Concrete Pavement Mixture Design and Analysis (MDA):

An Innovative Approach To Proportioning Concrete Mixtures

National Concrete Pavement Technology Center

Tech Center

Technical Report
March 2015

Sponsored through
Federal Highway Administration (DTFH61-06-H-00011 (Work Plan 25))
Pooled Fund Study TPF-5(205): Colorado, Iowa (lead state), Kansas, Michigan, Missouri, New York, Oklahoma, Texas, Wisconsin

IOWA STATE UNIVERSITY
Institute for Transportation

About the National CP Tech Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

Disclaimer Notice

Iowa State University Non-Discrimination Statement

Iowa Department of Transportation Statements

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No. TPF-5(205)	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Concrete Pavement Mixture Design and Analysis (MDA): An Innovative Approach To Proportioning Concrete Mixtures		**5. Report Date** March 2015 **6. Performing Organization Code**
7. Author(s) Peter Taylor, Ezgi Yurdakul, Xuhao Wang, and Xin Wang		**8. Performing Organization Report No.**
9. Performing Organization Name and Address National Concrete Pavement Technology Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Organization Name and Address Federal Highway Administration and Pooled Fund Partners U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590		**13. Type of Report and Period Covered** Technical Report **14. Sponsoring Agency Code** TPF-5(205)

15. Supplementary Notes

Visit www.cptechcenter.org for color pdfs of this and other research reports.

16. Abstract

Mixture proportioning is routinely a matter of using a recipe based on a previously produced concrete, rather than adjusting the proportions based on the needs of the mixture and the locally available materials. As budgets grow tighter and increasing attention is being paid to sustainability metrics, greater attention is beginning to be focused on making mixtures that are more efficient in their usage of materials yet do not compromise engineering performance. Therefore, a performance-based mixture proportioning method is needed to provide the desired concrete properties for a given project specification. The proposed method should be user friendly, easy to apply in practice, and flexible in terms of allowing a wide range of material selection.

The objective of this study is to further develop an innovative performance-based mixture proportioning method by analyzing the relationships between the selected mix characteristics and their corresponding effects on tested properties. The proposed method will provide step-by-step instructions to guide the selection of required aggregate and paste systems based on the performance requirements. Although the provided guidance in this report is primarily for concrete pavements, the same approach can be applied to other concrete applications as well.

17. Key Words concrete materials—concrete mixtures—mixture proportioning		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 50	**22. Price** NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

CONCRETE PAVEMENT MIXTURE DESIGN AND ANALYSIS (MDA): AN INNOVATIVE APPROACH TO PROPORTIONING CONCRETE MIXTURES

Technical Report
March 2015

Principal Investigator
Peter Taylor, Associate Director
National Concrete Pavement Technology Center, Iowa State University

Authors
Peter Taylor, Ezgi Yurdakul, Xuhao Wang, and Xin Wang

Sponsored by
FHWA Pooled Fund Study TPF-5(205): Colorado, Iowa (lead state), Kansas, Michigan, Missouri, New York, Oklahoma, Texas, Wisconsin

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation

A report from
National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 Fax: 515-294-0467
www.cptechcenter.org

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This research was conducted under the Federal Highway Administration (FHWA) Transportation Pooled Fund Study TPF-5(205) with support from the following state departments of transportation (DOTs):

- Colorado
- Iowa (lead state)
- Kansas
- Michigan
- Missouri
- New York
- Oklahoma
- Texas
- Wisconsin

The authors would like to express their gratitude to the Iowa DOT and the other pooled fund state partners for their financial support and technical assistance.

The researchers would also like to acknowledge the agencies and contractors that allowed them to be on their construction sites and to take samples.

EXECUTIVE SUMMARY

The aim of this report is to describe an innovative approach to proportioning concrete mixtures that can provide guidance for concrete producers, specifiers, contractors, and engineers. Although the provided guidance in this report is primarily for concrete pavements, a similar approach can be applied to other concrete applications.

The concept is to proportion concrete mixtures in three iterative steps:

1. Select the aggregate system.
2. Select the quality of the paste.
3. Select the relative volumes of paste and aggregate.

The selection of aggregate system includes consideration of the following factors (among others not included in this work, such as durability):

- The gradation of the system should aim to achieve close to maximum density while still providing good workability and finishability.
- The voids between consolidated combined aggregate particles should be determined.

Selection of the paste systems for the desired performance criteria includes the following:

- Selection of a binder system of portland cement and supplementary cementitious materials (SCMs) to achieve desired performance, including durability and strength, using locally available materials
- Selection of an air void system to protect the system from frost effects
- Selection of the water-to-cementitious materials ratio (w/cm) to achieve required performance

Selection of the paste volume is based on providing sufficient paste in the mixture to fill all of the voids between the aggregates and a certain amount more to achieve workability goals. Insufficient paste leads to poor workability and an inability to fully consolidate the samples, which leads to very poor permeability and strength. Laboratory testing data also indicated that excess paste leads to a reduction in permeability and strength performance. Based on laboratory testing, it was observed that the preferred amount of paste is dependent on the aggregate mineralogy, size, and gradation. The desired ratio of paste to aggregate voids was found to be in the range of 1.25 to 1.75.

A spreadsheet has been developed to help users conduct the proportioning process based on this approach.

INTRODUCTION

Mixture proportioning is routinely a matter of using a recipe based on a previously produced concrete, rather than adjusting the proportions based on the needs of the mixture and the locally available materials (Lee et al. 2009, Ji et al. 2006). However, concrete is a heterogeneous and complex material in which there are multiple interactions between its components. It is well documented (Yurdakul et al. 2012, Hu and Wang 2011, Ashraf and Noor 2011, Wassermann et al. 2009, Kim et al. 2005, Jamkar and Rao 2004) that overall concrete performance is affected by the nature of the mix components and their quantities. Each mix component has an impact on both fresh and hardened concrete properties, albeit at varying levels. For example, when every other parameter is kept constant, increasing water content increases the workability, whilst adversely affecting concrete strength and durability due to the increased capillary porosity (Popovics 1990, Kennedy 1940, Abrams 1920). Furthermore, in addition to the individual effect of each mix component on concrete performance, the interactions between these variables also affect the concrete properties. Concrete mixture proportioning, therefore, has to be a well-thought and iterative process that often requires decisions to balance mutually exclusive requirements for workability, durability, and cost effectiveness.

Another challenging issue is that many mixture specifications are predominantly prescriptive-based and may promote the use of higher amounts of some materials than needed. Such approaches may result in increased cost and potentially reduced durability and longevity due to effects such as shrinkage-related cracking (Yurdakul et al. 2012, Grove and Taylor 2012, Lee et al. 2009, Shilstone and Shilstone 2002). Using excessive amounts of some materials, such as cement, also has a negative impact on the environment because cement production results in carbon emissions and energy consumption. Therefore, a performance-based mixture proportioning method is needed to fulfill the desired concrete properties for a given project specification. The proposed method should be user friendly, easy to apply in practice, and flexible in terms of allowing a wide range of material selection.

The objective of this study is to further develop an innovative performance-based mixture proportioning method by analyzing the relationships between the selected mix characteristics and their corresponding effects on tested properties. The proposed method will provide step-by-step instructions to guide the selection of required aggregate and paste systems based on the performance requirements of concrete pavements.

BACKGROUND

What is Mixture Proportioning?

Mixture proportioning is the process of determining the required quantities of concrete components to achieve the specified concrete properties (Taylor et al. 2006). The critical aim of mixture proportioning is to ensure that "it fits for the purpose for which it is intended and for the expected life during which it is to remain in service" (Neville 2000). In addition, the mixture proportions should be optimized for economy and sustainability.

Moving from Prescriptive toward Performance-based Specifications

Currently, many concrete mixes are proportioned based on recipes that have been used before and/or on prescriptive-based specifications. These specifications define the limits on the type, amount, and proportions of the mix components to ensure that the performance is met (Ozyildirim 2011). To ensure the quality and performance of concrete, the minimum compressive strength, maximum water-to-cementitious materials ratio (w/cm), replacement level of supplementary cementitious materials (SCMs), and minimum cementitious materials content are often specified, regardless of the aggregate system in use. This has the potential to increase the cost and carbon footprint of concrete (Lobo et al. 2006). In addition, setting a limit on the minimum cementitious materials content may increase heat generation and shrinkage, thus leading to cracking and thereby compromising the longevity of concrete pavements (Ozyildirim 2011, Obla 2006). Studies (Chamberlin 1995) have shown that mixes designed by following the prescriptive-based specifications do not always provide the desired end results, leading to increased maintenance costs. In addition, many proportioning approaches were developed before water-reducing admixtures and supplementary cementitious materials were in common usage (Grove and Taylor 2012).

Current prescriptive-based specifications deliberately promote overdesigning mixes by using cement content as a safety factor. This has the effect of adversely affecting the environment because of the CO_2 footprint associated with manufacturing portland cement (Hendriks et al. 2004, Battelle Memorial Institute 2002). Therefore, developing a mixture proportioning method that is based on performance criteria and does not limit the efficient use of materials will be beneficial in improving sustainability.

As budgets grow tighter and increasing attention is being paid to sustainability metrics, greater attention is beginning to be focused on making mixtures that are more efficient in their usage of materials without compromising engineering performance. Therefore, the construction industry has been moving from prescriptive towards performance-based specifications (Bickley et al. 2010, Lobo et al. 2006, Day 2006, Taylor 2004).

A number of challenges are slowing the development of more performance-based specifications and mixtures in the U.S. market despite the available technology. These include the following:

- Resistance to change: The resistance to change is mostly due to the fact that prescriptive-based specifications have been used by agencies since the early 1900s; thus, most state agencies and contractors are very familiar with these recipe-type specifications and have little experience with performance-based specifications (Falker 2003, Kopac 2002).
- Resistance to any change in the distribution of risk: In concrete pavement construction, risk can be defined as the responsibility for the long-term performance of the pavement. In prescriptive-based specifications, agencies take almost 100% of the risk because as long as contractors properly follow the step-by-step instructions, they often are not held responsible for the quality and performance of the end product after the concrete is placed and construction has been approved (Falker 2003). However, in performance-based specifications, contractors are responsible because the approval criteria for construction are based on the performance of the end product.
- A lack of good performance tests: One of the major barriers in adopting performance-based specifications is the lack of good performance tests that are reliable, inexpensive, consistent, and standardized to measure concrete performance in a timely manner (Hooton and Bickley 2012).

In addition to the listed factors, misconceptions regarding the relationship between mix components and their effect on concrete properties also hinder the implementation of performance-based specifications. These misconceptions are provided below.

Misconception 1: Increasing Cement Content Increases Concrete Strength

Cement, the main component of concrete, is a common material used in many kinds of construction. Cement content is perceived to control concrete strength. Based on this perception, a minimum cement content is often specified that may exceed the amount needed to achieve the desired strength and durability. For example, in the U.S. many state departments of transportation (DOTs) and other agencies specify a minimum cement content between 550 and 600 lb./yd.^{3} for slip-form pavement mixtures, as presented in Table 1 (Rudy 2009).

However, these cement contents are often conservative and may exceed the amount needed for the desired strength and durability. Previous studies (Popovics 1990, Wasserman et al. 2009) suggest that once the cement content reaches an optimum value, using more cement does not achieve higher strength for a given w/cm. In addition, increasing cement content will cause the concrete to become sticky, increase permeability, and increase the risk of shrinkage and cracking problems. Therefore, cement content should be balanced to achieve the desired performance while minimizing the risk of these problems.

Table 1. Minimum cement content specifications for slip-form paving mixtures (after Rudy 2009)

State	Minimum cement content for plain concrete (lb./yd.^{3})
Illinois (ILDOT 2007)	565
Indiana (INDOT 2008)	564
Iowa (Iowa DOT 2008)	573
Kansas (KDOT 2007)	521
Michigan (MDOT 2003)	564
Missouri (MoDOT 2008)	560
New York (NYSDOT 2008)	605
Ohio (ODOT 2008)	600
Pennsylvania (PennDOT 2009)	587
Virginia (VDOT 2007)	564
Wisconsin (WisDOT 2008)	565

Misconception 2: Strength Correlates with Durability

Strength is often used as a quality indicator for the overall performance of a mixture. While strength is important for structural performance, it has no direct correlation with durability. Potential durability can be defined as the concrete's capability of maintaining the serviceability, in a given environment, over its design life without significant deterioration (Alexander and Beushausen 2010, Shilstone and Shilstone 2002). While there may be a general trend that both properties improve in the same direction, it is not conservative to predict potential durability from strength or vice-versa. Therefore, meeting strength requirements does not necessarily ensure the concrete will have the required durability (Obla et al. 2005).

Misconception 3: Supplementary Cementitious Materials Dilute Concrete Properties

Some engineers and contractors are cautious about using supplementary cementitious materials, especially when used in ternary blended concrete mixtures (a combination of three cementitious materials that are blended to balance fresh properties, durability, strength, and economy). This is because it is perceived that incorporating supplementary cementitious materials adversely affects concrete properties, for example by causing low early strength, increasing plastic shrinkage cracking, and extending time of setting (Tikalsky et al. 2011). While these situations may be true, it is well documented (Liu et al. 2012, Bagheri and Zanganeh 2012, Johari et al. 2011) that supplementary cementitious materials generally also do the following:

1. Improve the workability of concrete
2. Decrease the tendency of the concrete to bleed and segregate by enhancing the packing density

3. Reduce the pore size and porosity of both the cement matrix and the interfacial transition zone, thereby increasing performance
4. Increase the ultimate durability in terms of decreasing permeability
5. Reduce alkali-aggregate expansion

The negative side effects can normally be compensated for by modifying mixture proportions and practices on the construction site. In situations when incorporating high amounts of a single type of SCM (binary mixtures) results in unacceptable side effects such as extended setting time, ternary mixtures can be used to balance fresh and hardened properties (Schlorholtz 2004, Tikalsky 2012).

Mixture Proportioning Procedure

Concrete may be considered to comprise two fractions: paste and aggregates. The mixture proportioning procedure discussed below was developed based on evaluating and selecting the paste and aggregate systems separately, followed by analysis of the interactions between them.

The fundamental philosophy is that the aggregate system is largely responsible for the workability of the fresh concrete, while the quality of the paste system is the primary controller of long-term performance, assuming the aggregates are durable. The relative volumes of the two systems are balanced to achieve the desired overall performance, including sustainability-based parameters.

Selection of the Aggregate System

Aggregates occupy up 60% to 90% of the total volume of concrete (Ashraf and Noor 2011). Despite this high percentage in concrete, specifications mostly focus on the minimum cementitious materials content, maximum water-to-cementitious materials ratio, and strength of concrete (Ley et al. 2012). According to a study conducted by Dhir et al. (2006), aggregate properties have a greater impact on many aspects of performance than changing cement content at a given w/cm ratio. Concrete properties such as workability and resistance to bleeding and segregation are greatly affected by aggregate size, gradation, particle shape, surface texture, porosity, void content, specific gravity, absorption, and impurities (Alexander and Mindess 2005, Smith and Collis 2001). For example, spherical, well-rounded, smooth-surfaced aggregates increase workability, whereas angular, elongated, rough-surfaced aggregates decrease workability. Recent work by Ley (2104) has indicated that optimum workability performance can be achieved by holding the combined gradation within an envelope called the “Tarantula Curve”.

The volume of voids remaining in a fully compacted aggregate system is a key factor in determining the paste volume requirements (Koehler and Fowler 2006). Therefore, instead of considering the voids of the fine, intermediate, and coarse aggregates separately, the voids between the combined compacted aggregates are determined.

Selection of the Paste System

The paste system should be selected to achieve all of the required performance criteria. Mix components such as type and amount of cementitious materials, w/cm, the presence of chemical admixtures, and target air content all influence strength and durability performance.

Air is considered part of the paste in order to keep the model a little simpler. Varying air content in a batch will markedly affect the paste volume, but this approach is considered adequate for a design application.

For example, as w/cm decreases, the porosity of the paste decreases, and concrete becomes less permeable, thereby resulting in increased strength and enhanced durability (Wassermann et al. 2009, Dhir et al. 2004). On the other hand, having a good air void system increases durability when concrete is subjected to freezing and thawing conditions and improves the workability and consistency of concrete mixtures by increasing the paste volume for a given w/cm (Kosmatka et al. 2008, Taylor et al. 2006). However, increasing air (particularly the large voids) can adversely affect strength due to the increased porosity.

Selection of the Paste Volume

In concrete mixes, enough cement paste should be provided to not only fill the voids between aggregates but also to cover the aggregates and separate them to reduce the inter-particle friction between aggregates when the mixture is in the fresh state (Kosmatka et al. 2008, Koehler and Fowler 2007, Hu and Wang 2007, Ferraris and Gaidis 1992, Kennedy 1940). This is known as "excess paste theory" (Kennedy 1940). Therefore, a new parameter is needed that integrates the required amount of paste with the aggregate system. This study applies a new concept by using the parameter of paste-to-voids volume ratio (V_{paste}/V_{voids}).

The V_{paste}/V_{voids} is calculated by calculating the paste volume of concrete mixtures and dividing that value by the volume of voids between the combined compacted aggregates. The paste volume includes the volume of water, cementitious materials, and measured air in the system. The voids refer to the space between the compacted combined aggregates that is determined by following the procedure in ASTM C29 (2009).

The following section describes work conducted in the laboratory aimed at developing the information needed to be able to apply this approach to concrete mixtures.

LABORATORY WORK – PHASE 1, PASTE QUALITY AND QUANTITY

A wide range of laboratory tests were conducted to provide background data to support the proposed proportioning method. The first phase comprised work using a fixed aggregate system to assess the paste-related issues.

Cementitious Materials

A single batch of the following cementitious materials was obtained:

- ASTM C150 Type I ordinary portland cement
- ASTM C618 Class F fly ash
- ASTM C618 Class C fly ash
- ASTM C989 Grade 120 slag cement

The chemical composition of the cementitious materials is presented in Table 2.

Table 2. Chemical composition of the cementitious materials, % by mass

Chemical composition	Type I cement	Class F fly ash	Class C fly ash	Slag cement
Silicon dioxide (SiO_2)	20.13	52.10	36.70	37.60
Aluminum oxide (Al_2O_3)	4.39	16.00	20.10	9.53
Ferric oxide (Fe_2O_3)	3.09	6.41	6.82	0.44
Calcium oxide (CaO)	62.82	14.10	23.30	40.20
Magnesium oxide (MgO)	2.88	4.75	4.92	11.00
Sulfur trioxide (SO_3)	3.20	0.59	1.88	1.14
Potassium oxide (K_2O)	0.57	2.36	0.48	0.44
Sodium oxide (Na_2O)	0.10	1.72	1.62	0.45
Loss on ignition	2.55	0.09	0.25	0.00

Aggregates

- One in. nominal maximum size crushed limestone
- No 4 sieve size nominal maximum size river sand

Chemical Admixtures

- ASTM C494 Type F polycarboxylate-based high-range water-reducing admixture (HRWRA)
- ASTM C260 tall oil–based air-entraining admixture (AEA)

Mixtures

In this phase, the results of 118 mixes are presented to assess the effects of various mix characteristics on performance. The details of the mix characteristics are presented in Table 3.

Table 3. Mix characteristics selected for the experiment

Mix characteristics	Selected values
Portland cement	100%
Class F fly ash	15% 20% 30%
Class C fly ash	15% 20% 30%
Slag cement	20% 40%
Cementitious materials content (lb./yd.^{3})	400 500 600 700
w/cm	0.35 0.40 0.45 0.50
Air content (%)	2 4 8
Coarse aggregate size (in.)	1
Coarse aggregate type	Crushed limestone
Fine aggregate type	River sand

Experimental Work

The commonly used performance criteria for concrete mixtures are durability, strength, constructability (workability, placeability, and finishability), and appearance (surface texture) (Shilstone and Shilstone 2002). Therefore, performance was evaluated by conducting tests such as rapid chloride penetration, surface resistivity, air permeability, compressive strength, air content, workability, and setting time. A summary of the tests conducted is provided in Table 4.

Table 4. Test matrix

Concrete properties	Method	Age (days)
Slump	ASTM C143	-
Air content	ASTM C231	-
Setting time	ASTM C403	-
Compressive strength	ASTM C39	28
Rapid chloride penetration	ASTM C1202	28, 90
Surface resistivity	AASHTO TP-95	28, 90
Air permeability	University of Cape Town	28, 90

Results and Discussion

Selecting the Aggregate System

Choosing the Size and Shape of Aggregates

From a workability point of view, rounded aggregates are preferred. However, considering that the slump requirement of concrete pavements is relatively low compared to that of other types of construction, and because the desired slump range can still be achieved with angular particles, crushed limestone is generally preferred because it leads to higher strength in pavements (Taylor et al. 2006). Therefore, in this study, due to their availability and their common use in concrete pavements, crushed limestone as the coarse aggregate and river sand as the fine aggregate were selected to achieve the desired fresh and hardened properties.

Combined Aggregate Gradation

The use of well-graded aggregate particle distribution has received attention in recent years due to the efforts of reducing the costs and improving the sustainability of concrete mixtures (Ley et al. 2012). Optimum combined aggregate gradation is important because concrete produced using well-graded aggregates minimizes the paste requirement, has less water demand, maintains adequate workability, requires less finishing time, consolidates without segregation, positively impacts the air-void structure of the paste, and improves both strength and long-term pavement performance (Delatte 2007, Kohn and Tayabji 2003).

The gradation of the selected fine and coarse aggregates was combined and plotted using various charts to determine the best combination for this research study. According to the FHWA 0.45 power curve (Bureau of Public Roads 1962), Shilstone workability factor chart, and specific surface charts shown in Figure 1 (a through c), the fine aggregate-to-total aggregate ratios of

0.45, 0.42, and 0.39, respectively, resulted in the best fitting combination. The fine aggregate-to-total aggregate ratio was selected as 0.42 by mass based on the average of these three charts. The appropriateness of the selected aggregate distribution of 42% fine aggregate and 58% coarse aggregate was checked by plotting the data in an ASTM C33 (2013) plot (Figure 1-d) and a "haystack" plot (Figure 1-e).

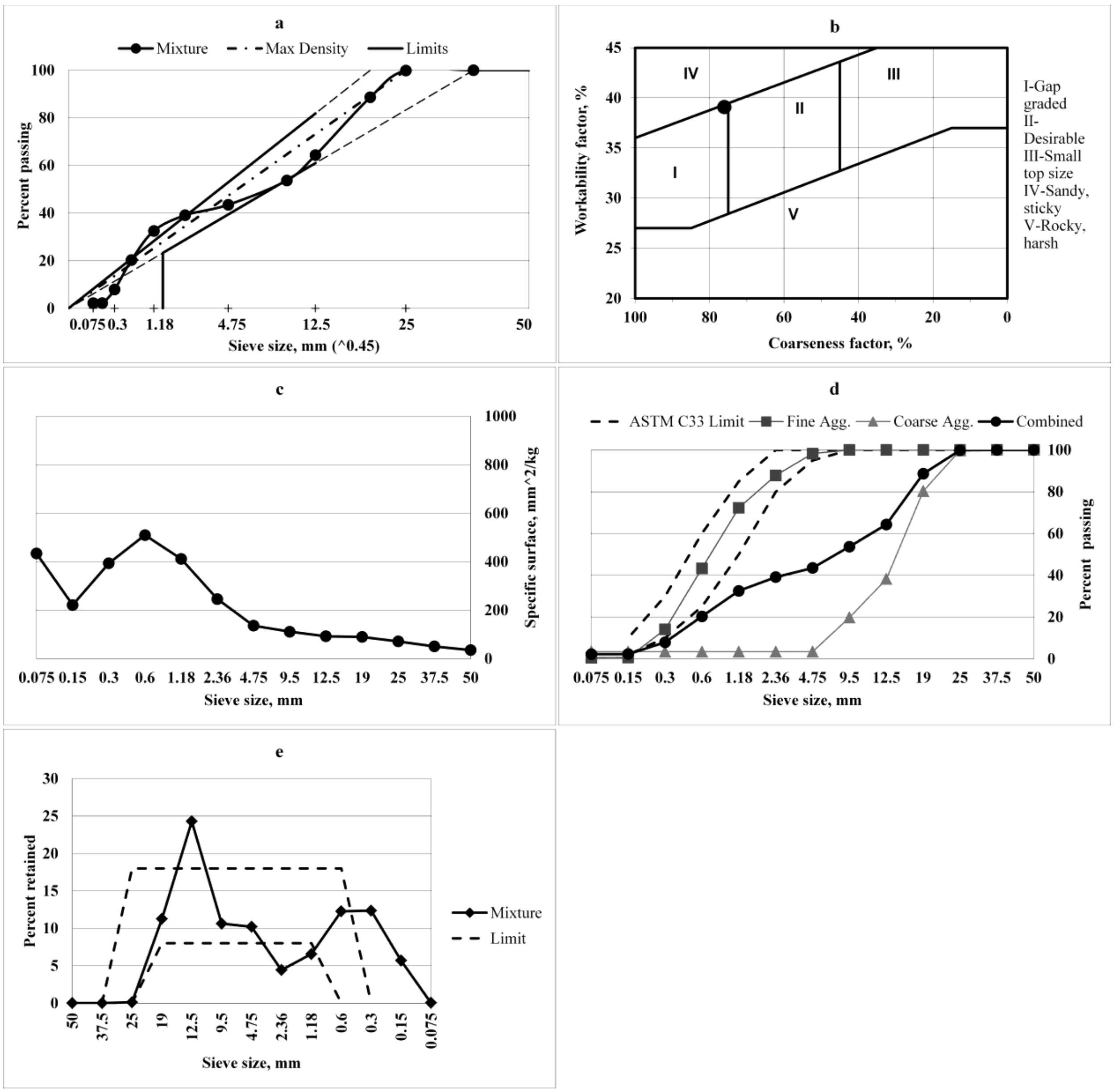


Figure 1. Combined aggregate gradation curves

The haystack plot did not present an ideal combination, but was the best combination that could be achieved with the materials available. While not ideal, this type of gradation is common in many concrete pavement mixtures, especially given the fact that, for concrete pavement mixtures, an aggregate distribution of 60% coarse aggregate and 40% fine aggregate, regardless of gradation and availability of aggregates, has been used as the norm (Ley et al. 2012). Therefore, the fine aggregate-to-total aggregate ratio of 0.42 is an appropriate combination for this research study.

Voids in the Selected Aggregate System

The voids in the combined aggregate system were determined following a modified version of the procedure in ASTM C29 (2009). The difference between ASTM C29 and the procedure followed in this study is that ASTM C29 calculates the void content for a single aggregate type (either for fine or coarse aggregate individually), whereas in this study combined aggregate systems were tested. The void percentage of the combined aggregates was kept constant at 19.8% (average value of three repeats) for all the mixtures based on the selected fine-to-total aggregate ratio of 0.42.

Selecting the Paste System

The variables used to investigate the paste system are summarized in Table 3. The ranges of variables were selected to include the extreme ends of the spectrum to clearly show their effects on the tested properties. The results are presented based on the parameter of V_{paste}/V_{voids} to determine the paste volume required to fill the voids between aggregate particles, coat the surfaces of the aggregates, and lubricate the aggregates to provide adequate workability.

Required Paste System for Desired Workability

It is a common practice to increase the workability by adding water to make the finishers' job easier. However, added water negatively affects the w/cm and decreases the resistance against segregation.

If high workability is desired, to maintain the required w/cm and prevent segregation, water-reducing admixtures (WRAs) may be used because they decrease the yield stress while having a minor effect on viscosity. However, Figure 2 illustrates that if there is insufficient water (paste) in the system, WRAs provide little benefit. When the water content was lower than 200 lb./yd.^{3}, all the mixes exhibited a 2 in. or lower slump, regardless of the cementitious materials type and WRA dosage. However, as the water content was increased above 200 lb./yd.^{3}, increasing water content increased slump, as expected. The degree of improvement for workability was affected by the type of the cementitious material and admixture dose.

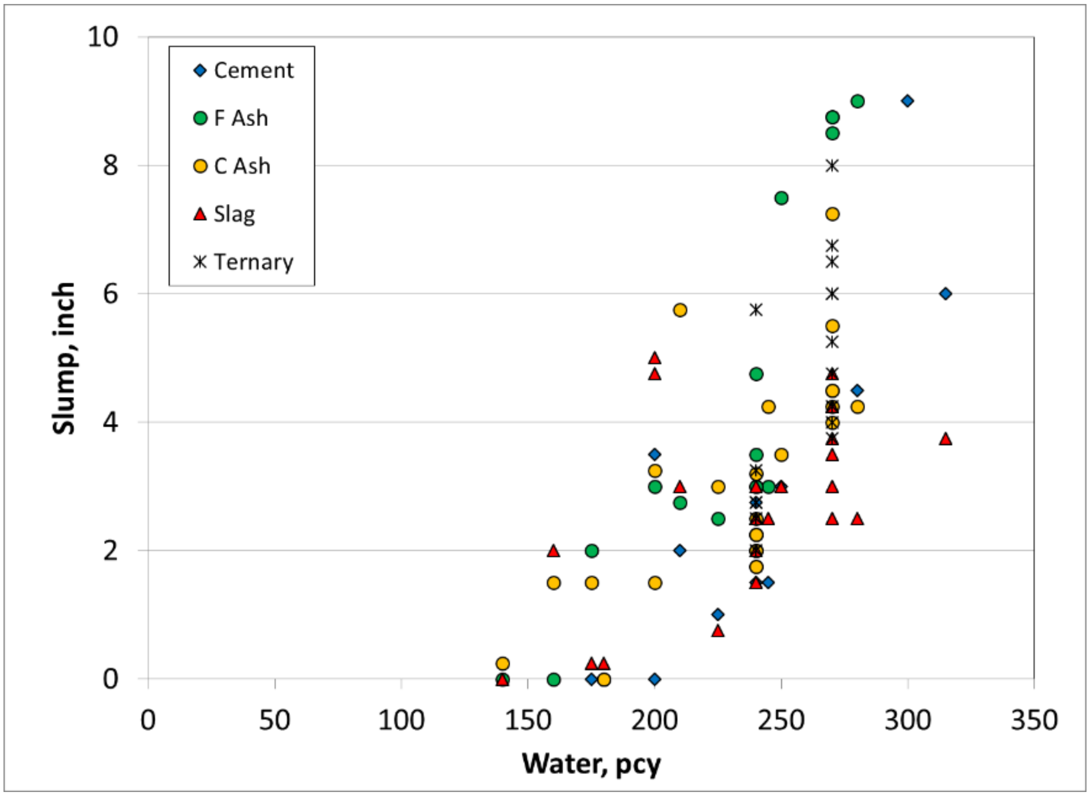


Figure 2. Effect of water content on workability

For concrete pavements, the desired slump often ranges between 1 and 3 in. Mixes performing within this range are presented in Figure 3.

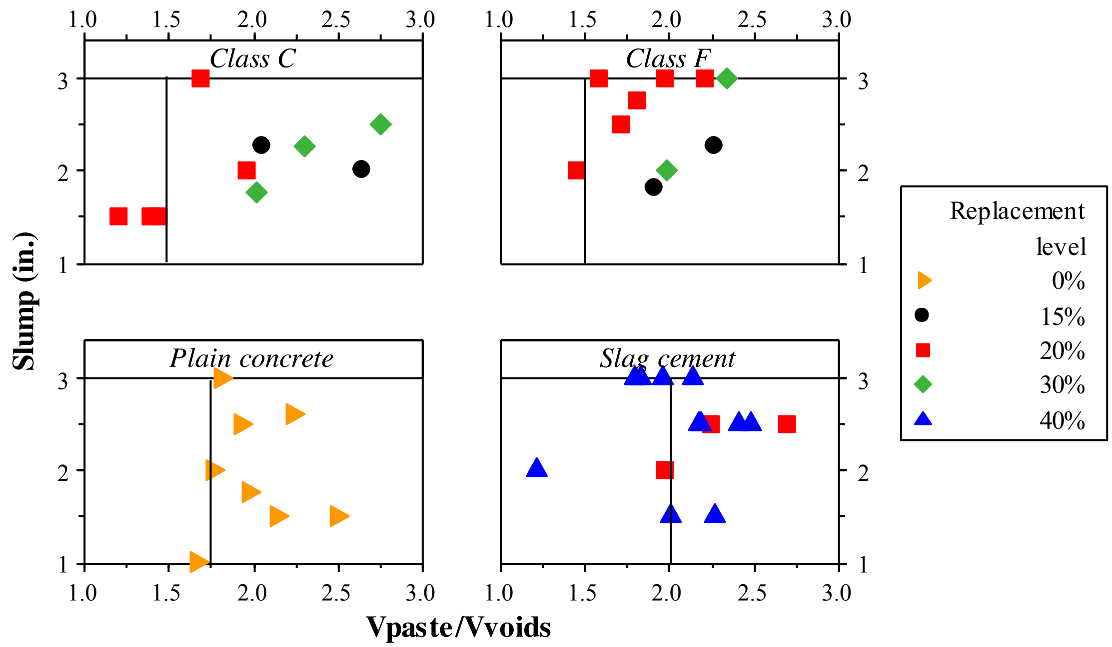


Figure 3. Required paste system for workability

The target slump was selected as 2 in., and HRWRA was added, as needed up to the manufacturer's maximum recommended dosage, to achieve the target slump. It was notable that a minimum amount of water was required in the system to achieve any workability. Only when that value was exceeded could the water-reducing admixtures be used to increase slump. Despite the addition of HRWRA and the use of SCMs, mixes having V_{paste}/V_{voids} lower than 1.25 resulted in zero slump. This indicates that a minimum of 1.25 times more paste than the voids between the aggregate particles is required to achieve a workable mix. Below this number, even a high dosage of HRWRA cannot contribute to workability due to an insufficient amount of paste (Figures 2 and 3). This is illustrated in the images of cylinders made from mixtures with increasing paste content in Figure 4. Those with insufficient paste could not be consolidated.

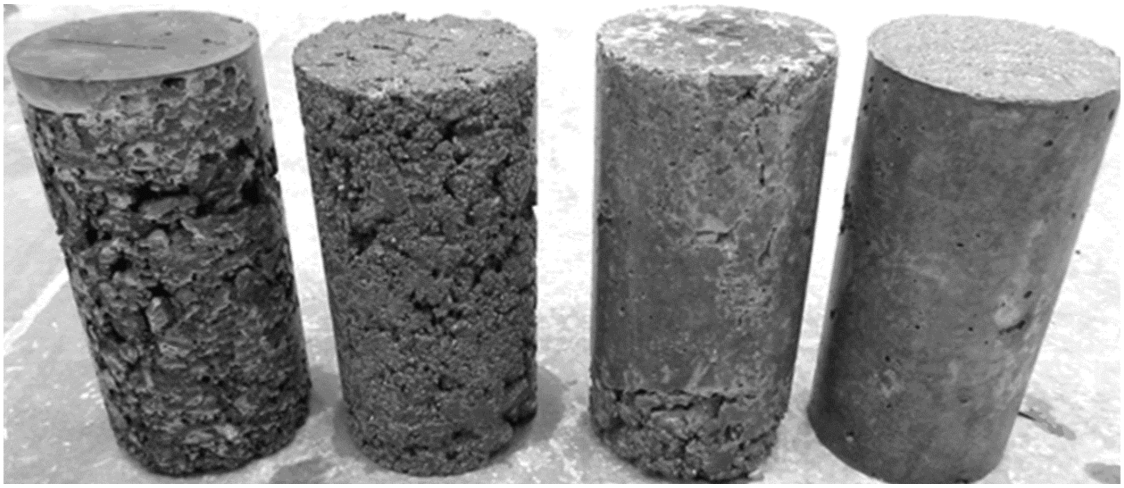


Figure 4. Cylinders made with mixtures with increasing cementitious content from 400 to 700 lb./yd.[3]

Depending on the SCM type and replacement level, V_{paste}/V_{voids} within the range of 1.5 to 2.5 is sufficient to provide the desired slump for concrete pavements for the aggregate systems tested in this study. In the plain concrete mixtures, this range was about 1.75 to 2.25. However, for mixtures containing fly ash, the V_{paste}/V_{voids} limit was decreased to 1.5 due to the beneficial effect of the fly ash. For mixes containing slag cement, the desired slump of 1 to 3 in. was obtained when V_{paste}/V_{voids} was around 2 to 2.5. Slag cement required slightly higher paste quantity to achieve the desired slump, likely due to higher fineness and thus higher water demand (Hale et al. 2008).

Required Paste System for Setting Time

From the contractor's point of view, initial set is important because it provides information regarding when the contractor can finish, texture, and saw-cut concrete pavements. The final set time is also important, because it indicates an estimate of the time when the pavement can sustain a certain degree of load. This study analyzed both the initial and final set time of mixes containing various types and amounts of SCMs to determine the required paste quantity for the desired set time. The test results of the initial and final set time are shown in Figures 5 and 6, respectively.

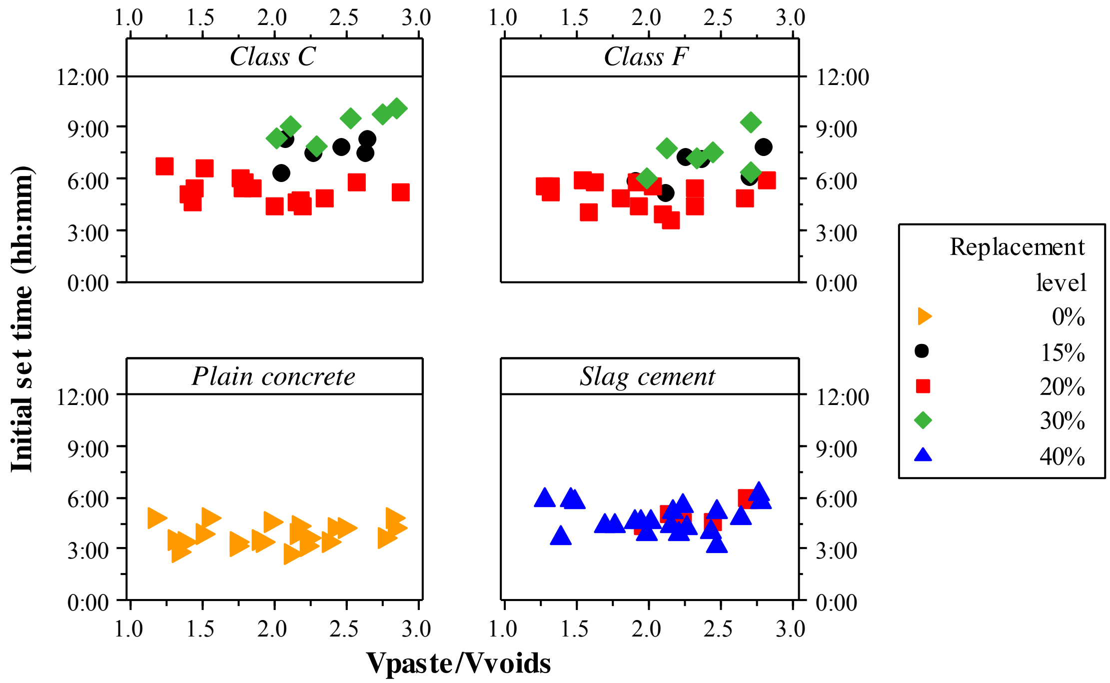


Figure 5. Required paste system for initial set time

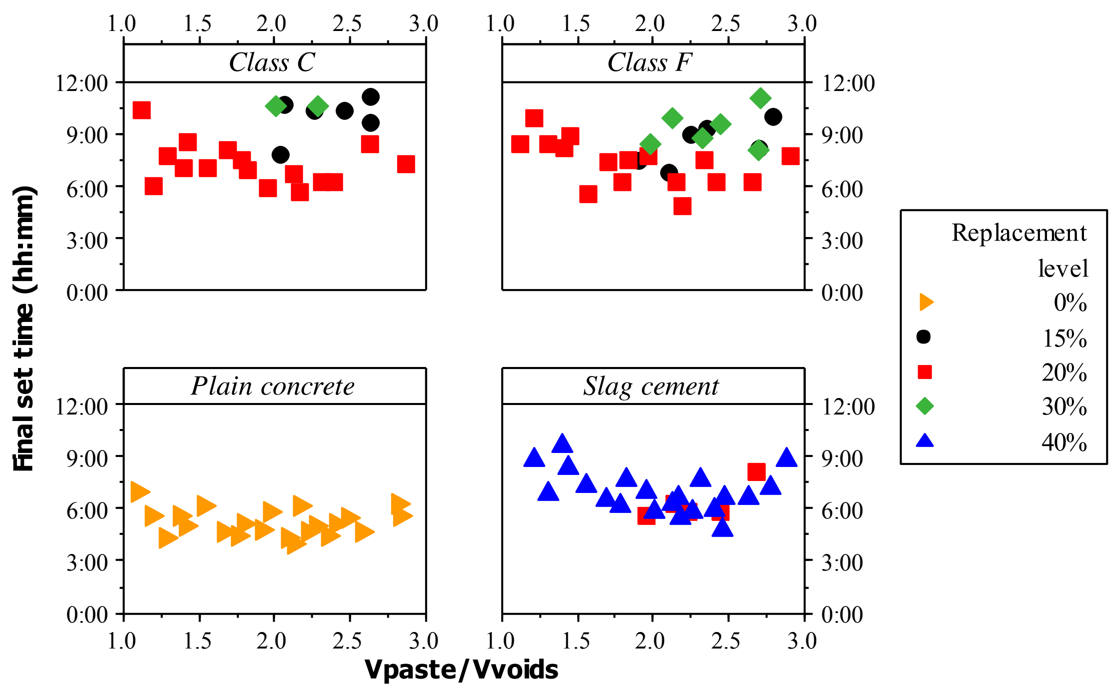


Figure 6. Required paste system for final set time

Figures 5 and 6 show that increasing the paste quantity did not affect set time. However, mixes where the paste quantity was increased due to increasing the w/cm exhibited higher setting time. This result is expected because it is well documented (Wenglas 2008, Schindler 2002) that increasing w/cm results in a greater distance between cement particles; thus, it takes longer for hydration products to interlock.

The addition of both Class C and Class F fly ashes increased the setting time compared to the control mixture, likely as a result of their dilution of the portland cement (Fajun et al.1985). Therefore, mixtures containing fly ash could be used in hot weather concrete pavements because the addition of fly ash may help lower the rate of setting. However, they should be used carefully in cold weather because their use would result in delaying the finishing operation and opening to traffic (Juenger et al. 2008). On the other hand, the addition of slag cement resulted in similar setting times to the control mixture. This result is consistent with the literature (Tikalsky et al. 2011).

Although changing the replacement level of SCM slightly affected the set time of concrete having Class C and Class F fly ashes, it did not affect the slag mixtures. This information is consistent with the finding by Hooton (2000) that slag does not delay setting above the threshold temperature of 68°F (20°C). Further increasing the paste quantity did not significantly affect the set time.

Required Paste System for Compressive Strength

The 28-day compressive strength data is presented in Figure 7.

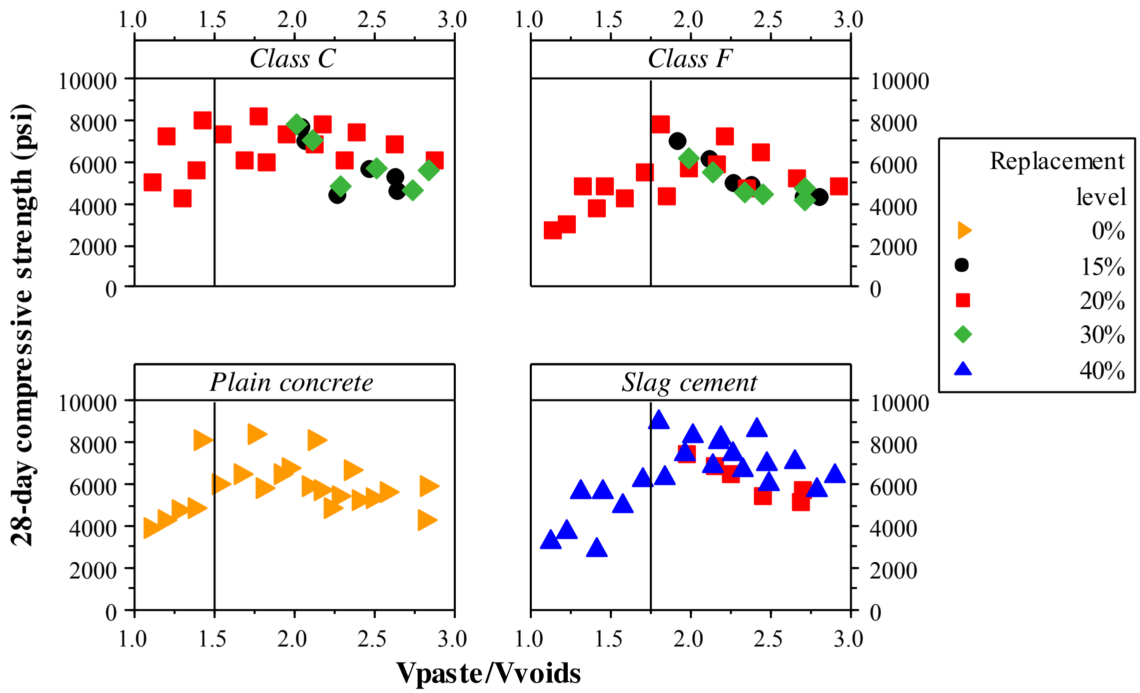


Figure 7. Required paste system for 28-day compressive strength

As shown, increasing paste content increased strength up to a plateau, after which strength was not improved by further increasing the paste content. In some cases, increasing paste content slightly decreased the compressive strength, likely due to not all of the cementitious materials participating in the pozzolanic reaction (Liu et al. 2012). Therefore, this elbow-shaped trend shows that there is a need to determine the V_{paste}/V_{voids} to ensure that strength is not being compromised by further increasing the paste content.

The mixtures containing Class C fly ash exhibited similar strengths to the control mixtures at 28 days. However, due to the slow pozzolanic reactivity of Class F fly ash, they exhibited lower 28-day compressive strengths compared to the control mixtures. Similarly, increasing the slag cement replacement dosage did not significantly affect the 28-day compressive strength (Hooton 2000). Increasing the replacement level of fly ash also did not significantly affect the compressive strength.

For concretes containing plain portland cement or portland cement with Class C fly ash, strength continues to increase as the paste volume increases until V_{paste}/V_{voids} reaches about 1.50. For mixes including slag cement or Class F fly ash, strength continues to increase until V_{paste}/V_{voids} reaches about 1.75 to 2.0. This is because there is a need for sufficient paste content to fully coat the aggregates and lubricate them. However, after exceeding a V_{paste}/V_{voids} value of 2, strength begins decreasing with a further increase in paste quantity. Therefore, the paste volume should not be more than double the voids volume within the combined aggregate system to achieve the desired strength for pavements.

Required Paste System for Chloride Penetration Resistance

The effect of the paste system on 28-day and 90-day rapid chloride penetration is presented in Figure 8.

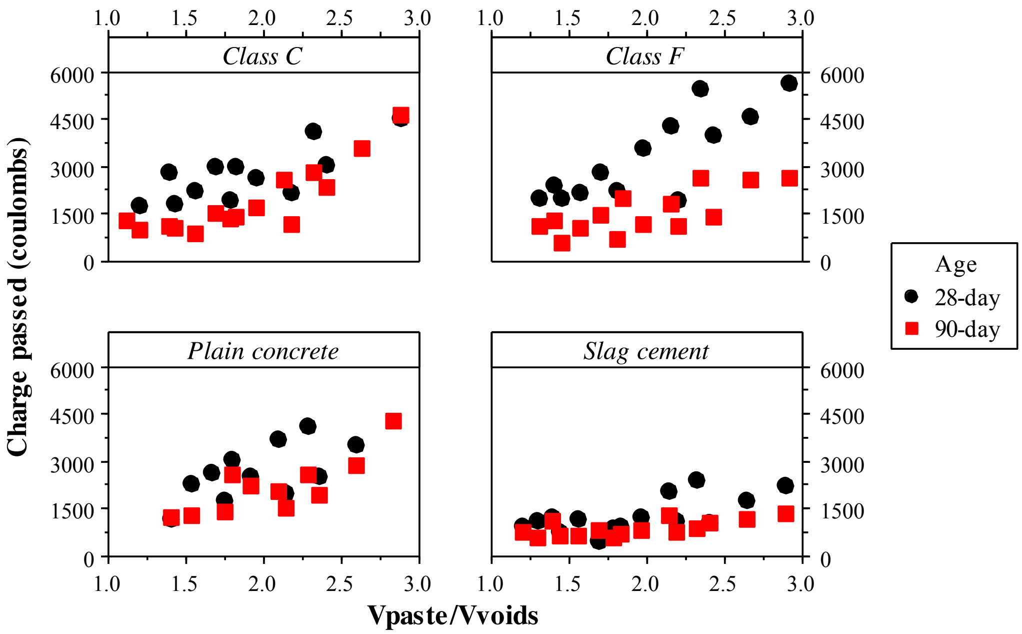


Figure 8. Required paste system for 28-day and 90-day chloride penetration resistance

Hydration and the incorporation of SCMs, especially at later ages, helped to fill some of the capillary voids and reduce penetrability. The mixtures containing slag cement exhibited the lowest penetration compared to the plain mixes at 28 days. This is likely because slag cement immobilizes the chloride ions by binding with them (Soutsos 2010). Mixes with Class C fly ash and Class F fly ash did not exhibit improved resistance against chloride penetration at 28 days, likely due to the initially slower hydration rate of fly ash. However, at 90 days, plain concrete showed higher penetrability than mixtures with Class F fly ash. This result is not surprising because increasing the testing age of the mixes incorporating SCMs reduces the porosity of the concretes as a result of the continued pozzolanic reaction (Bagheri and Zanganeh 2012, Liu et al. 2012). Fly ash produces its beneficial effects by combining with the calcium hydroxide, converting it to more durable calcium silicates, and reducing permeability through denser packing (Soutsos 2010). Fly ash also contains oxides of alumina, which are able to bind chloride ions. The reduction in penetration of concretes containing SCMs may also be due to their contribution to improving the interfacial transition zone between the cement paste and aggregates (Toutanji et al. 2004).

Increasing V_{paste}/V_{voids} increased the chloride penetrability, which is consistent with the literature (Arachchige 2008). This can be explained by the differences between aggregate and paste. In general, aggregates are likely to be denser than cement paste (especially at early ages) and have a lower permeability than cement paste, so concretes with low paste content tend to have lower permeability, despite the introduction of the more porous interfacial transition zones (Scrivener and Nemati 1996). Therefore, it is ideal to keep the V_{paste}/V_{voids} at a (practical) minimum from a durability perspective.

Required Paste System for Air Permeability Resistance

Air permeability index is the negative log of the Darcy coefficient of permeability (m/s), and it uses a log scale (Buenfeld and Okundi 2000). Therefore, lower air permeability index indicates higher permeability. As reported by Alexander and Beushausen (2010), the following interpretation can be applied to the results:

- API >10.0 – Excellent
- 9.5< API<10.0 – Good
- 9.0< API<9.5 – Poor and
- API < 9.0 – Very poor

The effect of the paste system on 28-day and 90-day air permeability is presented in Figure 9.

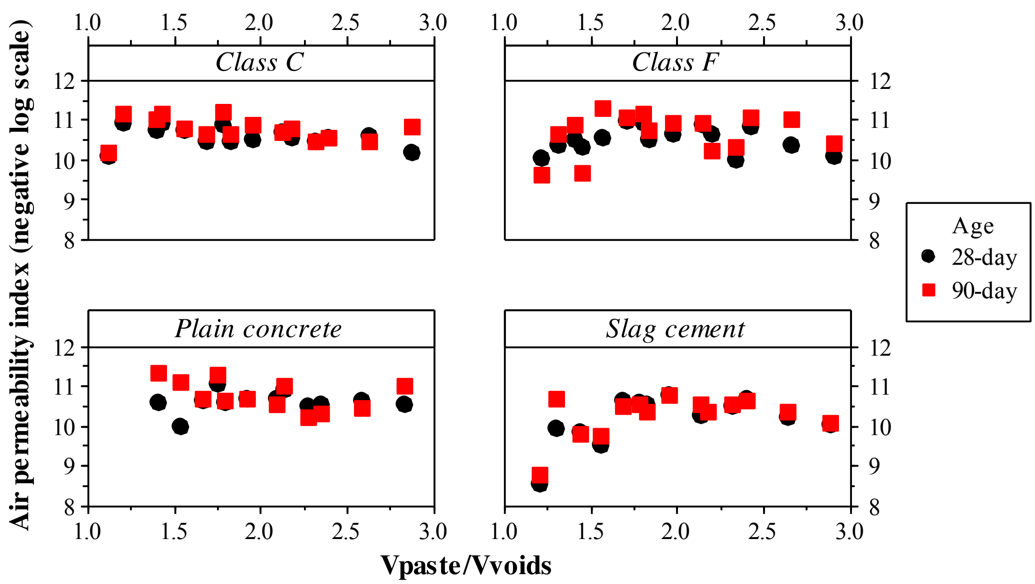


Figure 9. Required paste system for resistance against 28-day and 90-day air permeability

Figure 9 shows that, for mixes containing Class F fly ash or slag cement, increasing paste volume above a certain value decreased permeability. When V_{paste}/V_{voids} was increased from 1 to 2, air permeability decreased, likely because the mixtures with a low cementitious materials content had macro porosity. This result is consistent with the findings in the literature that compaction plays a more critical role than concrete microstructure on air permeability (Buenfeld and Okundi 2000). Once the required paste content (V_{paste}/V_{voids} of 2) was provided, further increasing the paste content slightly increased permeability because air tends to penetrate through the relatively porous paste faster than through aggregates. The replacement of ordinary portland cement with various types of SCMs does not appear to have had a significant effect on air permeability. However, as concrete age increases, concrete becomes less permeable because cement hydration continues over time and the pore sizes get smaller.

Summary

Based on the data reported above, the following conclusions can be drawn:

- A minimum void ratio of about 125% to 150% is suggested to achieve a minimum workability for the aggregates tested in this study.
- The void ratio to achieve strength efficiently is between 125% and 175%. Excess paste appears to lead to reduced strength.
- Increasing paste appears to reduce durability.
- The measured performance of supplementary cementitious materials in binary and ternary systems was consistent with findings reported in the literature.

LABORATORY WORK – PHASE 2, EFFECTS OF THE AGGREGATE SYSTEM

The second phase of the laboratory work involved conducting a more limited suite of tests to assess the effects of different aggregate systems. The only properties measured were those related to workability on the basis that the hardened properties of a mixture are primarily governed by the paste quality.

Cementitious Materials

The cementitious materials used in this phase of the work are described in Table 5.

Table 5. Chemical composition of cementitious materials

Chemical composition	Type I/II cement, %	Class C fly ash, %
SiO_2	20.10	36.71
Al_2O_3	4.44	19.42
Fe_2O_3	3.09	6.03
SO_3	3.18	1.97
CaO	62.94	25.15
MgO	2.88	4.77
Na_2O	0.10	1.64
K_2O	0.61	0.46
P_2O_5	0.06	0.84
TiO_2	0.24	1.84
SrO	0.09	0.32
BaO	-	0.67
LOI	2.22	0.18

Aggregates

Two types of coarse aggregates were selected to represent commonly used aggregate types: rounded gravel and crushed limestone.

Three nominal maximum sizes were obtained of each type: ¾ in., 1 in. and 1½ in. as coarse aggregate. A single natural fine aggregate was obtained from a local supplier. The gradations of aggregate are shown in Table 6 and Figure 10.

In the following graphs, mixes are shown based on their constituent aggregate type (designated "G" for gravel and "LS" for limestone) and the nominal maximum size of aggregate (¾ in., 1 in., or 1½ in.).

Table 6. Gradations of coarse and fine aggregate

Sieve size		Cumulative percent passing						
		Limestone			Gravel			Sand
No.	**mm**	**1½ in.**	**1 in.**	**¾ in.**	**1½ in.**	**1 in.**	**¾ in.**	**N/A**
1½ in.	**37.5**	96.2	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	**25.0**	27.9	99.3	100.0	59.2	100.0	100.0	100.0
¾ in.	**19.0**	3.6	74.9	98.1	15.5	82.0	94.6	100.0
½ in.	**12.5**	0.6	37.0	56.6	4.0	37.0	62.2	100.0
$^3/_8$ in.	**9.5**	0.4	19.2	24.7	1.0	13.0	41.2	100.0
#4	**4.75**	0.3	2.7	2.5	0.3	0.6	8.5	98.9
#8	**2.36**	0.3	0.7	0.6	0.0	0.2	1.0	92.4
#16	**1.18**	0.2	0.5	0.5	0.0	0.2	0.0	77.5
#30	**0.60**	0.2	0.4	0.4	0.0	0.1	0.0	47.7
#50	**0.30**	0.2	0.4	0.4	0.0	0.1	0.0	11.0
#100	**0.15**	0.2	0.3	0.4	0.0	0.1	0.0	0.8
#200	**0.075**	0.2	0.3	0.0	0.0	0.1	0.4	0.0
Specific gravity		2.67	2.68	2.66	2.71	2.72	2.72	2.66

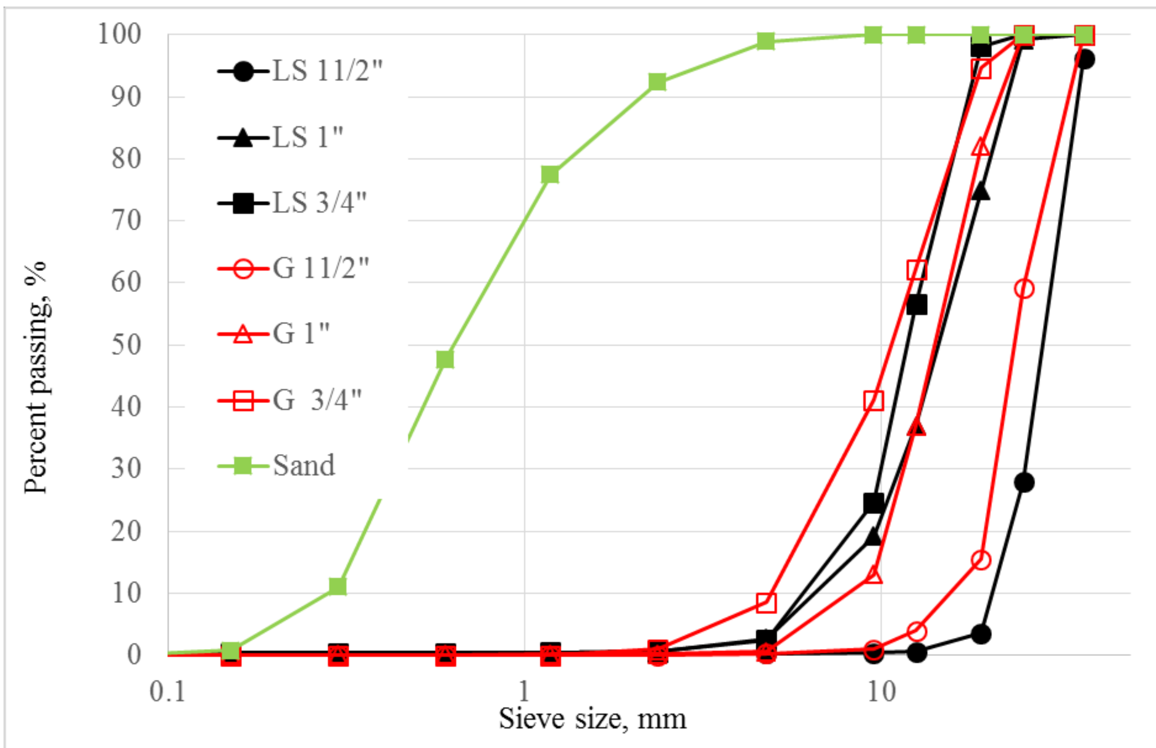


Figure 10. Gradations of coarse and fine aggregate

Four different gradations were prepared from each of the types and sizes:

- A blend of a single coarse and fine combination at proportions selected to come as close as possible to the power 45 curve without re-sieving
- Blends and re-sieved samples to get as close as possible to the power 45 curve
- Blends and re-sieved samples to be close to the power 45 curve while staying within a Tarantula envelope (Ley et al. 2012)
- An arbitrary 50/50 blend of coarse and fine with the intention of representing a poor gradation

A total of 12 different aggregate combinations were prepared for a given aggregate type, as shown in Table 7.

Table 7. Aggregate combinations

	Nominal maximum size of aggregates		
Aggregate type	¾ in.	1 in.	1½ in.
Gravel	G0.75 Plain	G1.0 Plain	G1.5 Plain
	G0.75 ^45	G1.0 ^45	G1.5 ^45
	G0.75 Tarantula	G1.0 Tarantula	G1.5 Tarantula
	G0.75 50/50	G1.0 50/50	G1.5 50/50
Limestone	LS0.75 Plain	LS1.0 Plain	LS1.5 Plain
	LS0.75 ^45	LS1.0 ^45	LS1.5 ^45
	LS0.75 Tarantula	LS1.0 Tarantula	LS1.5 Tarantula
	LS0.75 50/50	LS1.0 50/50	LS1.5 50/50

Chemical Admixtures

A commercial vinsol-based air-entraining admixture was the only chemical admixture used in this phase.

Tests

The initial aim of the work was to determine the effect of different gradation systems on the voids in the combined material. All of the combinations were tested in accordance with ASTM C29 (2009) to determine their voids content.

The second aim of the work was to observe the effects of gradation on concrete workability. The following four systems were selected for testing in concrete mixtures:

- G1.0 Tarantula
- G1.0 50/50
- LS1.0 Tarantula
- LS1.0 50/50

Each mixture was tested with V_{paste}/V_{voids} of 1.25, 1.50, and 1.75, achieved by adding paste to each mixture after the suite of tests was conducted. In many cases, mixtures with V_{paste}/V_{voids} of 1.75 were not tested because the slump of those mixes already exceeded the maximum target value of 2 in. Care was taken to return all of the materials to the mixer after testing. All rounds of tests were completed within 90 minutes of initial mixing. The following tests were conducted:

- Slump (ASTM C 143)
- Air content (ASTM C 231)
- Box (Cook et al. 2013). A visual rating of 2 or less is considered acceptable.
- VKelly (Taylor et al. 2015). A VKelly Index of 0.8 in./√in. is considered acceptable.

Results

The voids in the aggregate systems (V_{voids}) are shown in Table 8.

Table 8. The voids in the aggregate systems, %

	Plain	^45	Tarantula	50/50
LS0.75	27.4	28.0	27.3	27.7
LS1.0	26.6	28.9	26.3	27.5
LS1.5	27.9	27.3	27.7	25.2
G0.75	26.3	26.7	26.7	26.7
G1.0	25.3	26.4	25.3	27.1
G1.5	25.6	26.4	24.7	24.7

The test results for the concrete mixtures are shown in Table 9, Figures 11 and 12, and Appendix A.

Table 9. Test results

	G1.0 50			LS1.0 50			G1.0 Tarantula		LS1.0 Tarantula	
Void Ratio	125	150	175	125	150	175	125	150	125	150
Cementitious, lb./yd.^{3}	424	500	543	462	544	617	427	505	444	524
Air content, %	8.0	5.1	3.9	5.0	5.8	4.8	3.4	3.5	4.9	4.4
Slump, inch	0.5	0.75	1	1	3	7	1	1.75	3	4
Box, VR	4	4	3	4	2	4	2	2	2	1
V-Kelly, in/√s	0.38	0.52	0.65	0.75	0.92		0.81	1.18	1.05	1.34

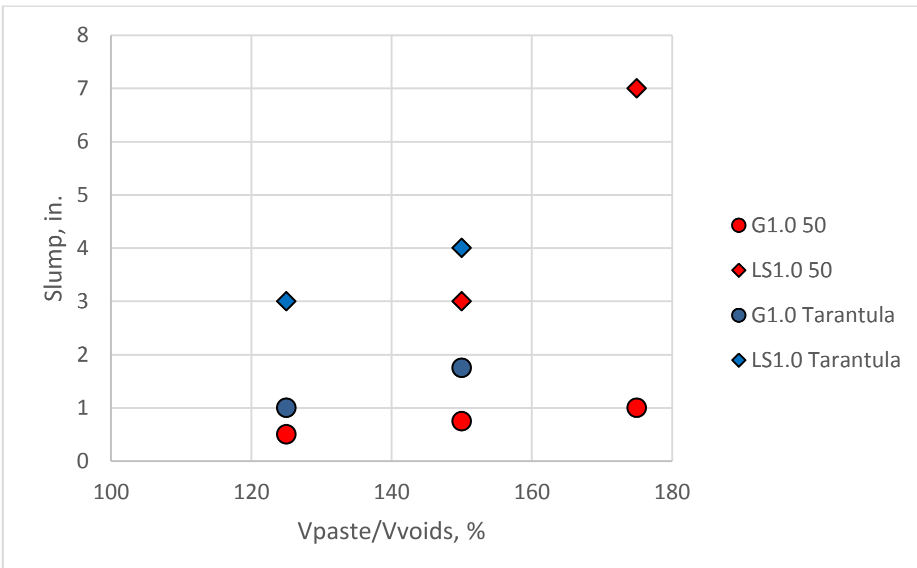


Figure 11. Slump versus V_{paste}/V_{voids}

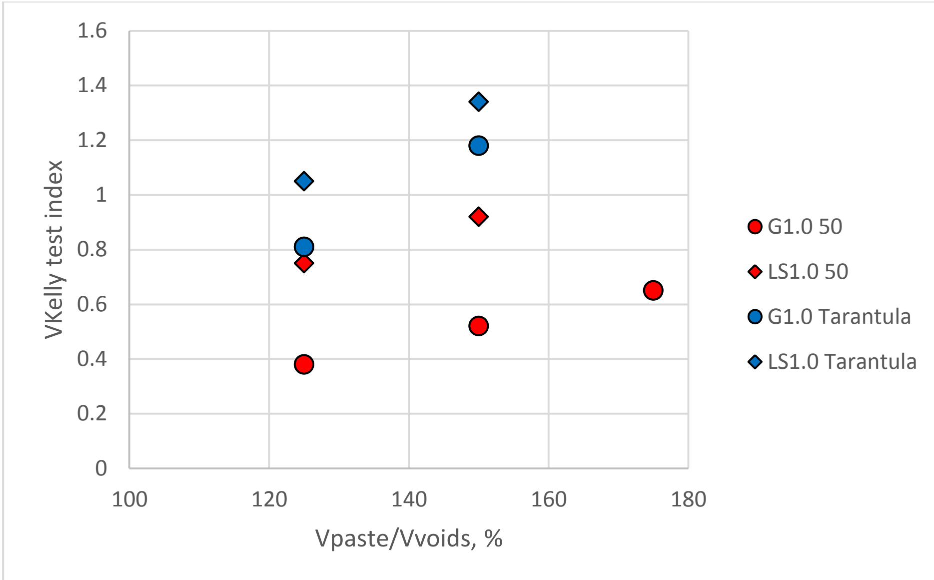


Figure 12. VKelly test index versus V_{paste}/V_{voids}

Discussion

The results of the voids tests were somewhat surprising. The range between the highest and lowest voids for a given nominal size were smaller than expected, considering that the void content of the aggregate system tested in Phase 1 was significantly lower at about 19%. The ranking of the different combinations was also unexpected in that the ^45 combinations did not always give the lowest voids.

The mixture test results were also enlightening. The void ratio required to achieve a workability appropriate for slip-form paving was about 1.25 for the good gradations and 1.75 for the poor gradations for the mixtures tested. This finding supports the concept that the minimum required paste content depends on other factors, such as the aggregate shape.

A satisfactory workability for the well-graded systems was achieved with significantly lower paste contents than for the poor gradations. The data support the contention that the Tarantula Curve provides an effective guideline for selecting a combined aggregate gradation.

A surprising result was that crushed limestone yielded higher workability than the gravel systems. Also notable is that the slope of the lines are steeper for the limestone mixtures are steeper than the gravel, meaning that as paste content increases the response to vibration increases more for limestone. No explanation has been developed for these observations. It can be noted that the same fine aggregate was used in both mixtures, which is the ingredient that likely dominates effects on workability.

Conclusions

Based on the observations in this phase, the following conclusions may be drawn:

- The voids in different aggregate sizes and types should be measured.
- The required void ratio varies depending on the aggregate system available, but a good starting point for trial batches is about 1.25.
- Increasing paste content increases workability, as expected, albeit at different rates for different aggregate systems.

MIXTURE PROPORTIONING METHOD

The data collected in Phases 1 and 2 have supported the proportioning concept discussed above:

- Select an appropriate aggregate gradation system. Current recommendations are to stay within the Tarantula Curve while trying to stay close to the power 45 curve. A spreadsheet tool has been developed that allows the best combination of up to three aggregates to be obtained based on input sieve analyses using the solver function. Having determined the desired aggregate system, measure the voids volume (V_{voids}) for the combination in the laboratory.
- Select the paste parameters to achieve the desired strength- and durability-related performance:
    - Binder type and percentages
    - Air content
    - w/cm

  Select an initial V_{paste}/V_{voids} value as an input, probably in the range 1.25 to 1.75. These parameters are entered into the second page of the spreadsheet.
- Calculate the paste content and aggregate content based on all the parameters determined above. This is achieved using another solver function on the third page of the spreadsheet. The output from the spreadsheet is a set of mixture proportions in lb./yd.^{3}, excluding admixture dosages.
- Prepare trial batches to assess fresh properties and adjust V_{paste}/V_{voids} and admixture dosages as necessary. Prepare a final trial batch and measure hardened properties.

Screenshots from the spreadsheet pages are shown in Figures 13 to 15.

Aggregate System

National Concrete Pavement Technology Center
CP Tech Center

IOWA STATE UNIVERSITY
Institute for Transportation

Project	**Gravel 1"**	**12/11/2014**	
Materials		**Blue= Input Data**	
		Red = Calculation	Don't touch!
Cementitious	428	Yellow = Output	Don't touch!
Coarse Agg	Gravel	Black = Working	Don't touch!
Fine Agg	River		
Intermediate			

Sieve Analysis Data

Max nominal aggregate size **1.00** inch (0.75, 1.0 or 1.5)

	Coarse	Gravel	Fine	River	Intermediate	0	Combined			Fineness
							Percent	Cum.	Sieve	Modulus
Percent mass 100.0		64.3		35.7		0.0	Passing	Retained	Retained	
Sieve:	% Pass	% Mix	% Pass	% Mix	% Pass	% Mix	%	%	%	
2"	100.0	64.3	100.0	35.7	0.0	0.0	100.0	0.0	0.0	
1 1/2"	100.0	64.3	100.0	35.7	0.0	0.0	100.0	0.0	0.0	
1"	100.0	64.3	100.0	35.7	0.0	0.0	100.0	0.0	0.0	
3/4"	82.0	52.7	100.0	35.7	0.0	0.0	88.4	11.6	11.6	
1/2"	55.0	35.3	100.0	35.7	0.0	0.0	71.1	28.9	17.4	
3/8"	30.0	19.3	100.0	35.7	0.0	0.0	55.0	45.0	16.1	0.0
# 4	5.0	3.2	98.9	35.3	0.0	0.0	38.5	61.5	16.5	1.1
# 8	0.2	0.1	92.4	33.0	0.0	0.0	33.1	66.9	5.4	7.6
# 16	0.2	0.1	77.5	27.7	0.0	0.0	27.8	72.2	5.3	22.5
# 30	0.1	0.1	47.7	17.1	0.0	0.0	17.1	82.9	10.7	52.3
# 50	0.1	0.1	11.0	3.9	0.0	0.0	4.0	96.0	13.1	89.0
# 100	0.1	0.1	0.8	0.3	0.0	0.0	0.4	99.6	3.7	99.2
# 200	0.1	0.1	0.0	0.0	0.0	0.0	0.1	99.9	0.3	
					0	0				2.72

Coarsness Factor	67.29	Power 45 least difference	0.0	Tarantula error	0.0
Workability Factor	33.14	Power 45 error	34.2		
Adjustments	0.00				
Adjusted Workability Factor	33.14				

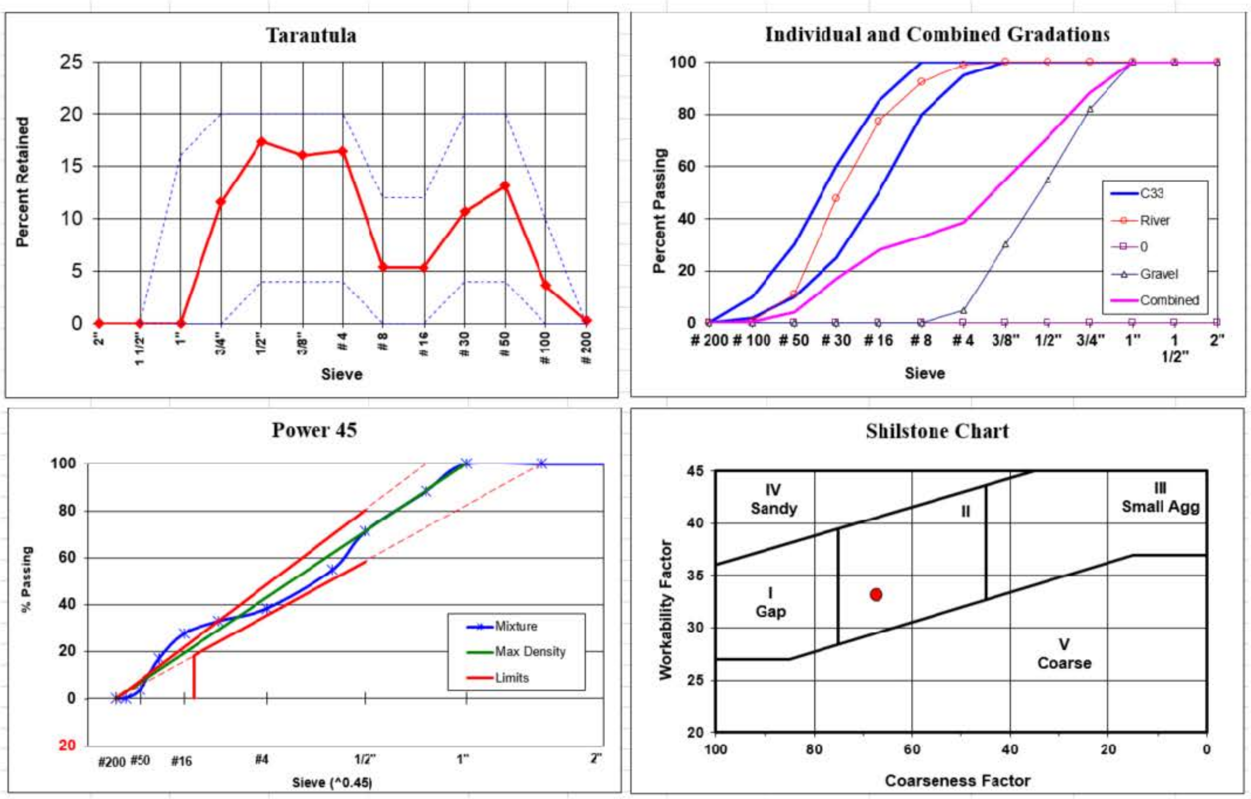


Figure 13. Screenshots from the spreadsheet pages for the aggregate system

		Paste Quality		
Project	**Gravel 1"**		**12/11/2014**	
Materials				
		Targets		
			R.D.	
Cement	**Type I**		3.15	
SCM 1	**F Ash**		**2.65**	
SCM 2	**Slag**		**1.00**	
Coarse Agg	**Gravel**		**2.72**	
Fine Agg	**River**		**2.66**	
Intermediate	**0**		**1.00**	
Water			1.00	
Cementitious		428	pcy	
w/cm		**0.42**		
Air %		**5.0**	%	
% SCM 1		**20**	%	
% SCM 2		**0**	%	
Voids in aggregate		**25.3**	%	
Required Vp/Vv		**125**	%	
Strength		4000	psi	7 days
RCP		1500	coulomb	56 days
Wenner		27	kΩ-cm	28 days

Figure 14. Screenshot from the spreadsheet pages for paste quality

		Mixture Proportions			
Project	**Gravel 1"**		**12/11/2014**		
Mixture Proportions					
		Targets		**Actual**	
			Pounds	R.D.	Volume
Cement	Type I		342	3.15	1.74
SCM 1	F Ash		86	2.65	0.52
SCM 2	Slag		0	1.00	0.00
Coarse Agg	Gravel		2220	2.72	13.08
Fine Agg	River		1234	2.66	7.43
Intermediate	0		0	1.00	0.00
Water			180	1.00	2.88
Air %			5.0		1.35
			4061		27.00
Cementitious		428	428	pcy	
Volume of paste			24.0	%	
Volume of aggs			76.0	%	
Volume of voids			19.2	%	
vp/vv		125	125.0	%	
w/cm		0.42	0.42		
% SCM 1		20	20	%	
% SCM 2		0	0	%	
Mass aggs		3454	3454	pcy	

Figure 154. Screenshot from the spreadsheet pages for mixture proportions

CONCLUSIONS

Laboratory work has provided data to support an innovative proportioning approach based on the following steps:

- Select a combined aggregate gradation to achieve workability and density.
- Select the paste to achieve desired hardened properties (air void system, w/cm, and binder system).
- Select a void ratio to achieve workability as determined in trial batches.

A spreadsheet has been developed that aids in conducting these steps.

REFERENCES

Abrams, D. A., (1920). *Design of concrete mixtures*. Structural Materials Research Laboratory, Lewis Institute, Chicago.

Alexander, M. G., and Beushausen, H. (2010). "Durability design of reinforced concrete structures." Concrete Technology for Structural Engineers Workshop, South Africa.

Alexander, M., and Mindess, S. (2005). *Aggregates in concrete*. Taylor & Francis, NY.

Arachchige, A. D. M. (2008). "Influence of cement content on corrosion resistance." *Proceedings of the ICE – Construction Materials*, 161, 31–39.

Ashraf, W. B., and Noor, M. A. (2011). "Performance-evaluation of concrete properties for different combined aggregate gradation approaches." *The Proceedings of the Twelfth East Asia-Pacific Conference on Structural Engineering and Construction—EASEC12*, 14(2011), 2627–2634.

Bagheri, A. R., and Zanganeh, H. (2012). "Comparison of rapid tests for evaluation of chloride resistance of concretes with supplementary cementitious materials." *Journal of Materials in Civil Engineering*, 24(9), 1175–1182.

Battelle Memorial Institute. (2002). *Towards a sustainable cement industry*. World Business Council for Sustainable Development.

Bickley, J., Hooton, D., and Hover, K.C. (2010). "Chapter 12. Issues related to performance-based specifications for concrete." *Concrete durability: a practical guide to the design of durable concrete structures*, M. Soutsos, ed., Thomas Telford, London.

Buenfeld, N., and Okundi, E. (2000). "Effect of cement content on transport in concrete." *Magazine of Concrete Research*, 52, 73–76.

Bureau of Public Roads. (1962). *Aggregate gradation for highways: aggregate gradation, simplification, standardization and uniform application; and, a new graphical chart for evaluating aggregate gradation*. U.S. Bureau of Public Roads, Washington, DC.

Chamberlin, W. P. (1995). *Performance-related specifications for highway construction and rehabilitation*. NCHRP 212. Transportation Research Board, Washington, DC.

Cook, D., Ghaeezadeh, A., Ley, T., and Russell, B. (2013). *Investigation of optimized graded concrete for Oklahoma–Phase I*. Oklahoma State University, OK.

Day, K. W. (2006). *Concrete mix design, quality control and specification*. 3rd ed. Taylor & Francis, NY.

Delatte, N. (2007). *Concrete pavement design, construction, and performance*. Taylor & Francis, NY.

Dhir, R. K., McCarthy, M. J., Zhou, S., and Tittle, P. A. J. (2004). "Role of cement content in specifications for concrete durability: cement type influences." *Structures and Buildings*, 157(2), 113–127.

Dhir, R. K., McCarthy, M. J., Zhou, S., and Tittle, P. A. J. (2006). "Discussion: Role of cement content in specifications for concrete durability: aggregate type influences." *Structures and Buildings*, 159, 361–363.

Fajun, W., Grutzeck, M. W., and Roy, D. M. (1985). "The retarding effects of fly ash upon the hydration of cement pastes: the first 24 hours." *Cement and Concrete Research*, 15, 174–184.

Falker, E. M. (2003). Assessing the impact of performance-related specifications on concrete pavement construction. Master of Science thesis, Purdue University.

Ferraris, C. F., and Gaidis, J. M. (1992). “Connection between the rheology of concrete and rheology of cement paste.” *ACI Materials Journal*, 88, 388–393.
Grove, J., and Taylor, P. (2012). “Will more cement in your mixture hurt you?” 10th International Conference on Concrete Pavements, International Society for Concrete Pavements, Quebec, Canada.
Hale, W. M., Freyne, S. F., Bush Jr. T., D., and Russell, B. W. (2008). “Properties of concrete mixtures containing slag cement and fly ash for use in transportation structures.” *Construction and Building Materials*, 22, 1990–2000.
Hendriks, C. A., Worrell, E., de Jager, D., Blok, K., and Riemer, P. (2004). “Emission reduction of greenhouse gases from the cement industry.” Greenhouse Gas Control Technologies Conference, UK.
Hooton, R. D. (2000). “Canadian use of ground granulated blast-furnace slag as a supplementary cementing material for enhanced performance of concrete.” *Canadian Journal of Civil Engineering*, 27, 754–760.
Hooton, R. D., and Bickley, J. A. (2012). “Prescriptive versus performance approaches for durability design – The end of innocence?” *Materials and Corrosion*, 63(12), 1097–1101.
Hu, J., and Wang, K. (2007). “Effects of size and uncompacted voids of aggregate on mortar flow ability.” *Journal of Advanced Concrete Technology*, 5, 75–85.
Hu, J., and Wang, K. (2011). “Effect of coarse aggregate characteristics on concrete rheology.” *Construction and Building Materials*, 25(3), 1196–1204.
Jamkar, S. S., and Rao, C. B. K. (2004). “Index of aggregate particle shape and texture of coarse aggregate as a parameter for concrete mix proportioning.” *Cement and Concrete Research*, 34, 2021–2027.
Ji, T., Lin, T., and Lin, X. (2006). “A concrete mix proportion design algorithm based on artificial neural networks.” *Cement and Concrete Research*, 36, 1399–1408.
Johari, M. A. M., Brooks, J. J., Kabir, S., and Rivard, P. (2011). “Influence of supplementary cementitious materials on engineering properties of high strength concrete.” *Construction and Building Materials*, 25, 2639–2648.
Juenger, M., Won, M., Fowler, D., Suh, C., and Edson, A. (2008). *Effects of supplementary cementing materials on the setting time and early strength of concrete*. FHWA/TX-08/0-5550-1 Report. Center for Transportation Research, The University of Texas at Austin, TX.
Kennedy, C. T. (1940). “The design of concrete mixes.” *Journal of the American Concrete Institute*, 36, 373–400.
Kim, D. K., Lee, J. J., Lee, J. H., and Chang, S. K. (2005). “Application of probabilistic neural networks for prediction of concrete strength.” *Journal of Materials in Civil Engineering*, 17, 353–362.
Koehler, E. P., and Fowler, D. (2006). *ICAR mixture proportioning procedure for self-consolidating concrete*. Research Report ICAR 108-1. International Center for Aggregates Research, University of Texas at Austin, TX.
Kohn, S. D., and Tayabji, S. D. (2003). Best practices for airport portland cement concrete pavement construction. Report IPRF-01-G-002-1. Innovative Pavement Research Foundation, Airport Concrete Pavement Technology Program, Washington, DC.
Kopac, P.A. (2002). “Making roads better and better.” *Public Roads*, 66(1).
Kosmatka, S. H., Kerkhoff, B., and Panarese, W. C. (2008). *Design and control of concrete mixtures*. 14th ed. Portland Cement Association, Skokie, IL.

Lee, B. Y., Kim, J. H., and Kim, J. K. (2009). "Optimum concrete mixture proportion based on a database considering regional characteristics." *Journal of Computing in Civil Engineering*, 23, 258–265.

Ley, T., Cook, D., and Fick, G. (2012). "Concrete pavement mixture design and analysis (MDA): Effect of aggregate systems on concrete properties." National Concrete Pavement Technology Center, Ames, IA.

Liu, R., Durham, S. A., Rens, K. L., and Ramaswami, A. (2012). "Optimization of cementitious material content for sustainable concrete mixtures." *Journal of Materials in Civil Engineering*, 24(6), 745–753.

Lobo, C., Lemay, L., and Obla, K. (2006). *Performance-based specifications for concrete*. M. Ettouney, ed., ASCE, Omaha, NE.

Neville, A. (2000). "The question of concrete durability the answer: we can make good concrete today." *Concrete International*, 22, 21–26.

Obla, K. (2006). "Performance specification – Why wait? Act now!" *Concrete InFocus*, Spring, 27–28.

Obla, K., Lobo C., and Lemay L. (2005). "Specifying concrete for durability – performance-based criteria offer best solutions." *Concrete InFocus*, Winter, 42–50.

Ozyildirim, C. (2011). "Virginia's end-result specifications." *Concrete International*, 33(3), 41–45.

Popovics, S. (1990). "Analysis of concrete strength versus water-cement ratio relationship." *ACI Materials Journal*, 87(5), 517–529.

Rudy, K. A. (2009). Optimization of mixture proportions for concrete pavements - influence of supplementary cementitious materials, paste content and aggregate gradation. Ph.D. dissertation, Purdue University.

Schindler, A.K. (2002). Concrete hydration, temperature development, and setting at early ages. Ph.D. dissertation, University of Texas at Austin.

Schlorholtz, S. (2004). *Development of performance of ternary mixes: scoping study*. Report No. DTFH61-01-X-00042 (Project 13). Center for Portland Cement Concrete Pavement Technology, Ames, IA.

Scrivener, K., and Nemati, K. (1996). "The percolation of pore space in the cement paste aggregate interfacial zone of concrete." *Cement and Concrete Research*, 26, 35–40.

Shilstone, J. M. Sr., and Shilstone, J. M. Jr. (2002). "Performance-based concrete mixtures and specifications today." *Concrete International*, 24(2), 80–83.

Smith, M. R., and Collis, L. (2001). *Aggregates*. 3rd ed. The Geological Society of London, UK.

Soutsos, M. (2010). *Concrete durability*. Thomas Thelford, London, UK.

Taylor, P. (2004). "Performance-based specifications for concrete." *Concrete International*, 26, 91–93.

Taylor, P., Kosmatka, S. H., Voigt, G. F., et al. (2006). *Integrated materials and construction practices for concrete pavement: a state-of-the-practice manual*. FHWA HIF-07-004. Federal Highway Administration, Washington, DC.

Taylor, P., Wang, X., Wang, X. (2015). *Concrete Pavement Mixture Design and Analysis (MDA): Development and Evaluation of Vibrating Kelly Ball Test (VKelly Test) for the Workability of Concrete*. Technical Report TPF-5(205). National Concrete Pavement Technology Center, Ames, IA.

Tikalsky, P., Taylor, P., Hanson, S., and Ghosh, P. (2011). *Development of performance properties of ternary mixtures: laboratory study on concrete*. Report No. DTFH61-06-H-00011 Work Plan 12 Pooled Fund Study TPF-5(117). National Concrete Pavement Technology Center, Ames, IA.

Toutanji, H., Delatte, N., Aggoun, S., Duval, R., and Danson, A. (2004). "Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete." *Cement and Concrete Research*, 34(2), 311–319.

Wassermann, R., Katz, A., and Bentur, A. (2009). "Minimum cement content requirements: a must or a myth?" *Materials and Structures*, 42(7), 973–982.

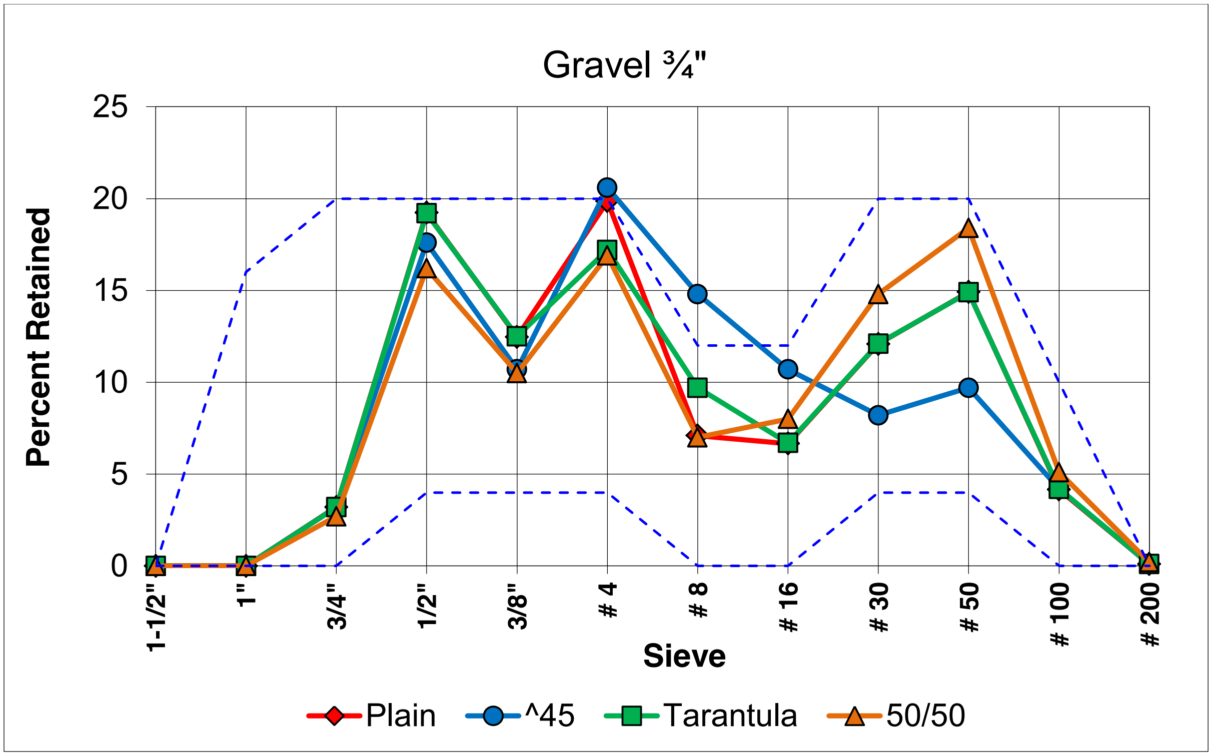
Wenglas, G. L. (2008). Quality evaluation of portland cement concrete at early age with free free resonant column. Ph.D. dissertation, University of Texas at El Paso.

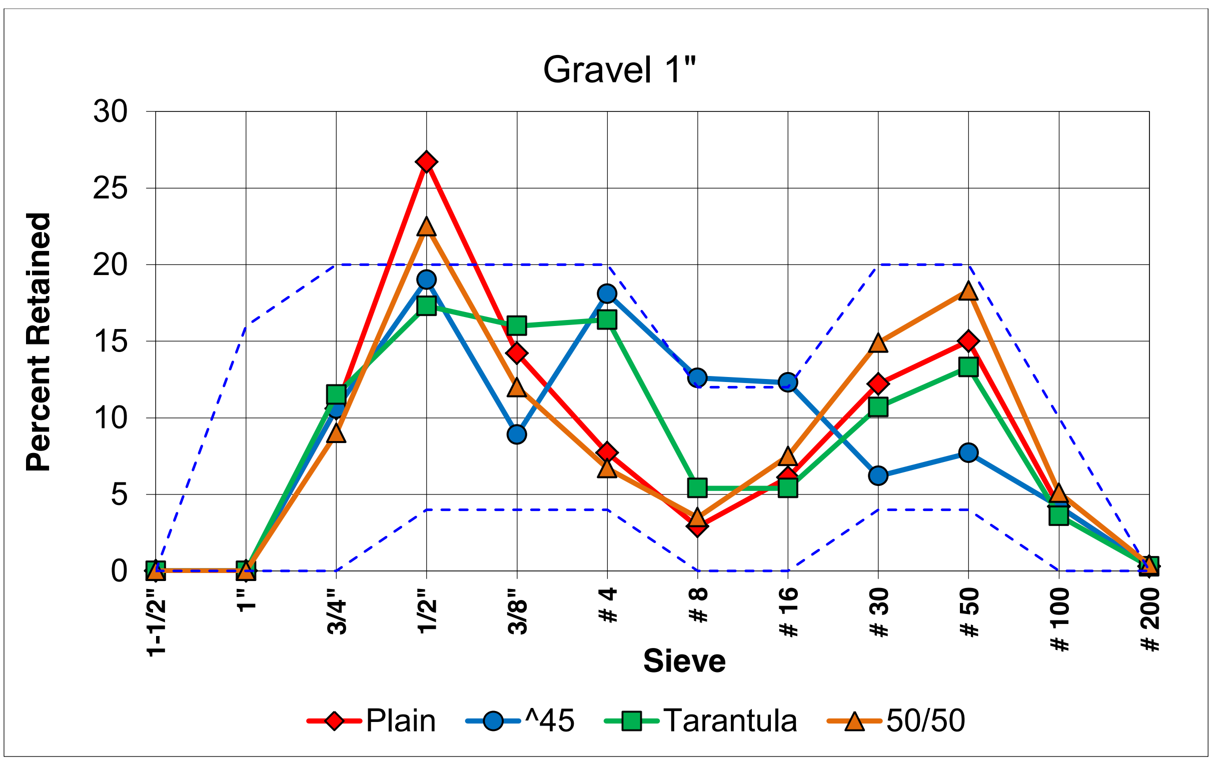
Yurdakul, E., Taylor, P. C., Ceylan, H., and Bektas, F. (2012). "Effect of paste-to-voids volume ratio on the performance of concrete mixtures." *Journal of Materials in Civil Engineering*, 25(12), 1840–1851.

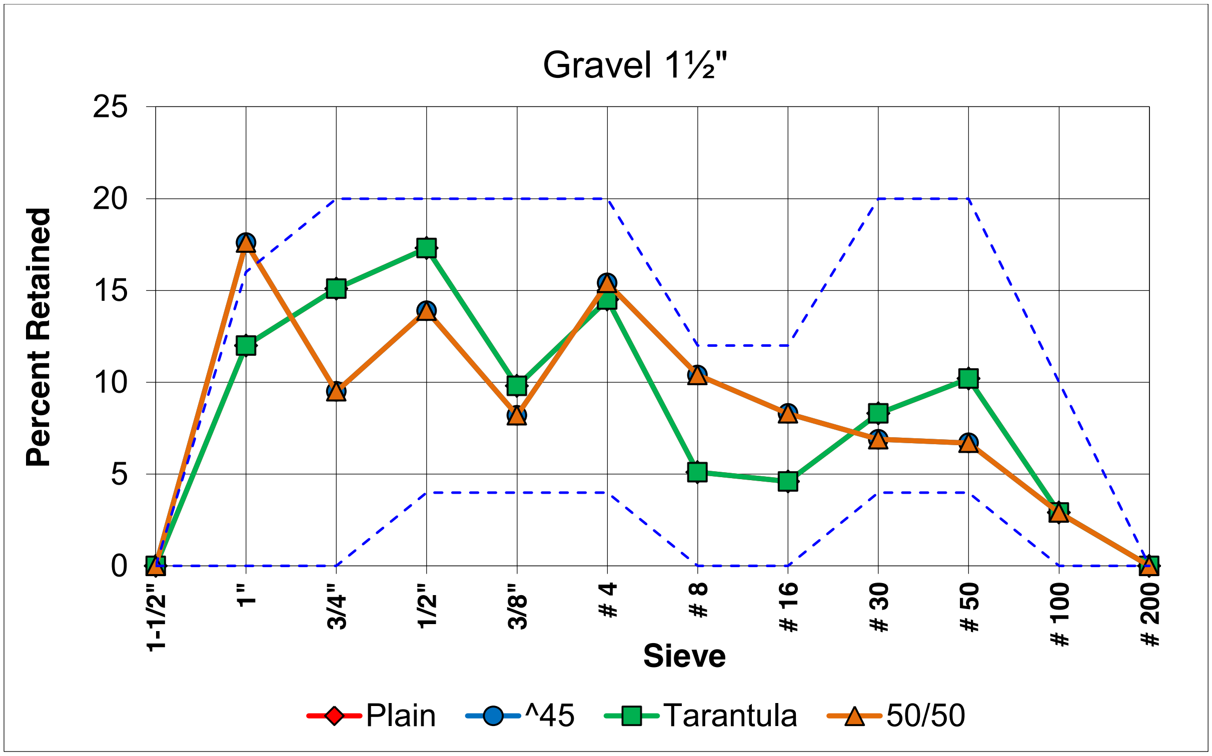
APPENDIX A. AGGREGATE GRADATIONS

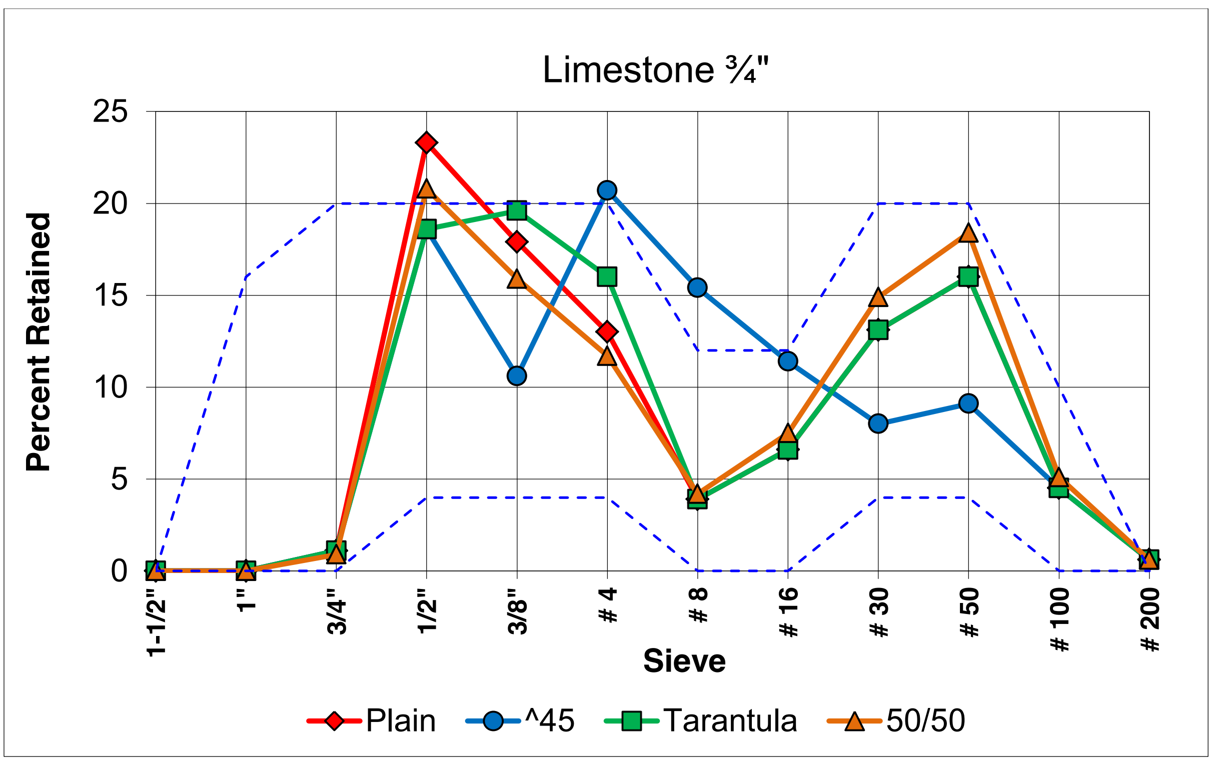
							Gravel						
Sieve Size			0.75				1.0				1.5		
No.	mm	Plain	^45	Tarantula	50/50	Plain	^45	Tarantula	50/50	Plain	^45	Tarantula	50/50
2"	50	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1-1/2"	37	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1"	25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	88.0	82.4	88.0	82.4
3/4"	19	96.8	96.8	96.8	97.3	89.4	89.4	88.5	91.0	72.9	72.9	72.9	72.9
1/2"	12.5	77.6	79.2	77.6	81.1	62.7	70.4	71.2	68.5	55.6	59.0	55.6	59.0
3/8"	9.5	65.1	68.5	65.1	70.6	48.5	61.5	55.2	56.5	45.8	50.8	45.8	50.8
#4	4.75	45.2	47.9	47.9	53.7	40.8	43.4	38.8	49.8	31.3	35.4	31.3	35.4
#8	2.36	38.2	33.1	38.2	46.7	37.9	30.8	33.4	46.3	26.2	25.0	26.2	25.0
#16	1.18	31.5	22.4	31.5	38.7	31.8	18.5	28.0	38.8	21.6	16.7	21.6	16.7
#30	0.6	19.4	14.2	19.4	23.9	19.6	12.3	17.3	23.9	13.3	9.8	13.3	9.8
#50	0.3	4.5	4.5	4.5	5.5	4.6	4.6	4.0	5.6	3.1	3.1	3.1	3.1
#100	0.15	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2
#200	0.075	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2

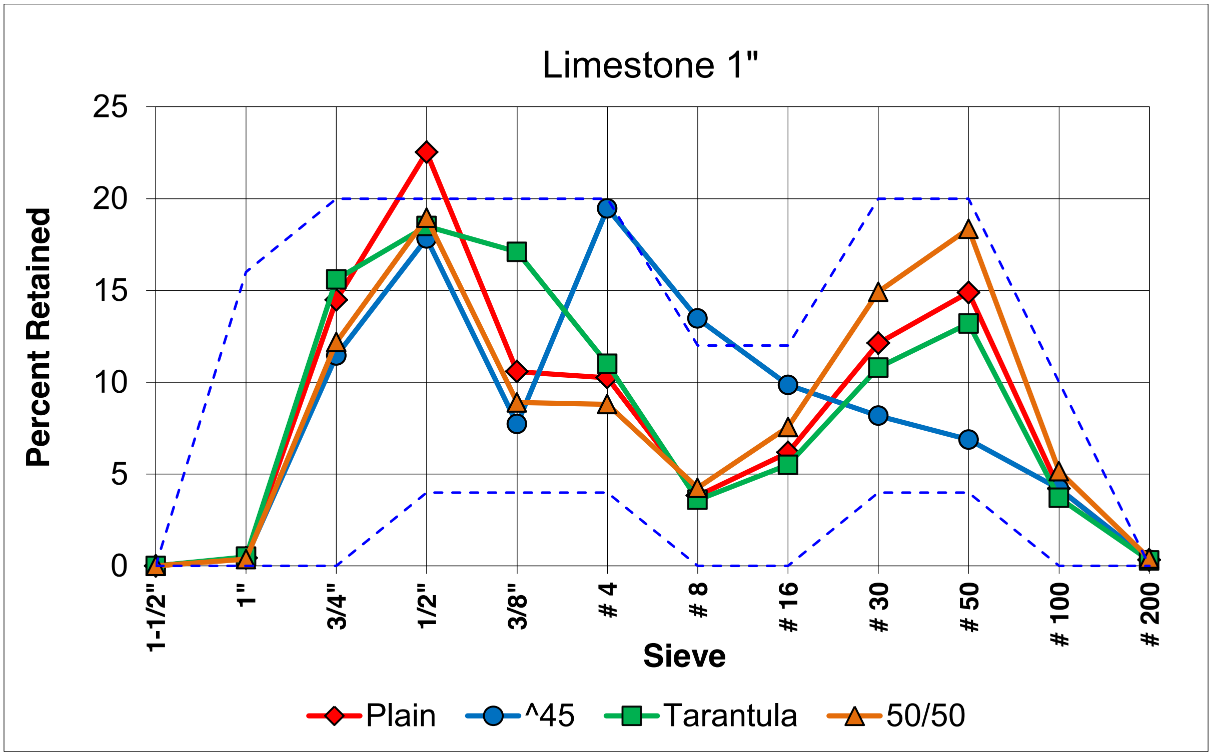
							Limestone						
Sieve Size			0.75				1.0				1.5		
No.	mm	Plain	^45	Tarantula	50/50	Plain	^45	Tarantula	50/50	Plain	^45	Tarantula	50/50
2"	50	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1-1/2"	37	100	100.0	100	100.0	100.0	100.0	100.0	100.0	99.1	99.1	99.1	98.1
1"	25	100	100.0	100	100.0	99.6	99.6	99.5	99.6	82.2	82.2	86.5	64.0
3/4"	19	98.9	98.9	98.9	99.1	85.1	88.1	83.9	87.5	75.4	72.7	75.4	51.8
1/2"	12.5	75.6	80.3	80.3	78.3	62.6	70.3	65.4	68.5	56.1	58.5	56.1	50.3
3/8"	9.5	57.7	69.7	60.7	62.4	52.0	62.6	48.3	59.6	41.7	50.4	41.7	50.2
#4	4.75	44.7	49.0	44.7	50.7	41.7	43.1	37.3	50.8	31.4	35.7	31.4	49.6
#8	2.36	40.8	33.6	40.8	46.5	37.9	29.6	33.7	46.6	28.6	24.8	28.6	46.4
#16	1.18	34.2	22.2	34.2	39.0	31.7	19.8	28.2	39.0	23.9	16.2	23.9	38.9
#30	0.6	21.1	14.2	21.1	24.1	19.6	11.6	17.4	24.1	14.8	9.4	14.8	24.0
#50	0.3	5.1	5.1	5.1	5.7	4.7	4.7	4.2	5.7	3.6	3.6	3.6	5.6
#100	0.15	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5
#200	0.075	0	0.0	0	0.0	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.1

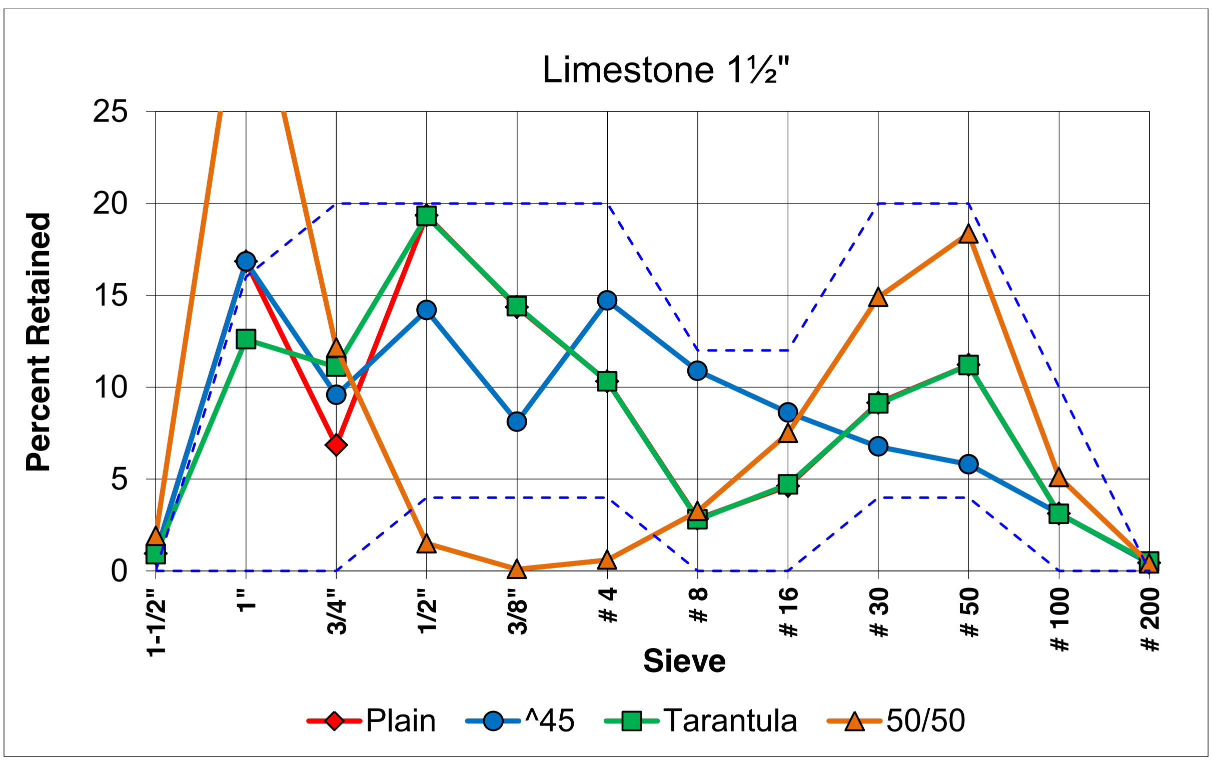

Gravel ¾"
Percent Retained
25
20
15
10
5
0
1-1/2"
1"
3/4"
1/2"
3/8"
4
8
16
30
50
100
200
Sieve
Plain
^45
Tarantula
50/50


Gravel 1"
Percent Retained
30
25
20
15
10
5
0
1-1/2"
1"
3/4"
1/2"
3/8"
4
8
16
30
50
100
200
Sieve
Plain
^45
Tarantula
50/50


Gravel 1½"
Percent Retained
25
20
15
10
5
0
1-1/2"
1"
3/4"
1/2"
3/8"
4
8
16
30
50
100
200
Sieve
Plain
^45
Tarantula
50/50


Limestone ¾"
Percent Retained
25
20
15
10
5
0
1-1/2"
1"
3/4"
1/2"
3/8"
4
8
16
30
50
100
200
Sieve
Plain
^45
Tarantula
50/50


Limestone 1"
Percent Retained
25
20
15
10
5
0
1-1/2"
1"
3/4"
1/2"
3/8"
4
8
16
30
50
100
200
Sieve
Plain
^45
Tarantula
50/50


Limestone 1½"
Percent Retained
25
20
15
10
5
0
1-1/2"
1"
3/4"
1/2"
3/8"
4
8
16
30
50
100
200
Sieve
Plain
^45
Tarantula
50/50