		14	7/22/2008	5060	14	7/22/2008	400
5%		28	8/5/2008	5210	28	8/5/2008	555
5%		7	7/16/2008	4460	7	7/16/2008	520
5%		14	7/23/2008	5040	14	7/23/2008	590
5%		28	8/6/2008	5760	28	8/6/2008	625
5%		7	7/17/2008	3330	7	7/17/2008	450
5%		14	7/24/2008	4040	14	7/24/2008	485
5%		28	8/7/2008		28	8/7/2008	
10%	LAB	3	3/15/2008	4040	3	3/16/2008	713
10%		7	3/19/2008	5377	7	3/20/2008	854
10%		14	3/26/2008	6031	28	4/10/2008	1067
10%		28	4/9/2008	6725	7	3/20/2008	761
10%		28	4/9/2008	6155			
10%	FIELD	7	7/21/2008	4420	7	7/15/2008	490
10%		14	7/28/2008	5060	14	7/22/2008	445
10%		28	8/11/2008	5440	28	8/5/2008	565
10%		7	7/22/2008	3560	7	7/16/2008	500
10%		14	7/29/2008	4610	14	7/23/2008	500
10%		28	8/12/2008	5050	28	8/6/2008	675
15%	LAB	3	3/14/2008	4229	3	3/14/2008	713
15%		7	3/18/2008	5039	7	3/18/2008	854
15%		14	3/25/2008	5884	28	4/8/2008	1067
15%		28	4/8/2008	6663	7	3/18/2008	761
15%		28	4/8/2008	6156			
15%	FIELD	7	7/31/2008	3540	7	4/1/1931	375
15%		14	8/7/2008	4660	14	4/8/1931	450
15%		28	8/21/2008	5130	28	4/22/1931	500
15%		7	8/1/2008	3540	7	4/2/1931	395
15%		14	8/8/2008	4150	14	4/9/1931	470
15%		28	8/22/2008	4570	28	4/23/1931	495

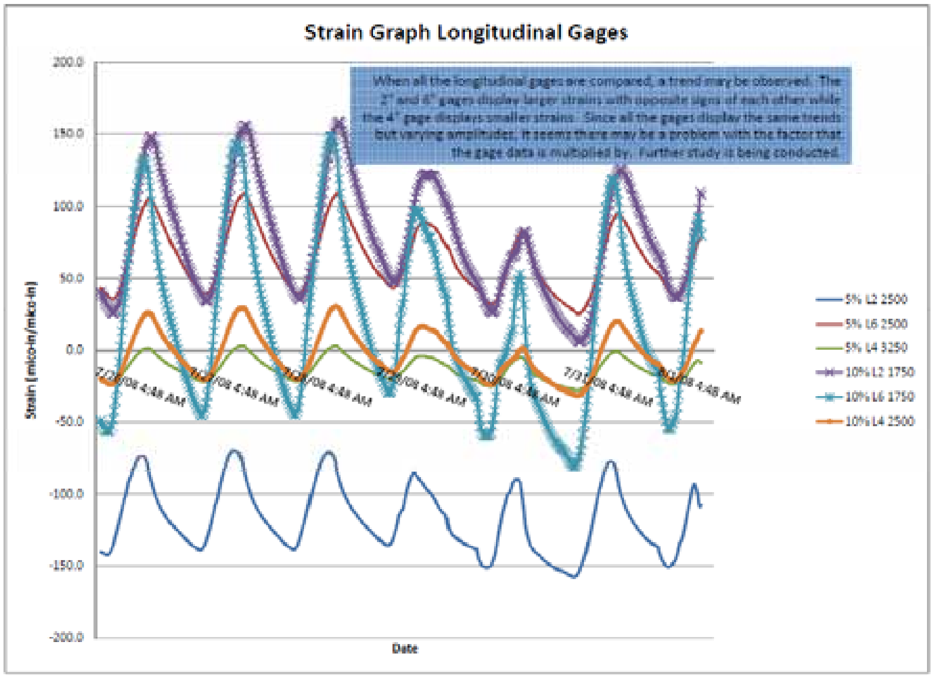


(a) (b)

(c) (d)

(e) (f)

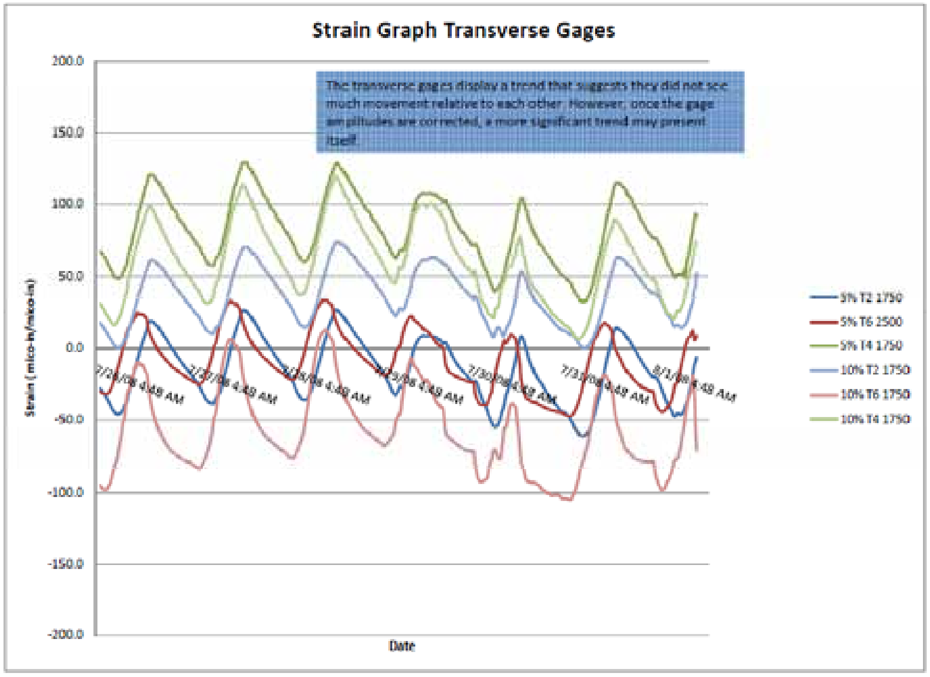
Figure B14. Flexural and Compression Data for Field and Laboratory Specimens



Strain Graph Longitudinal Gages

When all the longitudinal gages are compared, a trend may be observed. The 2" and 6" gages display larger strains with opposite signs of each other while the 4" gage displays smaller strains. Since all the gages display the same trends but varying amplitudes, it seems there may be a problem with the factor that the gage data is multiplied by. Further study is being conducted.

(a)



Strain Graph Transverse Gages

The transverse gages display a trend that suggests they did not see much movement relative to each other. However, once the gage amplitudes are corrected, a more significant trend may present itself.

(b)

Figure B15. Gage Analysis Data

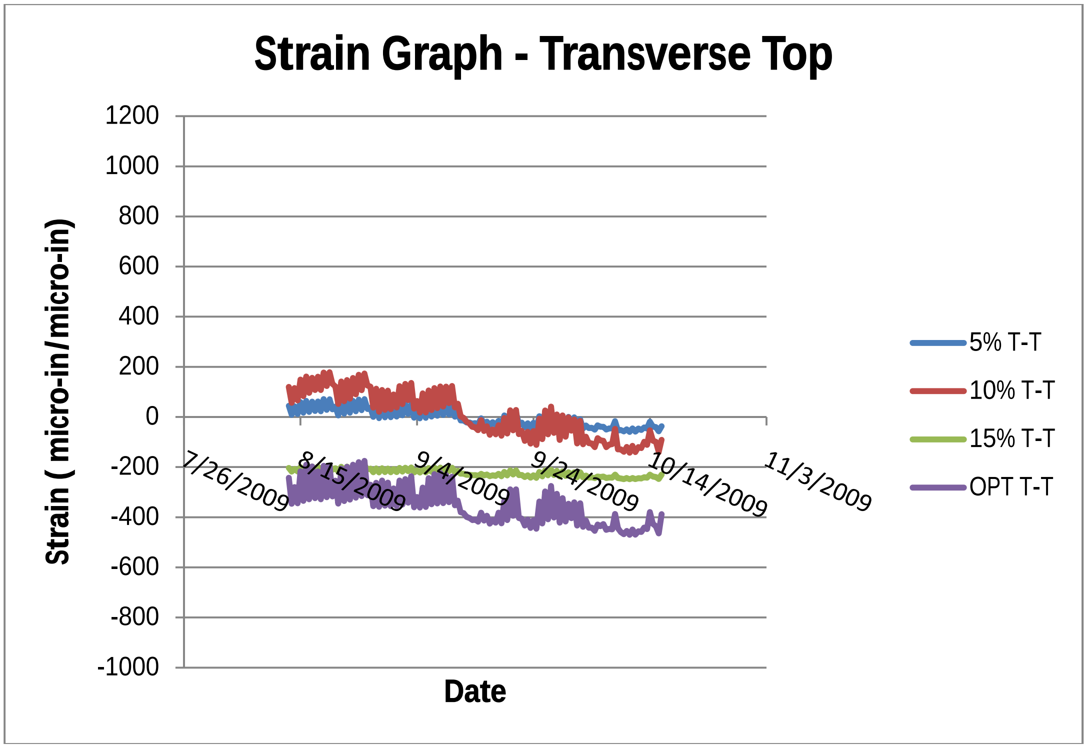


Figure B16. Top transverse gages for all sections

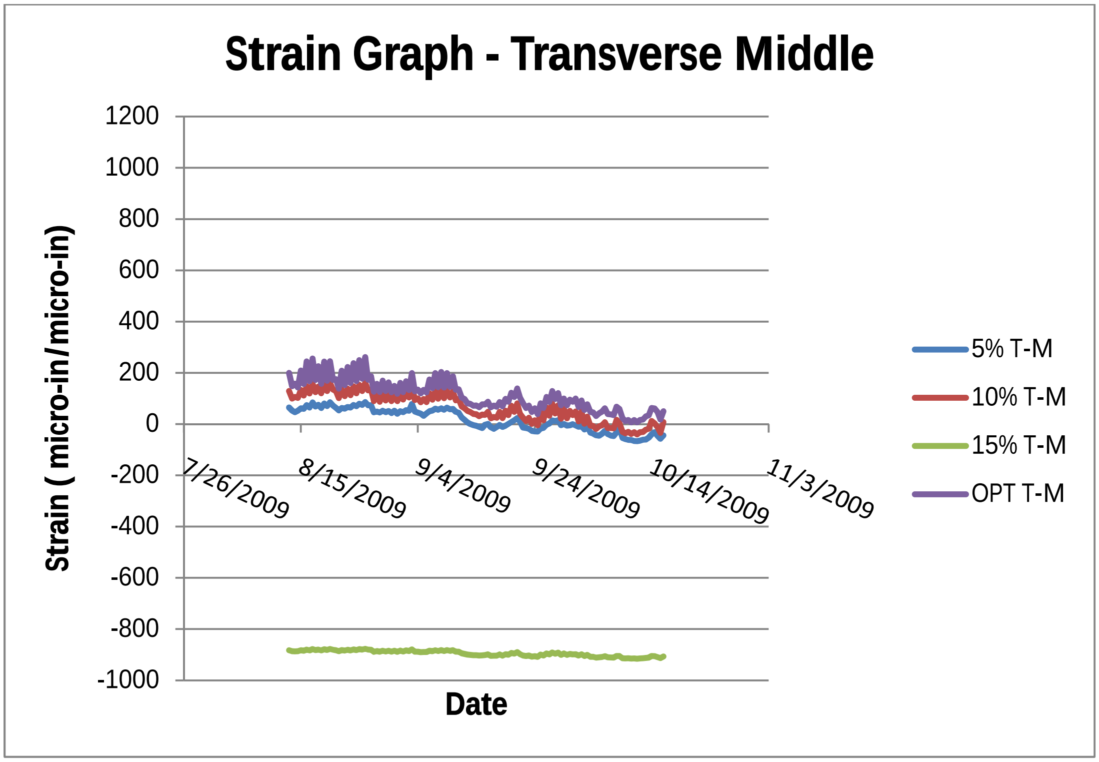


Figure B17. Middle Transverse Gages for All Sections

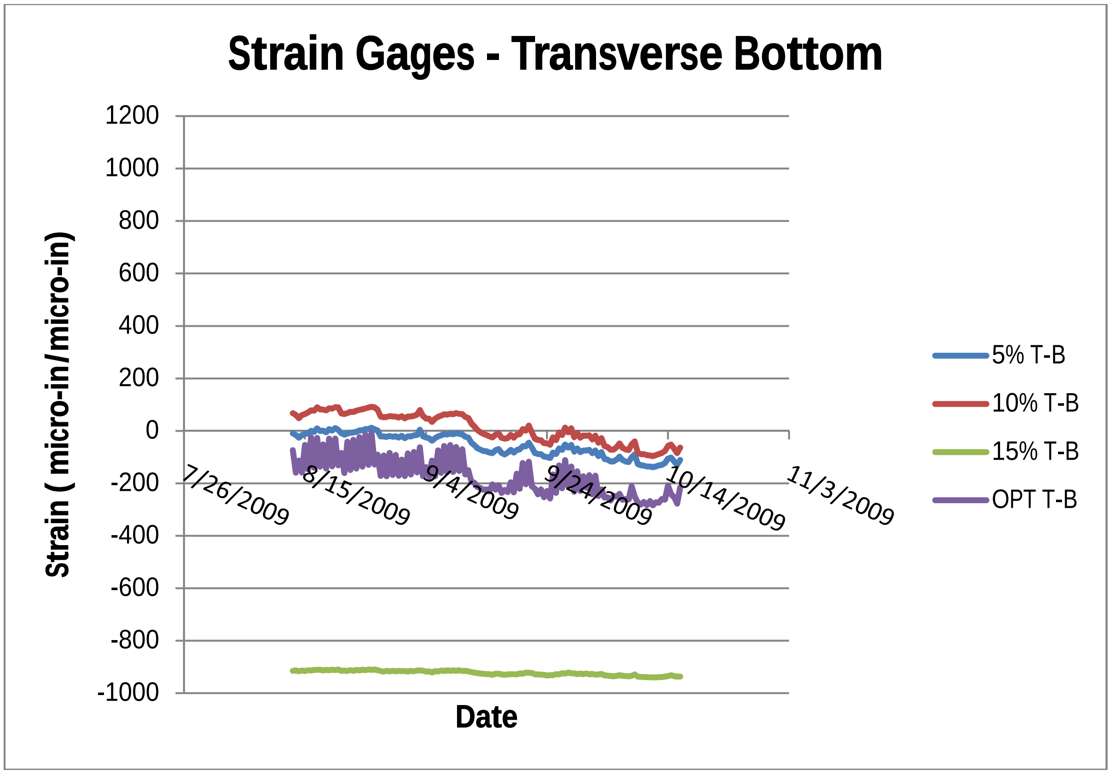


Figure B18. Bottom Transverse Gages for All Sections

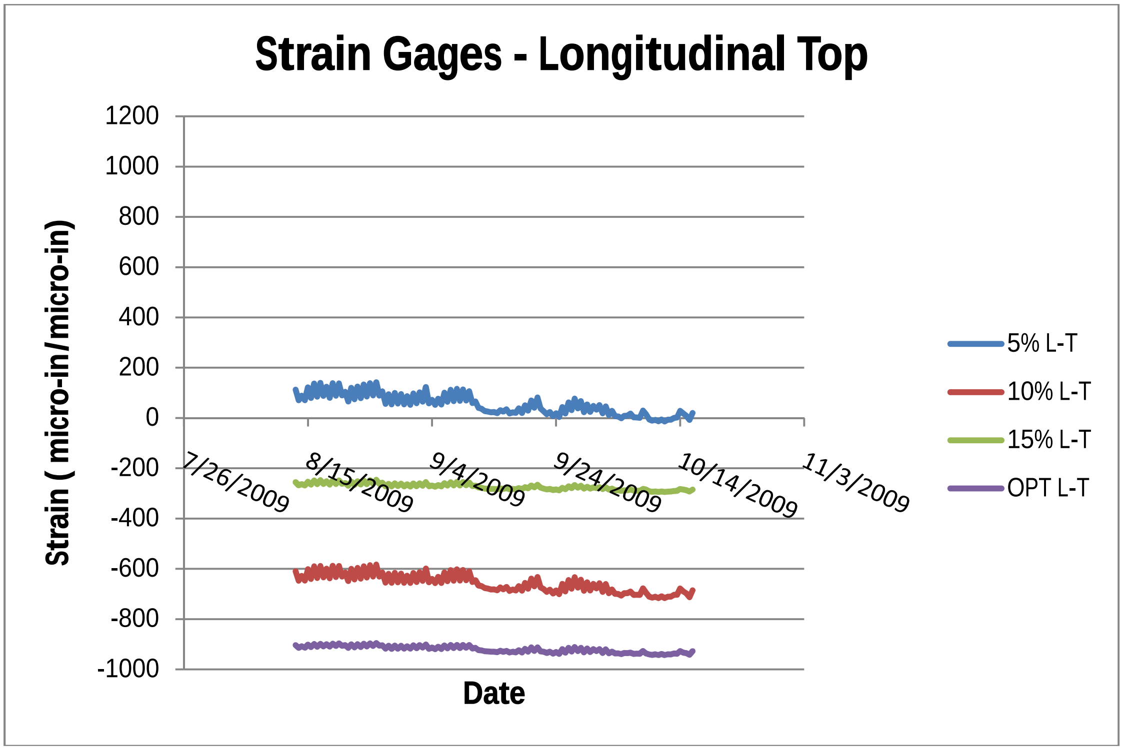


Figure B19. Top Longitudinal Gages for All Sections

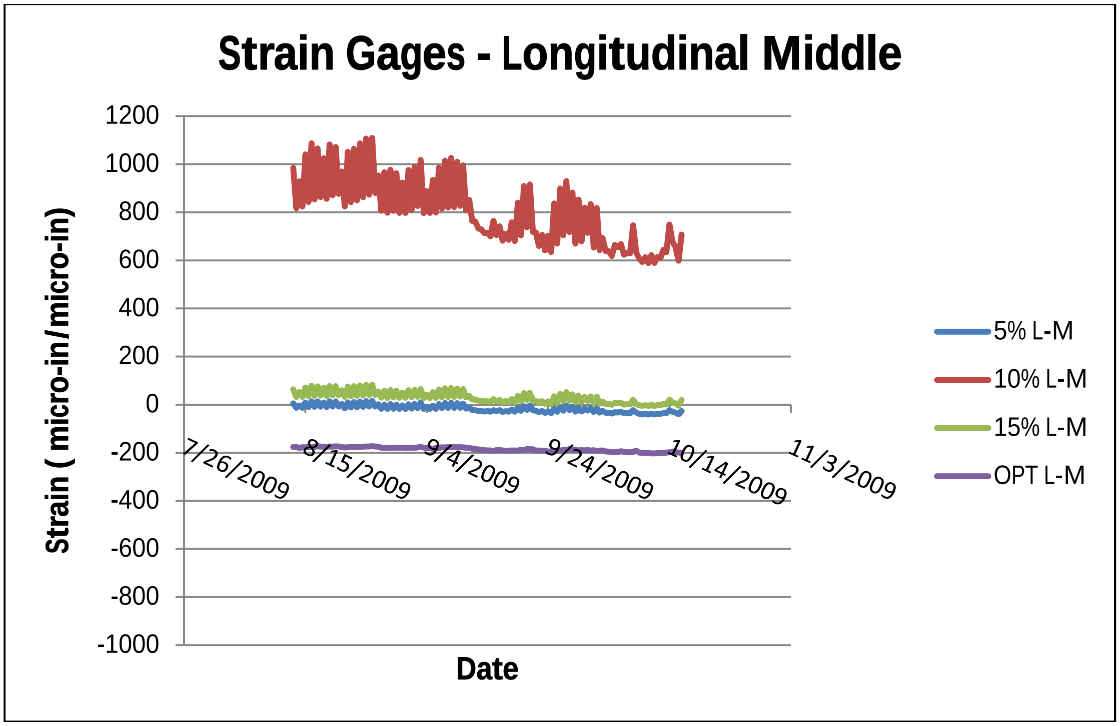


Figure B20. Middle Longitudinal Gages for All Sections

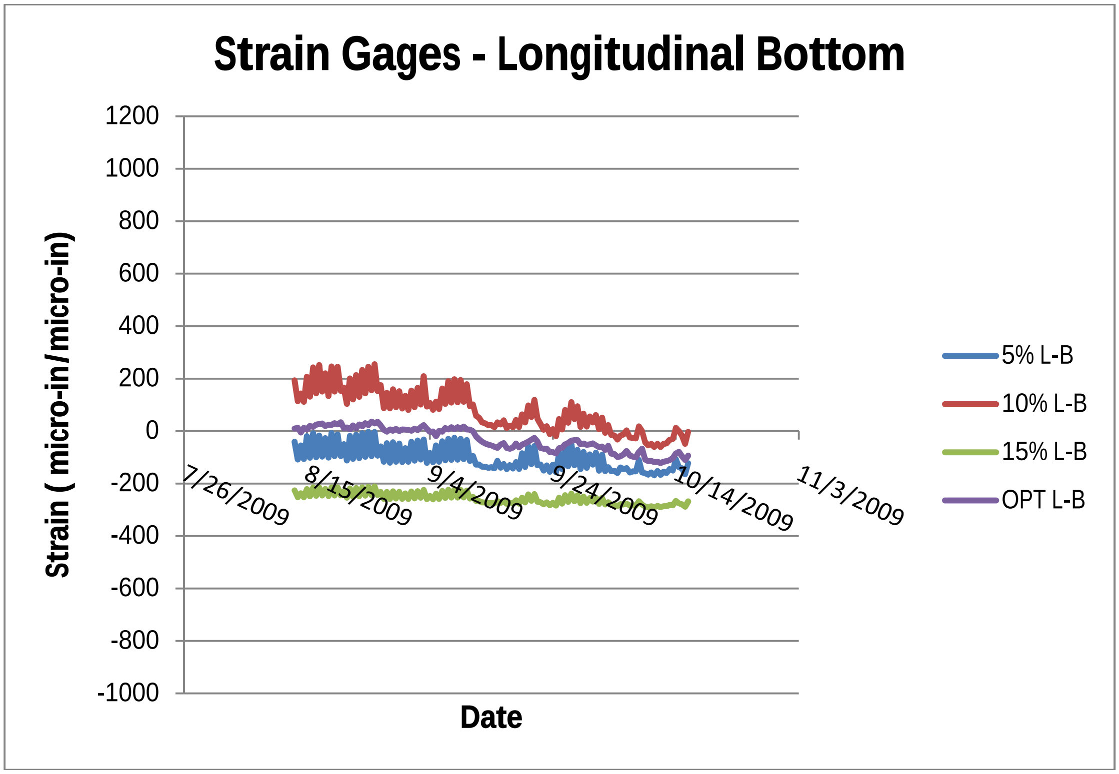


Figure B21. Bottom Longitudinal Gages for All Sections

Appendix C

Training Manual for Pavement Concrete Proportioning Method

TxDOT 5-9029-01-P1

5-9029-01-P1

TRAINING MANUAL FOR PAVEMENT CONCRETE PROPORTIONING METHOD

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TxDOT Project 5-9029-01: Implementation of the Use of Higher Micro-Fines in Concrete Pavements

DRAFT: AUGUST 2008; REVISED FEBRUARY 2010

Performing Organization: Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, Texas 78705-2650	**Sponsoring Organization:** Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080
Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.	

Disclaimers

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

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Products

This training manual is the stand-alone product for this submission and consists of this written documentation and the spreadsheet that includes all calculations described herein.

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Chapter 1. Introduction

Historically, *natural* sand aggregates have been used in pavement concrete. These sand particles have regular, smooth surfaces and are naturally graded to an optimum density simply by the natural process in which they are generated: running water and movement. In recent years, natural sands have begun to be depleted in areas where concrete use is high such as around large metropolitan areas, and where high quality natural sands were scarce in the first place. In these areas, the concrete industry has the option of shipping in natural sand from outside sources, or use manufactured sand. With the high cost of shipping and the advances that the industry has made with aggregate crushing systems, manufactured sands are a valid option for the concrete industry.

One problem that arises with the use of manufactured sand is how it should be proportioned based on particle size in a concrete mixture. Since the particles are crushed, they have irregular shapes depending on the crushing operation used; most are very angular. Additionally, they are not graded as well as natural sands, which are regularly shaped and generally rounded. Lastly, with the use of natural sands from river beds, particles in the sand that pass the No. 200 sieve, known as microfines, tend to be made up of deleterious materials such as clays. In the current ASTM aggregate grading standard, there is a limit on minus No. 200 fines of 3% for natural sands and 5 or 7% for manufactured sands with the lower limit specified for concrete to be exposed to abrasion. With manufactured sands, the microfines that are produced as the “dust of fracture” can approach 20% by weight of the fine aggregate in some cases. These microfine particles are not necessarily harmful to the concrete mixture since they are simply smaller particles of the same materials (unlike in the case of natural sands); however, their very small size results in a very high surface-area-to-volume ratio, which, in some cases results in greater water demand to provide workability.

In current practice, aggregate producers are required to follow the aggregate proportioning method that was developed for natural sands in ASTM C33. This method uses the grading of natural sands which are naturally optimally graded for its guideline. Manufactured sands can be re-graded to fit the ASTM C33 grading, but this regrading does not necessarily result in an optimum packing density due to the shape, angularity, and texture that result from the crushing operation. Additionally, in ASTM C33, aggregate producers are required to wash the fines to remove the minus No. 200 fine particles. One source estimates that up to 100 million tons of microfine material must be disposed of annually (Hudson 2002). This adds considerable labor and expense to the aggregate production cost.

Considerable efforts are being made to change the current state of the art in terms of the use of microfine particles in concrete mixtures. The microfine particles have not only been proven to have little to no deleterious effect on the hardened concrete properties, but in many cases have been shown to improve many of the qualities for the mixture.

This manual presents a method to proportion concrete paving mixtures made with manufactured sands and increased microfines percentages in a step-by-step manner. This method was adapted from Koehler’s (2007) proportioning method for self-consolidating concrete. A spreadsheet that performs these calculations was also developed and follows the outline presented in this manual.

Chapter 2. Spreadsheet Instruction

2.1 Step 1—Aggregate

2.1.1 Characterization

To properly proportion and design a concrete mixture, the aggregates must be tested and characterized. The tests used to characterize aggregates for this project are standard tests with the exception of one that is explained here. Each one has been developed to evaluate a critical property that influences the choice of aggregate and the mixture design process. In this report several properties are discussed that were not a part of this study. These properties may be of interest to the reader as items of further research or additional consideration in mixture design. The characterization properties that will be discussed include deleterious material content, resistance to polish, water demand, chemical resistance and grading.

Deleterious material (clays)

Deleterious materials such as clays and organic matter can be harmful to a concrete mixture as they may expand, contract, degrade over time, or react with other materials in the mixture (Dumitru, 1999). The methylene blue test for such materials is based on the ability of the clays to absorb methylene blue dye. Though many variations of this test exist, AASHTO TP 57-06 was used for this study. The Methylene Blue Value (MBV) resulting from the test depends on characteristics such as mineralogy, particle size, and porosity. Though research has found that some variance exists if samples are washed or unwashed, this test method uses washed aggregates (Quiroga, 2003). In a previous version of AASHTO TP 57, guidelines for acceptance were given. Though these guidelines were removed in the current version, generally, if the MBV is below 12, the aggregate is acceptable. Although high MBV can be an indicator of problems such as high water demand, further investigation should be done to accept or reject an aggregate, especially if that aggregate has high fines (Ahn, 2000).

Resistance to polish

In concrete subjected to direct traffic, *polishing* of concrete surfaces due to wearing and deterioration of surface aggregates can be a major problem for concrete made with carbonate fine aggregate. The acid insolubility test is performed to predict how an aggregate will weather and polish. For this research, test method Tex-612-J was used. Current specifications require a minimum 60% acid insolubility residue. With the use of many limestone aggregates, especially dolomitic limestones, this specification is not usually met. Where excessive wear is observed (or anticipated), mechanical means or skid resistant pavement coatings can be used to insure that the surface can maintain a safe skid resistant texture.

Water demand

Water demand can be estimated with the *single drop test.* Though no standard exists, this test was performed based on the description of Bigas and Gallias (2002) and Koehler (2007). In the single drop test, a bed of loosely packed, dry microfines is placed in an open dish. Using a pipette, a 0.2 mL drop of water is added to the dish of microfines. After approximately 20 seconds, the resulting agglomeration of water and microfines is carefully removed with a needle. Previous research in ICAR 107 recommends an upper limit for w/f = 1.5 based on Bigas, et al (2002). The most recent work in ICAR suggests that a lower limit of 0.70 is more realistic based on a number of microfines of various aggregate mineralologies. This limit will be further investigated in 0-6255.

The results of the test are expressed as the water-fines volume ratio of the agglomeration (w/f). In addition, the packing density of the fines in the agglomeration is computed. The test is repeated 15 times on each material (Koehler, 2007).

Durability

Aggregate porosity or absorption, measured by Tex 403-A or ASTM C127 and C128 for coarse and fine aggregate, respectively, may affect *durability* of a concrete as freezing of water in the pores of the aggregate particles can cause surface pop-outs and cracking in extreme case (Popovics, 1998). The relationship between freeze thaw and absorption has not been completely accepted, but nonetheless this test is a valuable initial indicator of soundness (Quiroga, 2003). Though no limits are defined, the implications of highly absorptive aggregates should be considered, especially if problems such as freezing and thawing are expected.

Chemical resistance

Though no specific testing was conducted in this research project for chemical resistance, chemical interactions between materials and environment must be considered and acknowledged in the design process for durability and performance of a given mixture design. There are many different chemical interactions that can be detrimental to concrete. A few are listed here with ways to mitigate their damage during mixture design. Alkali-silica reaction occurs internally and causes an expansion of the cement matrix from the reaction between alkalis (usually from the cement) and reactive silica (usually from the course aggregate). Though it is rare, it can be disastrous if it does occur. Several ways to limit its occurrence include avoiding total alkalis in the cement, testing aggregates for reactivity, or an excess of reactive silica may be provided to consume the alkali present in a non-expansive reaction product (Day, 2006). Sulphate attack is another chemical problem to which concrete may fall victim and one of the main risks of deterioration within concrete itself. Sulphates react with tricalcium aluminate in cement and expand. This may be solved by using cement with low tricalcium aluminate contents.

Grading

The particle size distribution, or grading, of every material in a concrete mixture is highly pertinent to the concrete performance. A variety of techniques must be used to characterize a full grading starting with proper sampling because of the tendency of aggregates and other granular materials to segregate by size (Koehler, 2007). Next, the minus No. 200 microfine particles are removed using the ASTM C117 standard to wash the particles from the sample. Last, a sieve analysis according to ASTM C136 or Tex-401-A is used to measure the grading of aggregates larger than the No. 200 sieve.

The grading of an aggregate sample with certain shape, angularity, and texture properties greatly affects the aggregate performance in a concrete mixture. For high quality concrete, it is well-known that aggregate must be well-graded with a wide range of particle sizes. As aggregate size decreases, their importance to concrete increases because they become more costly to produce, and the characteristics have a more dramatic impact on the concrete properties (Hudson 2002). In the case of manufactured sand the use of the same grading and volume as the natural sand it is replacing is suggested. However, because ideal grading depends on many factors, each aggregate should be evaluated independently (Hudson, 2003). The manufactured sands used in this project were graded with high percentages of minus No. 200 fines for research purposes and implemented to test their feasibility in the field. It was proven that microfines can successfully be used in pavement concrete. In this design methodology, however, after the initial washing with ASTM C117, the microfines are considered part of the powder portion and used in the paste composition calculations as opposed to the aggregate portion (Koehler, 2007).

2.1.2 Aggregate Proportioning

0.45 Power Curve & No. 200 0.45 Power Curve

The *0.45 Power Curve* is a graphical representation of the sieve size versus the percent of aggregate passing that size. However, the sieve size is raised to the 0.45 power. The curve was developed by the asphalt industry but was adopted by concrete producers when it was discovered how favorable a high packing density concrete mixture could be. The graph, shown in Figure 1(a), shows the straight, middle line extending from the origin to the maximum aggregate size representing optimal grading. The two straight lines on either side of this solid middle line are there as a guide and run from the origin to one size above and one size below the max aggregate size. No gradation will perfectly follow the straight middle line, but as long as the gradation falls within the zone of the two outer lines, the grading will have a high packing density. A coarser grading, as shown in Figure 2.1, one that falls toward or below bottom line of the graph can be harsh due to the lack of fine materials. A finer grading would fall at or above the top line and though it may demonstrate high HRWRA demand, it will usually have better overall workability (Koehler, 2007). This research project attempted to use as-received grading for each aggregate and blend them to achieve the optimum grading for the mixture.

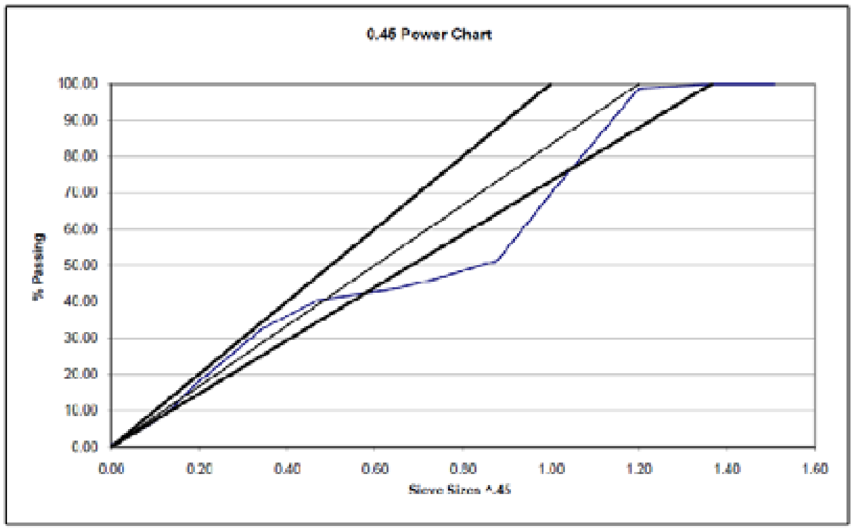


Figure 2.1: 0.45 Power Curve Example

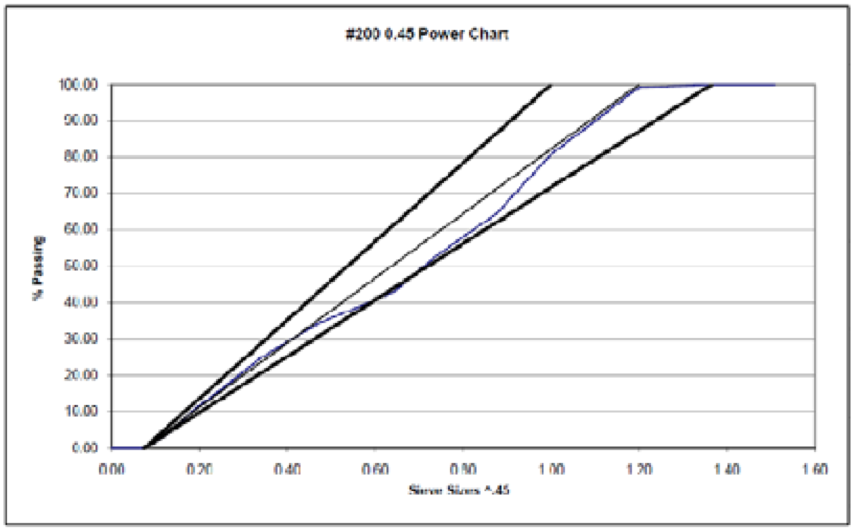


Figure 2.2: No. 200 0.45 Power Curve Example

This approach to aggregate proportioning has proven useful, but it does not account for the large volume of materials that can pass the No. 200 sieve, especially in the case of manufactured aggregate. As mentioned above, these microfine materials are more appropriately considered a part of the powder portion and should be considered in the paste composition. For this reason, in proportioning the aggregate, the microfines are not considered and thus the lines no longer start at the origin but at the No. 200 sieve size as shown in Figure 2.2. As a general guideline in a first approach, when combining two aggregates, the sand-aggregate ratio should be set at 0.40 to 0.50 (Koehler, 2007).

8-18 Method

The *8-18 grading system* is an attempt to limit the maximum and minimum amounts of aggregate fraction to produce uniform blends. This specification has been widely used, but is not intended for aggregate with high microfines (Quiroga, 2003). It is included in this design spreadsheet simply for completeness. Though this method has been adopted by a number of agencies, it should be noted that even aggregate systems falling within the graph lines could have workability problems and low packing densities (Quiroga, 2003). The graph shown in Figure 2.3 is an aggregate that is typical of the aggregate proportioning for this project. The grading does not fit exactly within the lines, but still works well as a concrete aggregate for paving.

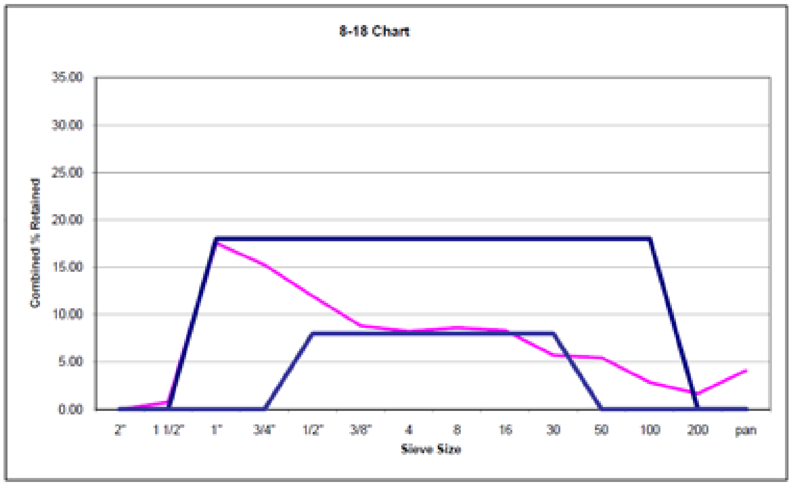


Figure 2.3: 8-18 Chart

Coarseness/Workability

The coarseness chart is not a grading system; it is simply a chart that helps ensure uniform blends of aggregate without major gaps in grading (Shilstone, 2002). The coarseness chart considers the grading of the entire range of aggregate, as opposed to considering coarse and fine aggregate separately. Aggregates are divided in three size fractions: large aggregate, Q, includes plus 3/8-in. sieve particles; intermediate aggregate, I, includes minus 3/8-in to plus No. 4; and fine aggregate, W, includes minus No. 4 and plus No. 200 sieve particles. Figure 2.4 presents the coarseness chart which is divided into 5 zones (Shilstone, 2002). The heavy diagonal bar separating zone V from the rest of the zones is the separation for rocky and sandy mixes. Mixtures below this line in zone V tend be harsh with little workability. Mixtures in zone I are prone to segregation, zone IV mixtures have too much fine aggregate making them likely to crack, yield early, and segregate. Zone II is the most desirable zone. Zone III is an extension of zone II for maximum size aggregates of 0.5 inches or less.

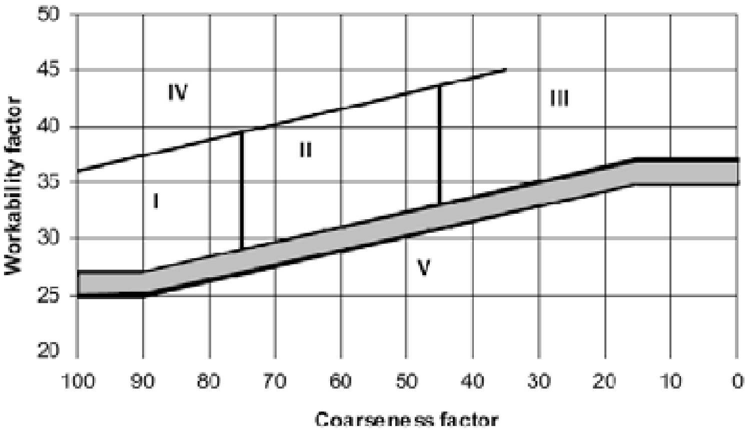


Figure 2.4: Coarseness Chart (Quiroga, 2003)

2.1.3 Maximum Aggregate Size

The *maximum size of aggregate*, or MSA, is an important factor in concrete mixture design that affects such properties as workability, strength, and shrinkage. Workability is improved with increased maximum aggregate size because of the decrease in surface area (Washa, 1998). The limit on maximum aggregate size comes from the application of the concrete mixture (i.e. rebar spacing restrictions), but also from the optimal maximum size of coarse aggregate. This optimal size results in concrete with the highest strength for a given mixture consistency and cement content (Popovics, 1998). Many factors affect this optimal maximum aggregate size. This optimization is beyond the scope of this paper, but some considerations may include the reduction in bond that results from the use of larger particles due to the smaller surface area-to-volume ratios. Alternatively, mixtures with large maximum size coarse aggregate usually experience reduced shrinkage and creep and have decreased fresh concrete water demand (Quiroga, 2003). In general the largest maximum size of aggregate that should be used in a mixture design is the largest that can practically be used for the application.

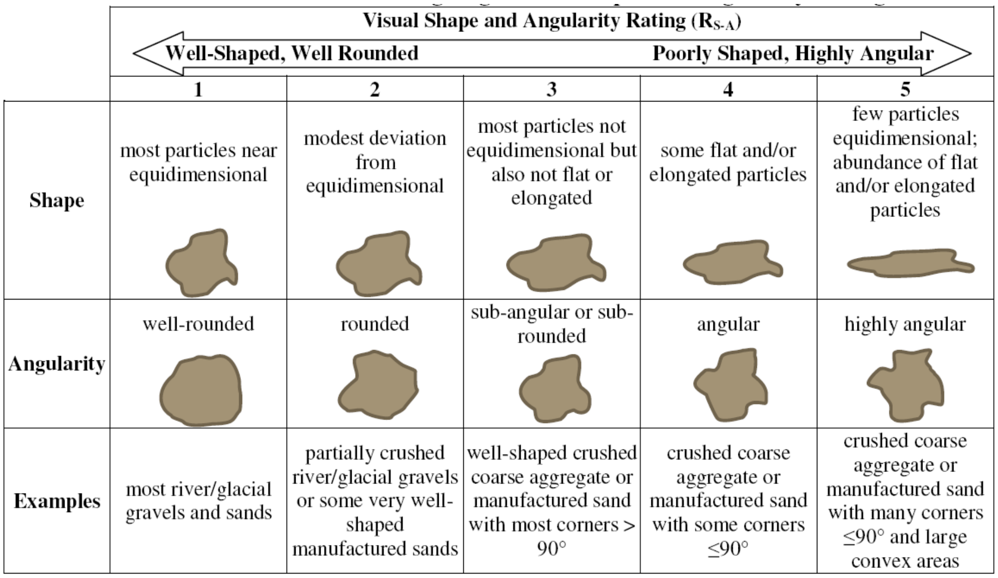
2.1.4 Dry Rodded Unit Weight, DRUW

The combined effect of shape, texture, and grading of the *entire* aggregate mixture is considered by means of the dry rodded unit weight (DRUW) Tex 404-A, rodded method.

2.1.5 Angularity and Shape Rating

Shape and angularity of aggregates affect workability by controlling the aggregate compacted voids content and the inter-particle friction between aggregates. Well-rounded spherical or cubic aggregates are best for workability; however, aggregates of varying shapes and angularities can be accommodated in pavement concrete by increasing the paste volume. Once the paste volume is satisfactory for a given aggregate, concrete workability can be further improved by adjusting the paste composition. A visual examination is typically sufficient for characterizing aggregate shape and angularity. Table 2.1 should be used to assign a single visual rating, on a scale of 1 to 5, representing both shape and angularity. A single rating should be assigned to each combined grading, so a weighted average rating would be made for combined grading.

Table 2.1: Visual Shape and Angularity Rating (Koehler, 2007)



	Visual Shape and Angularity Rating (R_{S-A})				
	Well-Shaped, Well Rounded				Poorly Shaped, Highly Angular
	1	**2**	**3**	**4**	**5**
Shape	most particles near equidimensional	modest deviation from equidimensional	most particles not equidimensional but also not flat or elongated	some flat and/or elongated particles	few particles equidimensional; abundance of flat and/or elongated particles
Angularity	well-rounded	rounded	sub-angular or sub-rounded	angular	highly angular
Examples	most river/glacial gravels and sands	partially crushed river/glacial gravels or some very well-shaped manufactured sands	well-shaped crushed coarse aggregate or manufactured sand with most corners > 90°	crushed coarse aggregate or manufactured sand with some corners ≤90°	crushed coarse aggregate or manufactured sand with many corners ≤90° and large convex areas

Various sources and blends of aggregate should be considered and evaluated for maximum aggregate size, grading, and shape and angularity. The compacted voids content and visual shape and angularity rating, R_{S-A}, should be determined on all aggregate blends (Koehler, 2007).

2.1.6 Compacted Voids Content of Mixture

The compacted voids content is calculated using Equation 1 (Koehler, 2007).

$$\%voids_{compacted\_agg} = \left(1 - \frac{DRUW}{\left(62.4\,{}^{lb}/_{ft^3}\right)\sum_{i=1}^{n}\left(p_i\left(SG_{OD}\right)_i\right)}\right)*100\%$$

(Eq. 1)

The minimum compacted voids content (maximum packing density) is optimal in most situations based on material economy—maximum packing of aggregate means minimum paste. The minimum voids content may not be ideal in cases where other influences must be considered such as segregation resistance or type of placement operation (Koehler, 2007).

2.2 Step 2—Paste Volume

2.2.1 Paste Spacing Range

The paste spacing range is the minimum amount of paste needed to provide space between aggregates. This value is presented as a range because it depends on the shape and angularity rating (Koehler, 2007). In this project, one aggregate was provided and tested. This procedure was modified based on this aggregate alone. A 3% to 8% range was determined to work well, but this may need to be adjusted based on future research.

Paste to provide spacing

The paste needed to provide spacing is calculated using Equation 2 (Koehler, 2007).

$$V_{paste-spacing} = 3 + \left(\frac{8-3}{4}\right)\left(R_{S-A} - 1\right) \qquad \text{(Eq. 2)}$$

Paste for filling ability

The minimum paste required for filling ability in this mixture is basically independent of the paste composition. The total paste volume for filling ability is a function of volume required for paste spacing and percent voids in the compacted aggregate and is calculated using Equation 3 (Koehler, 2007).

$$V_{paste-filling\_ability} = 100 - \frac{\left(100 - V_{paste-spacing}\right)\left(100 - \%voids_{compacted\_agg}\right)}{100} \qquad \text{(Eq. 3)}$$

Paste to fill voids

This value is back calculated from the relationship shown in Equation 4 (Koehler, 2007).

$$V_{paste-filling\_ability} = V_{paste-voids} + V_{paste-spacing} \qquad \text{(Eq. 4)}$$

Stability Factor

The stability is the ability of a mixture to minimize the effect of small changes in material properties in order to resist complications. This value should initially be adjusted by one percent at a time.

2.2.2 Total Paste Volume

Once the paste volume is calculated, it is recommended that tests on mixtures with small variations be conducted to confirm exact paste volume. Concrete without the minimum paste volume may not achieve the desired slump flow or viscosity, may exhibit severe bleeding and segregation, or appear harsh. Figure 2.5 illustrates the paste for filling and separation. Enough paste must be provided to fill the voids between compacted aggregates and to provide separation to achieve the desired workability. This paste provides lubrication to increase flowability and workability (Koehler, 2007). This total volume is then used in step 3 to determine composition of paste.

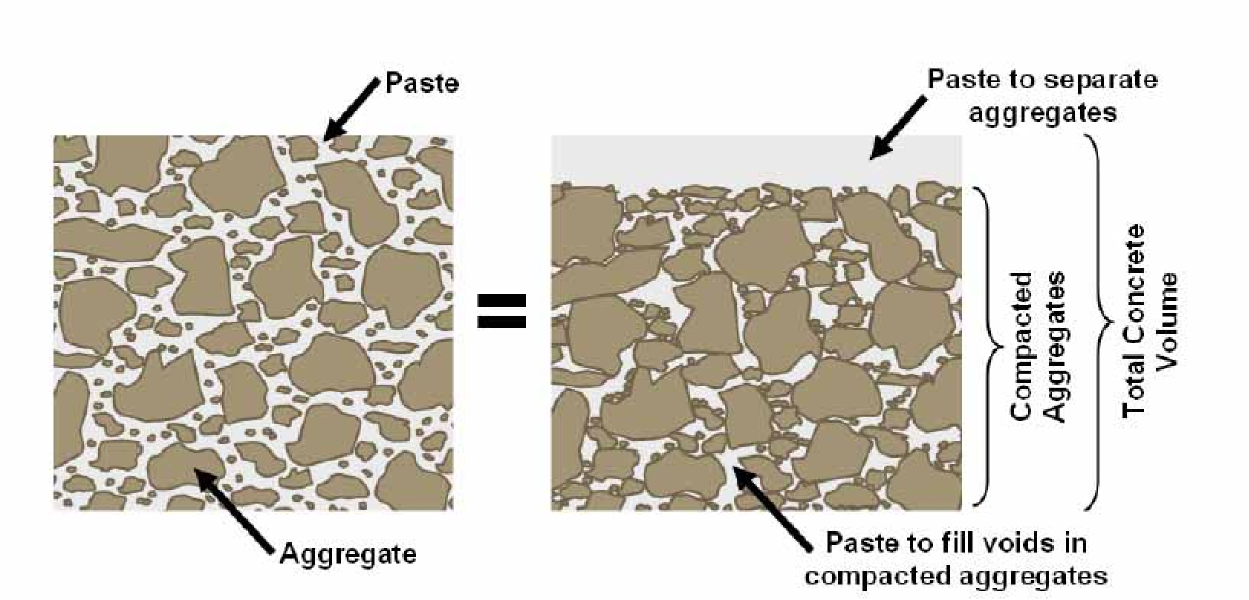


Figure 2.5: Representation of Aggregate in Cement Paste (Koehler, 2007)

2.3 Step 3—Paste Composition

2.3.1 Select Paste Components

Depending on desired properties and application of concrete, it is often necessary to include SCMs or mineral fillers as part of the powder portion. The powder must contain a minimum amount of cement for desired strength and durability. SCMs can be added to improve workability and durability, reduce heat of hydration, and reduce cost. Mineral fillers may contribute to workability and strength. This project sought to prove that microfine aggregate may be used as mineral filler. This aggregate did not necessarily improve the properties of the mix, but when the proper proportions were used it was able to be placed without problems and has performed well to date.

2.3.2 Select w/c

The water-to-cementitious material property ratio is one of the best indicators of long term hardened properties. TxDOT requires a 0.45 limit for Class P pavement concrete, but other limits exist depending on desired properties.

2.3.3 Air for durability

Air content requirements are similar to those for conventional concretes and are set forth in the TxDOT specification in section 421.4. Air contents may be difficult to maintain with additional angular particles as in the case of additional microfines. An additional air entraining agent may be necessary.

2.3.4 W/p implications

Water-to-powder ratio is an indicator of workability. Values of 0.30 to 0.45 are typical (Koehler, 2007).

2.3.5 Paste Composition

TxDOT specification, section 421 presents a list of allowable material specifications based on concrete environment and application.

2.4 Step 4—Batch Mixture Composition

In the spreadsheet, the microfines are considered separately from the aggregate for the entire mixture design process. During this step, the microfines are added back into the fine aggregates since they are considered as fine aggregates by the concrete producer for ease of batching.

Mixtures should be optimized to achieve desired filling ability, segregation resistance, hardened properties, and economy. The optimization of mixtures is often an iterative process. Once a viable mixture has been composed initial trial mixtures should be conducted to test fresh properties. Once a mixture with desirable fresh properties has been achieved, hardened properties should be tested and the mixture adjusted accordingly.

2.5 Step 5—Test Mixes

2.5.1 Fresh Properties

In this implementation project, a paving concrete was developed with fine aggregate containing high amount of microfines. Because it was to be placed with a slip-form paver, the mixture had specific guidelines for fresh properties. The TxDOT specification, section 421 gives the required slump and air content of fresh mixtures. These properties were tested using Tex-415-A for slump and Tex-414-A or Tex-416-A for air content. At the job site, temperature was monitored as described in Tex-422-A.

Workability and finishability are also important parameters but are not as easily measured. There is no standard test for these. In the research project these properties were tested in the lab when making and finishing test specimens including beams and cylinders. Additionally, one of the major components of the project was to implement the test mixtures. The implementation project served as a very large test of workability in the field. The high fines, manufactured aggregate concrete mix presented some new challenges for workability that the ready-mix plant, contractor, and supervisors were not familiar with, but they were addressed and handled well.

2.5.2 Hardened Properties

Once a mixture has been deemed useful in terms of fresh properties, hardened properties should be tested based on the TxDOT specification and in-service conditions that are expected at the site where the concrete will be used. TxDOT requires compressive strength to be tested using method Tex-418-A. Flexural strength should be tested using Tex-448-A test method. Required strengths, as described in the specification, must be met for the type of concrete, age of testing, etc. Additional tests that may be run based on environmental conditions include the freeze-thaw test using ASTM C666, shrinkage tests using ASTM C157, permeability test at 56-days using ASTM C1202, and the abrasion test using ASTM C944.

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Appendix A: Spreadsheet Instructions

Following are instructions for using the spreadsheet. Please note that explanation is also available within the yellow cells of the spreadsheet. Further explanation is available in the accompanying manual, presented in the main body of this document.

- You should have the Excel file open as these instructions follow the spreadsheet exactly. All of the information in this document is available in the Excel file as well.
- Save the file with your own filename.
- Fill in the green input cells. All other cells may be viewed to see the formulas but are protected by passwords to prevent the user from changing the formulas accidentally. If the user wishes to edit the locked cells, the password to unprotect the spreadsheet is "hfc".

The mixture proportioning procedure is divided into 4 broad steps.

- **Step 1 is aggregate proportioning.** This step starts with aggregate characterization and then allows the user to proportion each aggregate fraction based on output from graphs demonstrating different proportioning systems.
- **Step 2 is the determination of the paste volume.** This is the volume of space between the aggregate particles for the paste to fill in. Though some research has been completed in this area, more is necessary to apply this procedure more fully to pavement concretes with different aggregates.
- **Step 3 is the determination of the paste composition.** Properties such as hardened properties and workability depend heavily on the w/c ratios and other selected ratios.
- **Step 4 is the final composition** as determined from the paste composition step and aggregate proportioning.

Step 1: Aggregate

(You'll see the boxes below throughout this instruction document. They correspond directly to the spreadsheet tabs along the bottom of the pages.)

1a. Agg

Step 1-1. List aggregate description information and sieve data in tables 1 and 2.

List properties of each aggregate including source location, name, sieve data, dry rodded unit weight (DRUW), packing density, and specific gravity. *This tab input is straightforward. Do the tests and input the results.*

Fill in Table 1 with general aggregate description information. The DRUW and packing density values in this table are for each aggregate separately. Each aggregate should be evaluated separately here, then proportioned using information on Tab "1c. Agg". The "Microfines

Descrip." should be a simple description of the microfines in that fine aggregate sample. For example, if the fine aggregate description was “manufactured sand,” then the microfines description might be “MS fines.”

Fill in Table 2 with sieve data for each aggregate sample. The minus No. 200 microfine particles must be removed using the ASTM C117 standard to wash the particles from the sample. Last, a sieve analysis according to ASTM C136 or Tex-401-A is used to measure the grading of aggregates larger than the No. 200 sieve. In this design methodology, however, after the initial washing with ASTM C117, the microfines are considered part of the powder portion and used in the paste composition as opposed to the aggregate portion (Koehler, 2007).

1b. Agg

The “Aggregate Summary” table on Tab 1b is simply that—a summary and table for internal calculations. No input is required. To see any of the formulas for the cells, just unlock the cells.

1c. Agg

Step 1-2. Grading (based on a 0.45 power curve)

No one proportioning system is necessarily best; several should be considered to achieve optimum grading. See further explanation in the following paragraphs. Some trial and error is necessary to find a grading that is acceptable.

Use the green cells to proportion the aggregate. The graphs are provided in Figures 1 through 4 to see immediate feedback about the changes made. The percentage of aggregates must sum to 100%.

Proportioning System Information

The **0.45 Power Curve** is a graphical representation of the sieve size versus the percent of aggregate passing that size. However, the sieve size is raised to the 0.45 power. The curve was developed by the asphalt industry but was adopted by concrete producers when it was discovered how favorable a high packing density concrete mixture could be. Figure 2 of Tab 1c graphs the straight, middle line extending from the origin to the maximum aggregate size representing optimal grading. The two straight lines on either side of this solid middle line are there as a guide and run from the origin to one size above and one size below the max aggregate size. No gradation will perfectly follow the straight middle line, but as long as the gradation falls within the zone of the two outer lines, the grading will have a high packing density.

This approach to aggregate proportioning has been proven useful, but it does not account for the large volume of materials that can pass the No. 200 sieve, especially in the case of manufactured aggregate. These microfine materials are more appropriately considered a part of the powder portion and should be considered in the paste composition. For this reason, in proportioning the aggregate, the microfines are not considered and thus the lines no longer start at the origin but at the No. 200 sieve size. This graph, shown in Figure 1 of Tab 1c, is known as the No. 200 0.45 Power Curve. As a general guideline in a first approach, when combining two aggregates, the sand-aggregate ratio should be set at 0.40 to 0.50 (Koehler, 2007).

The **8-18 grading system** is an attempt to limit the maximum and minimum amounts of aggregate fraction to produce uniform blends. This specification has been widely used, but is not intended for aggregate with high microfines (Quiroga, 2003). It is included in this design spreadsheet and explained here simply for completeness. Figure 3 of Tab 1c shows the results of the 8-18 method for the chosen aggregate proportions.

The **coarseness chart** is not a grading system; it is simply a chart that helps ensure uniform blends of aggregate without major gaps in grading (Shilstone, 2002). The coarseness chart considers the grading of the whole aggregate, as opposed to considering coarse and fine aggregate separately. Aggregates are divided in three size fractions: large, intermediate, and fine aggregate. Figure 4 of Tab 1c demonstrates coarseness/workability rating with the yellow point. The long, lower diagonal bar separating zone V from the rest of the zones is the separation for rocky and sandy mixes. The outlying zones all have problem areas. Mixtures in zone I are prone to segregation; zone IV mixtures have too much fine aggregate, making them likely to crack, yield early, and segregate. Zone II is the most desirable zone. Zone III is an extension of zone II for maximum size aggregates of 0.5 inches or less.

1d. Agg

Step 1-3. Maximum Aggregate Size

The maximum size of aggregate, or MSA, is an important factor in concrete mixture design that affects such properties as workability, strength, and shrinkage. Workability is improved with increased maximum aggregate size because of the decrease in surface area. In general the largest maximum size of aggregate that should be used in a mixture design is the largest that can practically be used for the application

Step 1-4. Dry Rodded Unit Weight (using ASTM C29)

This DRUW is for entire aggregate mixture. The combined effect of shape, texture, and grading of the entire aggregate mixture is considered by means of the dry rodded unit weight Tex 404-A, rodded method.

Step 1-5. Rate shape, angularity, and texture using Table 1.

Rate general shape of aggregate pieces using Table 1 on Tab 1d.

Step 1-6. Determine compacted voids content of mixture.

The minimum compacted voids content (maximum packing density) is optimal in most situations based on material economy—maximum packing of aggregate means minimum paste.

Step 2: Paste Volume Determination

2. Paste Vol.

Step 2-1. Determine paste volume for filling ability.

The minimum paste required for filling ability in this mixture is basically independent of the paste composition. The total paste volume for filling ability is a function of volume required for paste spacing and percent voids in the compacted aggregate.

Step 2-1a. Paste Spacing Range

A range of 3–8% worked for my aggregate. This range may need to be adjusted slightly once more research is completed. The range for SCC concrete is 8–16%. The 3–8% range is a good starting place and should not be changed until trial mixes are run.

Step 2-1b. Calculate paste to provide spacing between agg.

This figure is calculated based on shape and angularity rating and the paste spacing range.

Step 2-1c. Calculate total amount of paste for filling ability.

The term *filling ability* is used in SCC to mean the ability of the concrete to flow under its own mass and fill formwork; in pavement concrete flowability is not necessary but the term is used to find paste necessary to form concrete efficiently with a paver; it is calculated based on compacted voids content and paste spacing.

Step 2-1d. Calculate past to fill voids.

This figure is the amount of paste required to fill voids, calculated based on paste for filling ability and paste spacing requirements.

Step 2-2. Add paste volume for mixture stability.

This additional paste helps to minimize the effects of small changes in the material properties of the mixture. Start with 0–1% and adjust after some trial mixes.

Step 2-3. Calculate total paste volume.

For SCC this is calculated based on filling and passing ability; for pavement, passing ability is not a major consideration, so only the filling ability is considered.

Step 3: Paste Composition

3. Paste Comp

Step 3-1. Select cement, SCMs, and mineral fillers.

Choose and describe cements, SCMs, and mineral fillers as part of the powder blend. For this mix design methodology, mineral fillers include the microfines portion of the fine aggregates. The methodology considers that the microfines as part of the powder blend.

Step 3-2. Select w/c limits.

The w/c limits are set based on desired early-age hardened properties (.45 for Class P concrete).

Step 3-3. Select air content.

Air content for desired durability should be selected. If no value is selected, use 2% as default.

Step 3-4. Select w/p and powder blend for workability.

The water/powder (w/p) ratio affects workability. The cement/cm, SCM1/cm, and SCM2/cm are used mainly to control costs. A minimum of cement should be used to achieve minimum cost and desired strength properties.

Step 3-5. Calculate past composition.

This iteration is automated. No input is necessary.

Step 4. Mixture Composition

4. Mix Comp

Step 4. Mixture Composition

The spreadsheet provides a mixture for batching (microfines are added back to fine aggregate portion). This mixture should be tested in the laboratory. Depending on how close the mixture is to becoming a viable pavement mixture, values for proportioning on Tab 1c, values for paste volume on Tab 2, or values for paste composition on Tab 3 may be altered. Guidelines are provided in this text for altering these values. This method requires creation of test mixtures, with adjustments to the mixture until a satisfactory mixture is achieved in the laboratory.