



5-9029-01-P1

TRAINING MANUAL FOR PAVEMENT CONCRETE PROPORTIONING METHOD

Authors:
Meredith McLeroy
David Fowler
Moon Won
David Whitney

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

AUGUST 2008; REVISED FEBRUARY 2010

Performing Organization: Center for Transportation Research The University of Texas at Austin 1616 Guadalupe, Suite 4.202 Austin, Texas 78701	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

Author's Disclaimer: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Project Engineer: David W. Fowler
Professional Engineer License State and Number: Texas No. 27859
P. E. Designation: Research Supervisor

Acknowledgments

The authors express appreciation to TxDOT Project Director, Lianxang Du, and TxDOT North Tarrant County Area Office including Ralph Browne, area engineer, Marty Stewart, project coordinator, and Tom Thompson for coordinating the pavement trial sections for this project in their area. The authors also wish to thank Victor Villareal and Frank Alonzo at TXI Ready Mix Concrete and John Hasjdaz and Brad Pustejovsky of the Sunmount Corporation for their efforts to make the material testing and implementation parts of this project a success.

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.

Table of Contents

Chapter 1. Introduction.....	1
Chapter 2. Spreadsheet Instruction	3
2.1 Step 1—Aggregate.....	3
2.1.1 Characterization	3
Deleterious material (clays)	3
Resistance to polish.....	3
Water demand	3
Durability	4
Chemical resistance	4
Grading	4
2.1.2 Aggregate Proportioning.....	5
0.45 Power Curve & No. 200 0.45 Power Curve.....	5
8-18 Method.....	6
Coarseness/Workability	7
2.1.3 Maximum Aggregate Size	8
2.1.4 Dry Rodded Unit Weight, DRUW	8
2.1.5 Angularity and Shape Rating	8
2.1.6 Compacted Voids Content of Mixture	9
2.2 Step 2—Paste Volume	9
2.2.1 Paste Spacing Range	9
Paste to provide spacing.....	10
Paste for filling ability	10
Paste to fill voids.....	10
Stability Factor.....	10
2.2.2 Total Paste Volume.....	10
2.3 Step 3—Paste Composition	11
2.3.1 Select Paste Components	11
2.3.2 Select w/c	11
2.3.3 Air for durability	11
2.3.4 W/p implications	11
2.3.5 Paste Composition.....	12
2.4 Step 4—Batch Mixture Composition	12
2.5 Step 5—Test Mixes	12
2.5.1 Fresh Properties.....	12
2.5.2 Hardened Properties	12
References.....	13
Appendix A: Spreadsheet Instructions	15

List of Figures

Figure 2.1: 0.45 Power Curve Example.....	5
Figure 2.2: No. 200 0.45 Power Curve Example.....	6
Figure 2.3: 8-18 Chart.....	7
Figure 2.4: Coarseness Chart (Quiroga, 2003)	7
Figure 2.5: Representation of Aggregate in Cement Paste (Koehler, 2007)	11

List of Tables

Table 2.1: Visual Shape and Angularity Rating (Koehler, 2007).....	9
--	---

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 mineralogies. 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 coarse 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 microfines 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.

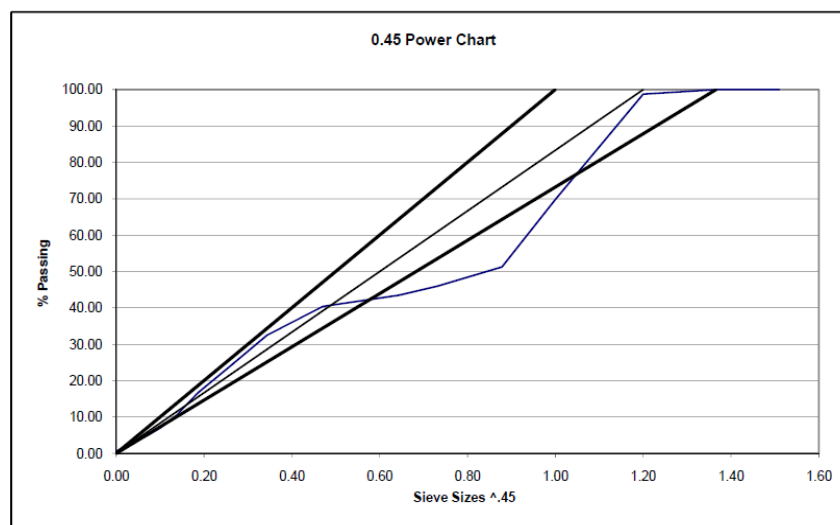


Figure 2.1: 0.45 Power Curve Example

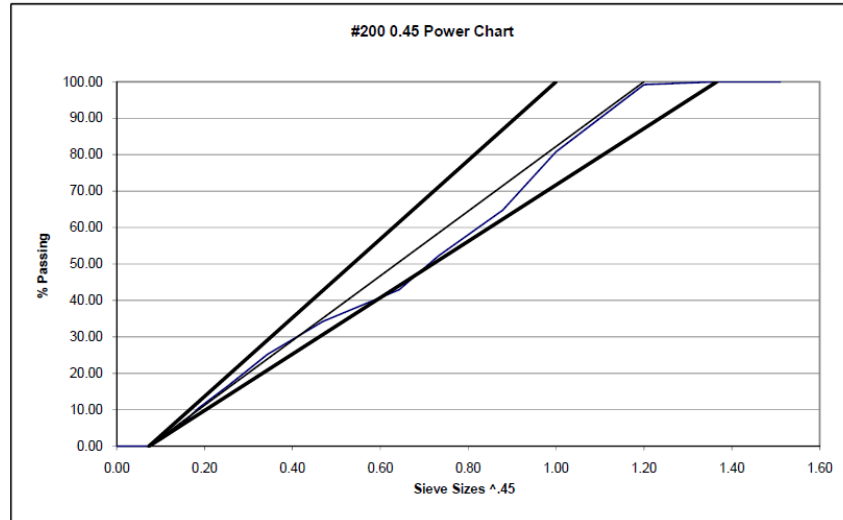


Figure 2.2: No. 200 0.45 Power Curve Example

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.

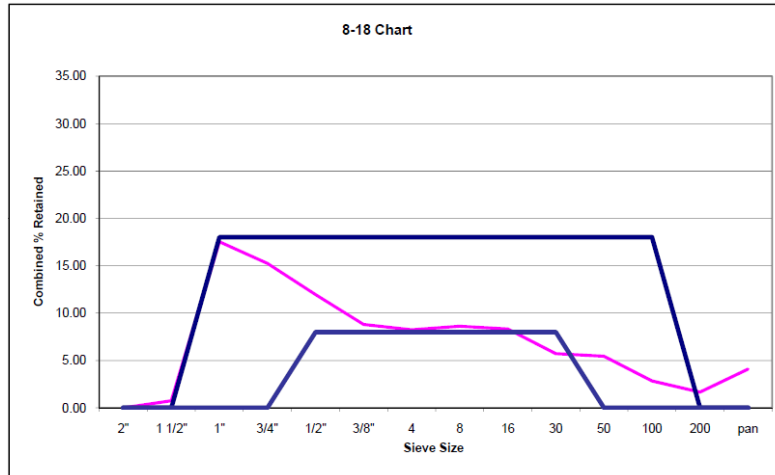


Figure 2.3: 8-18 Chart

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 to 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.

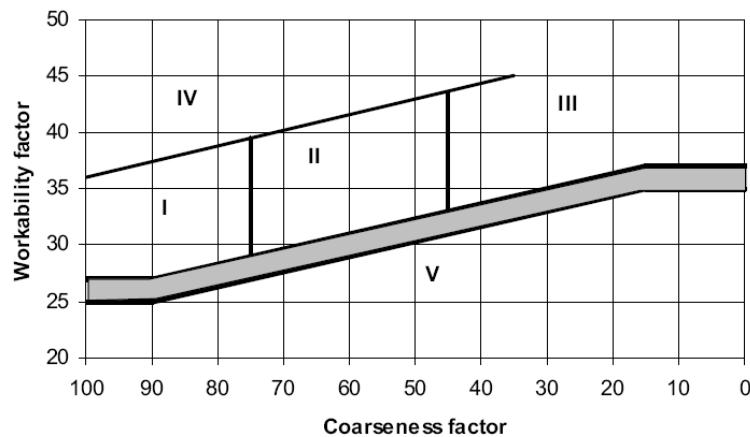


Figure 2.4: Coarseness Chart (Quiroga, 2003)

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.





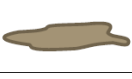





2.1.4 Dry Rodded Unit Weight, DRUW

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 $> 90^\circ$	crushed coarse aggregate or manufactured sand with some corners $\leq 90^\circ$	crushed coarse aggregate or manufactured sand with many corners $\leq 90^\circ$ 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).

$$\%voids_{compacted_agg} = \left(1 - \frac{DRUW}{\left(62.4 \frac{lb}{ft^3} \right) \sum_{i=1}^n (p_i (SG_{OD})_i)} \right) * 100\% \quad (\text{Eq. 1})$$

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).

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

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).

$$V_{paste-filling_ability} = 100 - \frac{(100 - V_{paste-spacing})(100 - \%voids_{compacted_agg})}{100} \quad (\text{Eq. 3})$$

Paste to fill voids

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

$$V_{paste-filling_ability} = V_{paste-voids} + V_{paste-spacing} \quad (\text{Eq. 4})$$

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.

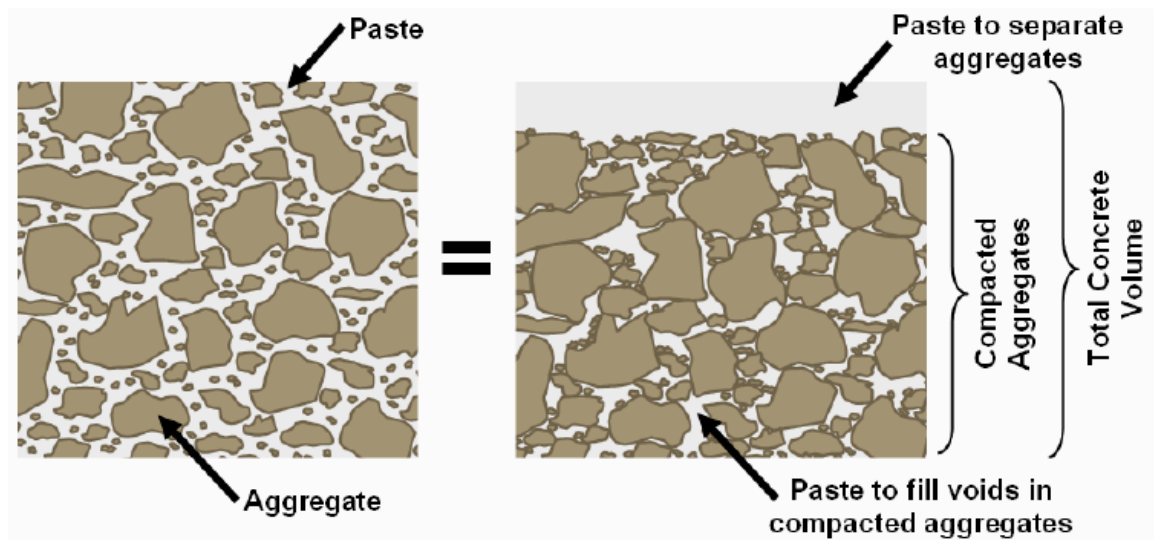


Figure 2.5: Representation of Aggregate in Cement Paste (Koehler, 2007)

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.

References

- Ahn, N. "An Experimental Study on the Guidelines for Using Higher Contents of Aggregate Microfines in Portland Cement Concrete" Ph.D. Dissertation, University of Texas at Austin, 2000.
- Bigas & Gallias, Effect of fine mineral additions on granular packing of cement admixtures. *Magazine of Concrete Research*, 2002, 54, No. 3, June, 155-164.
- Day, Ken (2006). *Concrete Mix Design, Quality Control and Specification*. New York, NY: Taylor & Francis.
- Dumitru, I., Zdrilic, T. and Crabb, R. "Methylene Blue Adsorption Value (MBV). Is It a Rapid and Test Method for the Assessment of Rock Quality?" Conference Proceedings 43rd Annual Conference of the Institute of Quarrying Australia. October 1999.
- Hudson, B. (2002). "Discovering the Lost Aggregate Opportunity: Part 1," *Pit and Quarry*, 95(6), 42-46.
- Hudson, B. (2003). "Discovering the Lost Aggregate Opportunity: Part 4," *Pit and Quarry*, 95(9), 40-43.
- Koehler, E. "Aggregates in Self-Consolidating Concrete" Ph.D. Dissertation, University of Texas at Austin, 2000.
- Popovics, S. "Strength and Related Properties of Concrete. A Quantitative Approach". John Wiley and Sons. 1998.
- Quiroga, P. "The Effect of the Aggregates Characteristics on the Performance of Portland Cement Concrete" Ph.D. Dissertation, University of Texas at Austin, 2000.
- Shilstone, J.M., and Shilstone, J.M. (2002). "Performance-Based Concrete Mixtures and Specifications for Today," *Concrete International*, 24(2), 80-83.
- Washa, G.W. "Workability", Chapter 5, *Concrete Construction Handbook*, ed. Dobrowolski, J. McGraw-Hill, 1998. 4th ed.

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 microfines 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 microfines 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 paste 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.