Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

PERFORMANCE ENGINEERED MIXTURES FOR CONCRETE PAVEMENTS IN THE US

Peter C. Taylor, PhD
Associate Director, National Pavement Technology Center, Ames, IA USA
ptaylor@iastate.edu

Ezgi Yurdakul, PhD
Concrete Scientist, Verifi LLC, Cambridge, MA USA
ezgi.yurdakul@verifitechnologies.com

Halil Ceylan, PhD
Associate Professor, Dept. of Civil Engineering, Iowa State University, Ames, IA USA
hceylan@iastate.edu

ABSTRACT

Many concrete pavement mixtures in the US are proportioned based on recipes that have been used before, or on prescriptive specifications. 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.

While the technology is largely available in the concrete industry, a number of challenges are slowing the development of more performance-based specifications and mixtures in the US market. These include resistance to change from familiar to less known, resistance to any change in the distribution of risk, and a lack of good performance tests.

This paper addresses these factors by clearly laying out the barriers to adoption of more performance-based specifications for mixtures, along with identifying the research that is needed to address them. Suggestions are made on the steps that can be taken to move the process forward. The paper also discusses work recently conducted to investigate an alternative approach to mix proportioning that is better able to deliver designed performance requirements for local materials.

KEY WORDS

CONCRETE PAVEMENTS / PERFORMANCE-BASED SPECIFICATIONS / PASTE-TO-VOIDS VOLUME RATIO / MIX PROPORTIONING / MIX OPTIMIZATION.

1. INTRODUCTION

A factor indirectly affecting concrete pavement quality is the type of specification followed (Falker 2003):

- Prescriptive-based specifications, which set instructions regarding the methods of construction, and limits the type and amount of materials.
- Performance-based specifications, which focus on the end-result by evaluating the fresh and hardened properties to ensure meeting the required performance

criteria while avoiding limitations on the components or proportions of the concrete mixture (Bickley et al. 2006).

Many concrete pavement mixtures in the US are proportioned based on recipes that have been used before, or on prescriptive specifications. These specifications were established based on years of experience, and conservatively define the limits on the type, amount, and proportions of the mix components to ensure that performance requirements are met (Ozyildirim 2011). To ensure the quality and performance of concrete pavements, the minimum compressive strength, maximum water-to-cementitious materials ratio, and minimum cementitious content are often specified, which results in an increased carbon footprint (Lemay et al. 2006). However, this prescriptive approach brings along potential problems. For example, strength is often used as a primary quality indicator. While strength is an important factor that is required to ensure the structural performance of concrete, it has little direct correlation with potential durability, which can be defined as the capability of maintaining the serviceability over its design life without significant deterioration (Shilstone and Shilstone 2002). Therefore, meeting a strength requirement does not necessarily assure the mixture meets the required durability, thus it cannot be solely relied on to assess performance (Obla et al. 2006). Specifications have also often been modified over time to address problems incurred on site. It is not uncommon for these modifications to induce negative unintended consequences.

Prescriptive-based specifications often encourage using more reactive materials than needed, which increases potential for shrinkage related cracking, thereby compromising the durability, longevity, and performance of concrete pavements (Ozyildirim 2011, Obla 2006). Studies (Chamberlin 1995) have shown that mixes designed by following prescriptive specifications did not always provide the desired end-results. It is not uncommon to come across a structure having a span life of 20 years that will start deteriorating within the first couple of years due to poor mix proportioning. Consequently, these structures require early rehabilitation, which sacrifices sustainability by requiring additional time, equipment, labor, materials, and cost. 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.

While the technology is largely available in the concrete industry, a number of challenges are slowing the development of more performance-based specifications and mixtures in the US market. These include:

- Resistance to change: The resistance to change is mostly due to the fact that prescriptive-based specifications have been used by agencies since 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).
- 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. Therefore, 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 will take on more risk because they are solely responsible for the performance of the end-product.
- A lack of good performance tests: One of the major barriers in adopting the 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 (Taylor 2013, Hooton and Bickley 2012).

This paper presents work recently conducted to investigate an alternative approach to mix proportioning that is better able to deliver designed performance requirements for local materials.

2. MATERIALS AND METHODOLOGY

2.1. Materials

Cementitious materials
- 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

Aggregates
- 1" (25-mm) nominal maximum size crushed limestone
- No 4 sieve size (4.75-mm) nominal maximum size river sand

Chemical admixtures
- ASTM C494 Type F polycarboxylate based high range water reducer (HRWR)
- ASTM C260 tall-oil based air entraining admixture

2.2. Mix design

In this experimental program, results of 118 mixes were prepared to analyze the effects of various mix characteristics on performance engineered mixes. The details of the mix characteristics are presented below:

Paste system
- Reference mixture with 100% ordinary portland cement
- Binary mixes with class F fly ash at the replacement level of 15%, 20%, and 30%
- Binary mixes with class C fly ash at the replacement level of 15%, 20%, and 30%
- Binary mixes with slag cement having the replacement level of 20%, and 40%

Paste content
- 400, 500, 600, and 700 pounds per cubic yard (pcy)

Water-to-cementitious materials ratio (w/cm)
- 0.35, 0.40, 0.45, and 0.50

Air content
- 2%, 4%, and 8%

Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

2.3. Test matrix

Concrete be considered to consist of two segments: paste and aggregates. Therefore, this paper will analyze performance by establishing a relationship between the desired performance criteria, and the paste and aggregate systems. Common performance criteria for concrete mixtures include durability, strength, constructability (workability and placeability), and appearance (surface texture) (Shilstone and Shilstone 2002). Therefore, performance was evaluated by conducting durability-indicating tests such as rapid chloride penetration, surface resistivity, and air permeability. Workability and setting time were used to represent constructability. A summary of the conducted tests is provided in Table 1.

Table 1 – Test matrix

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

3. RESULTS AND DISCUSSION

A cost-effective and sustainable solution to achieve the desired performance characteristics is by minimizing the voids between the aggregate system, which, in turn, reduces the paste requirement. Therefore, the results are presented in three steps that outline the fundamental of the proposed mix proportioning procedure:

- Step 1-Choose the aggregate system
- Step 2-Choose the paste system
- Step 3-Choose the paste volume

3.1. Step 1-Choose the aggregate system

Aggregate takes up 60% to 90% of total volume of concrete (Ashraf and Noor 2011). Despite this high portion in concrete, specifications mostly focus on the minimum cementitious content, maximum water-to-cement ratio, and strength of concrete (Ley et al. 2012). However, 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/c ratio. Concrete properties are greatly affected by the aggregate size, gradation, particle shape, surface texture, porosity, void content, specific gravity, absorption, and impurities (Alexander and Mindess 2005); therefore, these factors should be taken into account while selecting the aggregate system.

The optimum aggregate system is the one that would yield the mix with more aggregates to minimize the voids between particles, thereby requiring less paste to fill those voids, and coat the surface of particles for the desired workability. Having less paste requirement will not only be cost-effective, but also results in less thermal and shrinkage cracking, as well as being less permeable due to providing less area for the penetration of aggressive chemicals.

3.1.1. Particle shape and surface texture

Choosing the aggregate system based on particle shape and surface texture is limited due to the necessity of using local materials to minimize the cost. However, understanding their effect on the desired performance criteria is essential for mix proportioning.

Selecting the optimum shape and texture may vary depending on the performance criteria. For example, from workability point of view, round shaped and smooth textured aggregates (e.g. river gravel) are of advantage due to having lower water demand associated with lower friction between particles compared to angular and rough textured aggregates such as crushed limestone (Alexander and Mindess 2005). On the other hand, from mechanical properties perspective, angular and rough textured aggregates are preferred due to leading to better bonding between aggregates and paste, thus enhances strength (Yaqub and Bukhari 2006). Mixtures with crushed aggregates are also likely to require longer more tortuous crack paths, thus increasing the energy required to induce failure.

Considering the workability requirements for concrete pavements (low slump, high thixotropy, and high flow under energy), angular aggregates with rough texture such as crushed limestone is ideal due to their lead to higher strength (Taylor et al. 2006). Therefore, due to their positive impact on the desired properties and local availability, crushed limestone coarse aggregate with river sand was used in this study.

3.1.2. Maximum aggregate size

Increasing the aggregate size reduces both the water and cement demand by reducing the total surface area per unit volume of aggregate which the paste has to cover (Alexander and Mindess 2005). Using a larger maximum nominal aggregate size also results in producing an aggregate gradation that does not have an excessive amount of material on a single sieve size (Cook et al. 2013). Therefore, 1 to 1.5-in. nominal maximum aggregate size is preferred in concrete pavements.

3.1.3. Combined aggregate gradation

The combined aggregate gradation should be designed to increase workability while reducing the paste requirement. Optimum combined aggregate gradation is important because it 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). However, the current guidelines for optimized gradation concepts are not consistently identical. Therefore, the gradation of the selected combined fine and coarse aggregate mixtures were calculated and plotted using various charts to determine the best combination for this research study.

According to the FHWA 0.45 power curve, Shilstone workability factor chart, and specific surface charts shown in Figure 1 (a-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 based on the median of these three charts. The appropriateness of the selected aggregate distribution of 42% of fine aggregate and 58% of coarse aggregate was checked by plotting the data in an ASTM C33 plot (Figure 1-d) and a "Haystack" plot (Figure 1-e). 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 similar to common mixtures, in which an aggregate distribution of 60% coarse aggregate and 40% fine aggregate, is used regardless of gradation and availability of aggregates (Ley et al. 2012). The same fine-to-coarse aggregate ratio (42/58%) was used in all the mixtures.

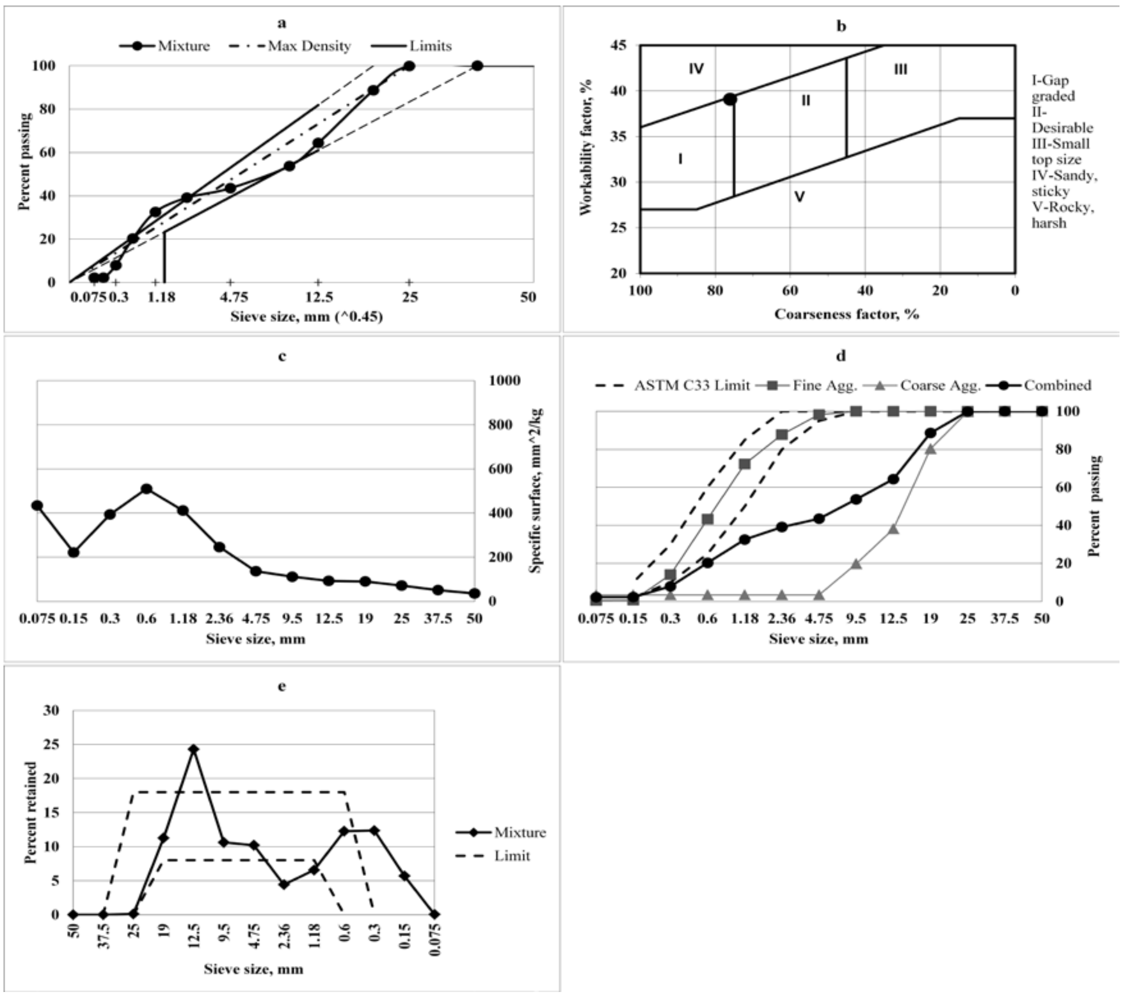

Figure 1 - Combined aggregate gradation curves

According to a recent study conducted by Cook et al. (2013), among Shilstone chart, power 45 curve, and the percent retained chart, the most reliable method for determining the optimum aggregate gradation has found to be the individual percent retained chart. The recommended limits for mixes used in concrete pavements which are subjected to vibration are presented in Figure 2 (Cook et al. 2013).

Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

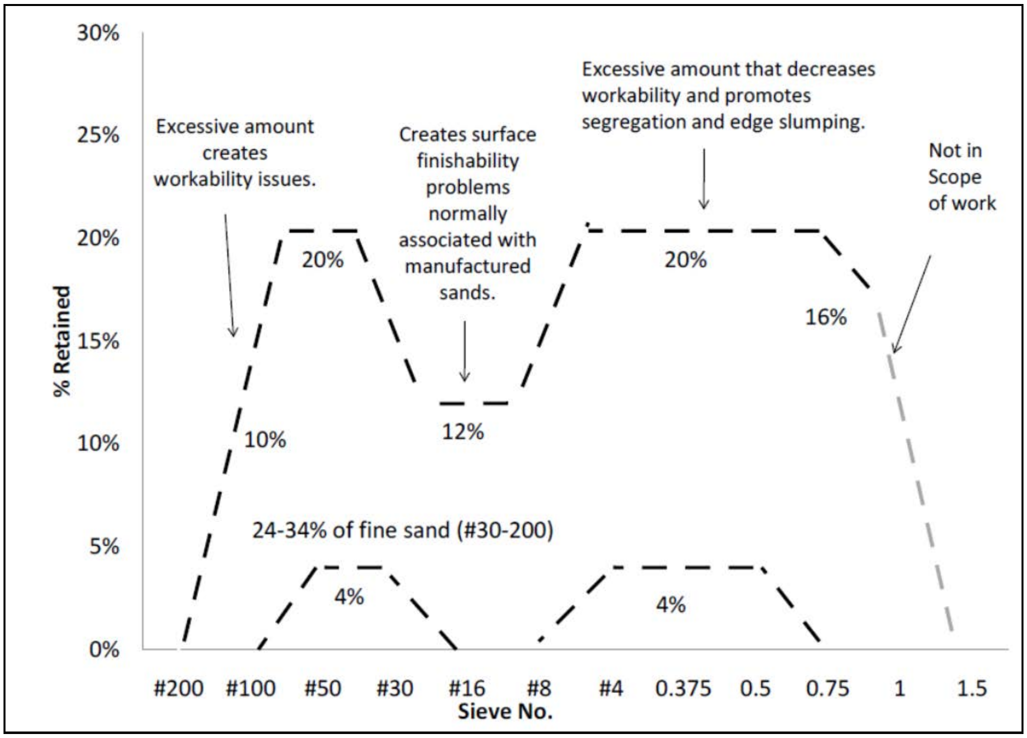

Figure 2 – Recommended limits for aggregate gradation (adapted from Cook et al. 2013)

3.1.4. Voids ratio

Determining the voids volume in the selected combined aggregate system is an essential step for mix proportioning as it determines the paste requirement. Higher the voids volume, higher the paste requirement needed to fill those voids. Therefore, it is critical to select the combined aggregate gradation that minimizes the voids in between the particles. The minimum voids volume that would yield the minimum paste requirement, thus in turn the reduced cost, heat, and shrinkage would be selected. For meeting the desired workability, it would be plotted in the "tarantula curve" presented in Figure 2 to ensure the selected gradation yielding the minimum voids does not fall in the potentially problematic part of the curve causing workability issues. If the minimum voids volume found for the desired paste requirement exceeds the recommended limits of the "tarantula curve", the minimum voids volume may be slightly compromised to balance the required properties. In such cases, the gradation that would fit in the recommended limits of the curve but provide the minimum voids volume should be selected.

The voids are determined following a modified procedure based on ASTM C29. The difference between the ASTM C 29 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 this study applied the same principle provided in ASTM C29 on the selected combined aggregate system. The void percentage of the combined aggregates of this study was found to be 19.8% (average value of three repeats).

3.2. Step 2-Choose the paste system

The paste system involves the selection of the cementitious system, water-to-cementitious materials ratio, target air content, and the presence of chemical admixtures. The paste system is selected based on the performance requirements of the project.

From contractors' point of view, workability, finishability, and setting time are important properties as they determine the ease of placeability of concrete, and the man-hours required to finish the surface. It is a common practice to increase the workability with the addition of water to make the finishers' job easier. However, although water decreases the yield stress as desired by the construction workers, it also decreases the viscosity of concrete, which decreases the resistance against segregation. Segregation is harmful for pavement because it causes strength loss, edge slump, spalling and scaling, thereby reducing the pavement service life (Taylor et al. 2006). Therefore, if high workability is desired, to maintain the required water-to-cementitious ratio (w/cm) and prevent segregation, mid-range or high-range water-reducing admixtures may be used as they decrease the yield stress while having a minor effect on viscosity.

Setting time is also a critical factor for contractors since longer the set time, longer the workers need to wait which increases the cost. Initial set time is of interest for contractors as it provides information regarding when they can finish, texture, and saw cut concrete pavements. The cementitious system affects both the workability and set time, therefore it should be wisely selected based on the desired properties. For example, due to the spherical morphology of fly ash, it reduces the inter particle friction, thus increases the workability whereas silica fume decreases the workability by increasing the water demand due its fine particle size having high surface area. Incorporating supplementary cementitious materials (SCM) may also affect the set time. For example, depending on its replacement level, fly ash increases the set time as a result of its dilution effect due to the partial substitution of cement with a less reactive material. Therefore, mixtures containing fly ash could be used in hot-weather concrete pavements as the addition of them may help lowering the rate of setting. However, in cold weather they may result in further increasing the setting time, which would result in delaying the finishing operation and opening to traffic and increased risk of cracking.

When concrete is exposed to the freeze-thaw condition, having a paste system with an appropriate air content is preferred to ensure durability. However, depending on its form, air can adversely affect the strength. Therefore, air entraining admixtures are required to provide a uniform distribution of small, stable air voids that allow a relief of hydraulic pressure (caused by the formation of ice) by the flow of water into these spaces.

A summary of a guideline for selecting the paste system based on the required properties is presented in Table 1.

Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

Table 1 – Selecting the paste system for the required properties*

Properties	**w/cm**	**air**	**F fly ash**	**C fly ash**	**slag**
Workability↑	↑	↑	↑	↑	↑
Ultimate strength ↑	↓	↓	↑	↑	↑
Permeability ↓	↓	↓	↓	↓	↓
Chloride ingress ↓	↓	↓	↓	↓	↓
Sulfate resistance ↑	↓	↓	↑	↕	↑
Freeze-thaw resistance ↑	↓	↑	↔	↔	↔
Durability ↑	↓	↓	↑	↑	↑

*The effects of chemical admixtures are not provided due to their effect depends on the type and dosage of the admixture being used.

3.3. Step 3-Choose the paste volume

According to the "excess paste theory" of Kennedy (1940), the amount of paste needed in mixtures is that required to fill the voids in the aggregate system, then with some extra to coat and lubricate the aggregate particles for workability and mechanical properties.

The paste volume was calculated by adding up the volume of water, the cementitious materials, and the measured air in the system. The volume of voids was determined based on the volume of aggregates in the mixture and the voids percentage determined as described in 3.1.4. A parameter of paste-to-voids volume ratio (Vpaste/Vvoids) is used to determine the required paste volume for the desired performance criteria.

3.3.1. Workability

For concrete pavements, the desired slump often ranges between 1 and 3-in and data within this range are presented in Figure 3 for families of binder type.

The target slump was selected as 2-in.; therefore, high-range water reducing admixture (HRWR) was added up to the recommended manufacturer's dosage as needed. Mixtures having a Vpaste/Vvoids of lower than 1.25 resulted in zero slump regardless of SCM type and dose. This shows that a minimum of 1.25 times more paste than the voids between the aggregate particles is required to achieve a workable mix at all. Below this number, even a high dosage of HRWR does not contribute to workability.

Depending on the SCM type and replacement level, Vpaste/Vvoids within the range of 1.5 to 2.5 is sufficient to provide the desired slump for concrete pavements. Once the required paste volume for base workability is determined, the paste volume required to achieve the mechanical properties should be determined.

Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

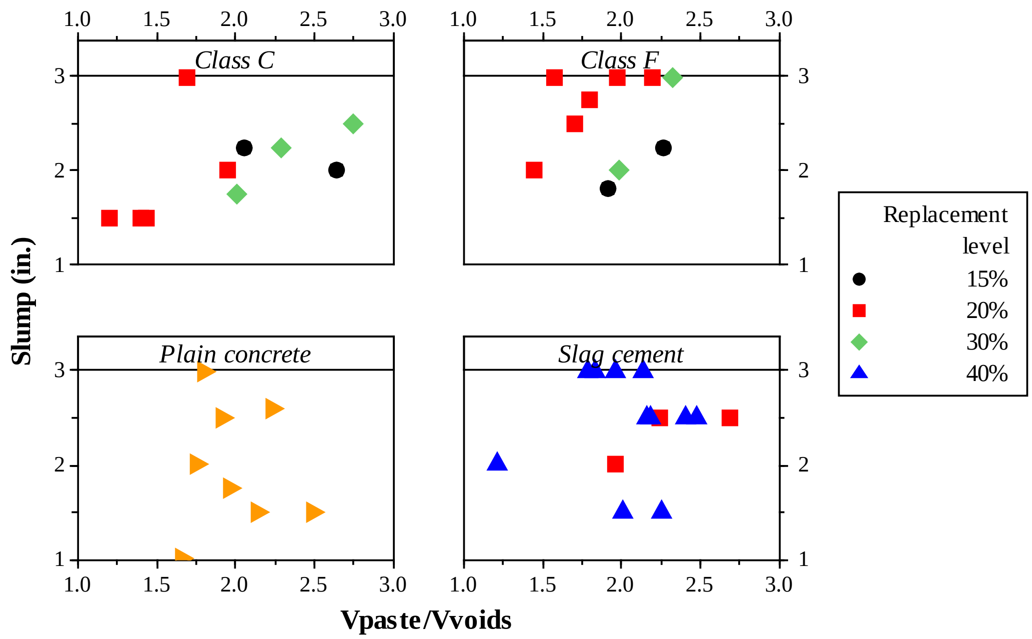

Figure 3 - The required paste volume for workability

3.3.2. Setting time

The test results of initial and final set time are depicted in Figures 4 and 5, respectively.

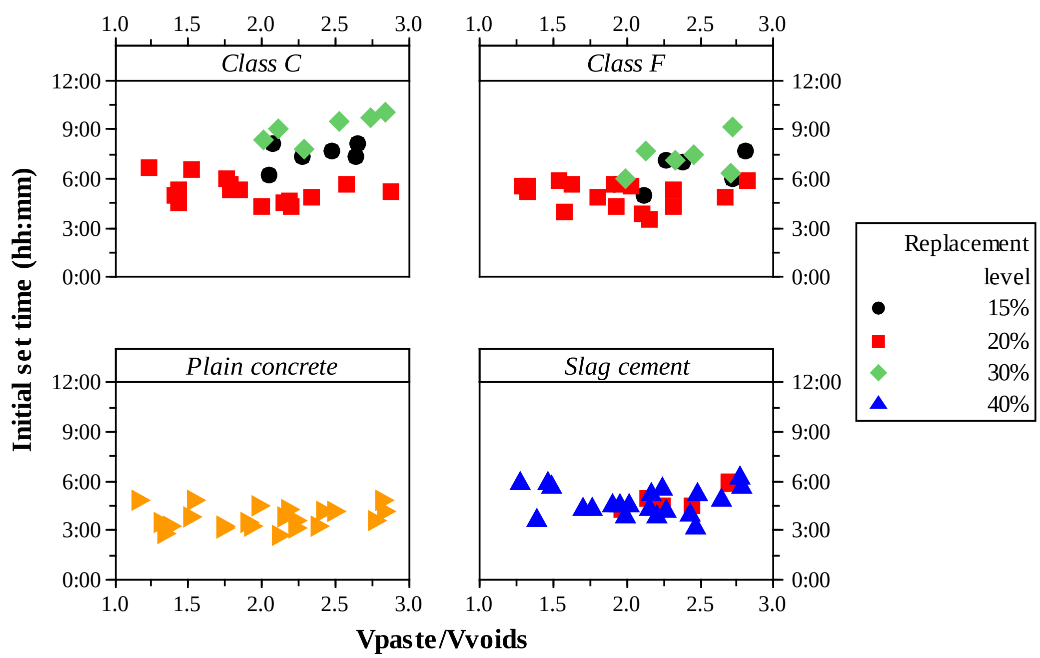

Figure 4 - The required paste volume for initial set time

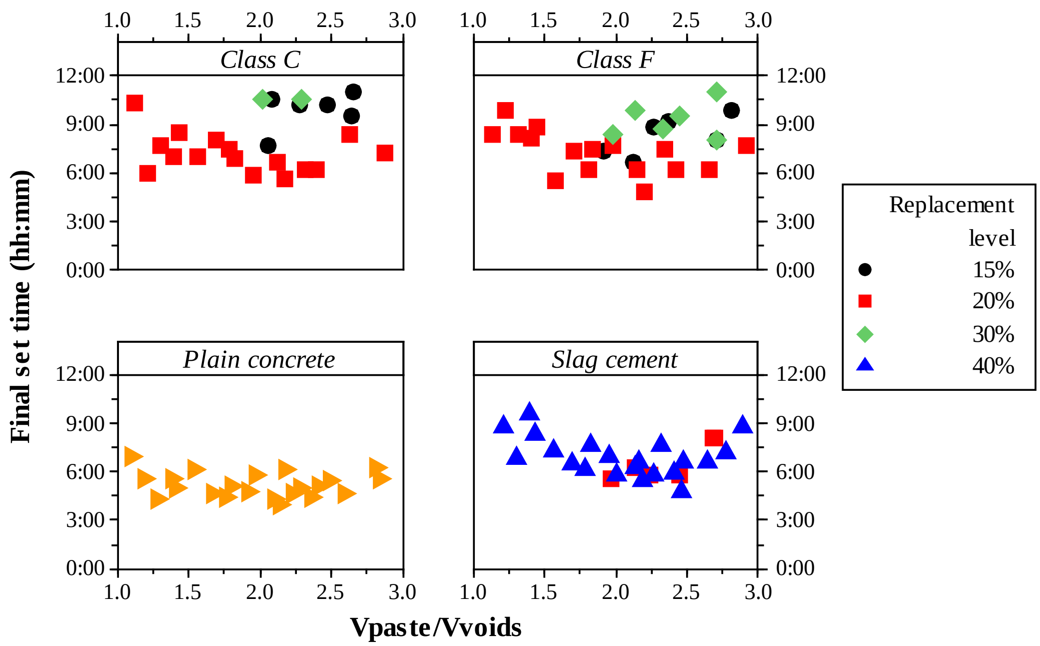

Figure 5 - The required paste volume for final set time

Figures above show that increasing paste content does not affect the setting time. However, in mixes where the paste volume was increased due to increasing w/cm exhibited higher setting time by slowing down the rate of hydration. This result is expected because it is well documented (Schindler 2002) that increasing w/cm results in a greater distance between cement particles, thus it takes longer time for hydration to complete before setting. Considering the concrete pavement construction is often subjected to the early opening traffic, thus requiring fast set time, it is important to maintain the w/cm within the range based on the desired set time criteria.

3.3.3. Compressive strength

The 28-day compressive strength data is presented in Figure 6. It can be seen that increasing the paste volume (up to Vpaste/Vvoids of 2) increased strength up to a limit, after which strength was not improved by further increasing the paste volume. After a maximum strength was achieved, 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 Vpaste/Vvoids limit to ensure strength is not being compromised by further increasing the paste volume. Based on the overall results, the paste volume should not be more than double of the voids volume between the combined aggregate system for the desired strength for pavements.

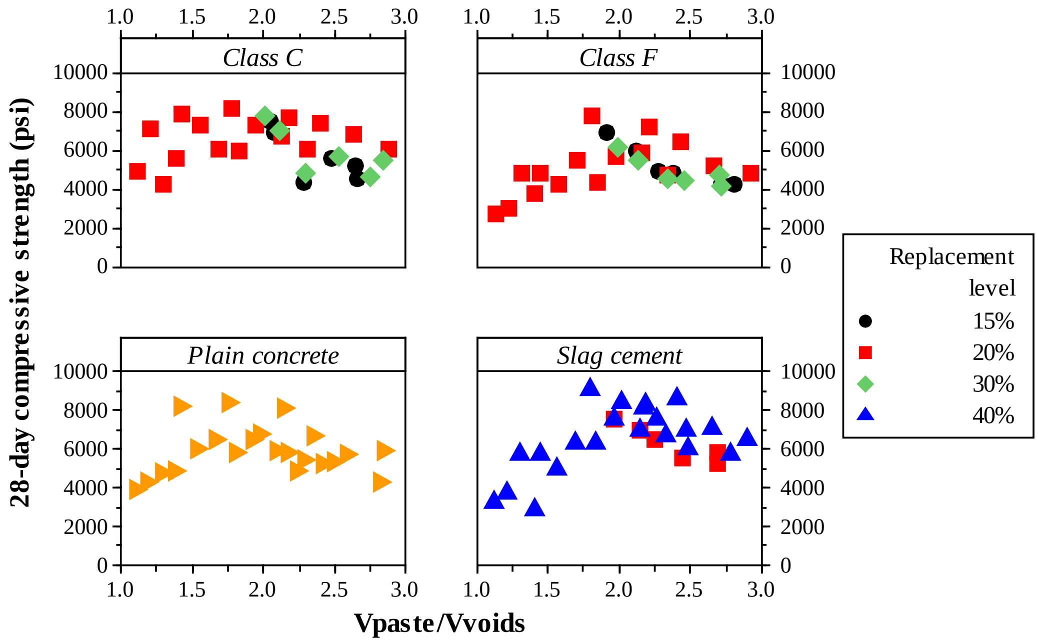

Figure 6 - The required paste volume for 28-day compressive strength

3.3.4. Durability

Chloride penetration and air permeability were tested to assess the durability. The effect of paste volume on rapid chloride penetration (RCP) and air permeability are presented in Figures 7 and 8.

Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

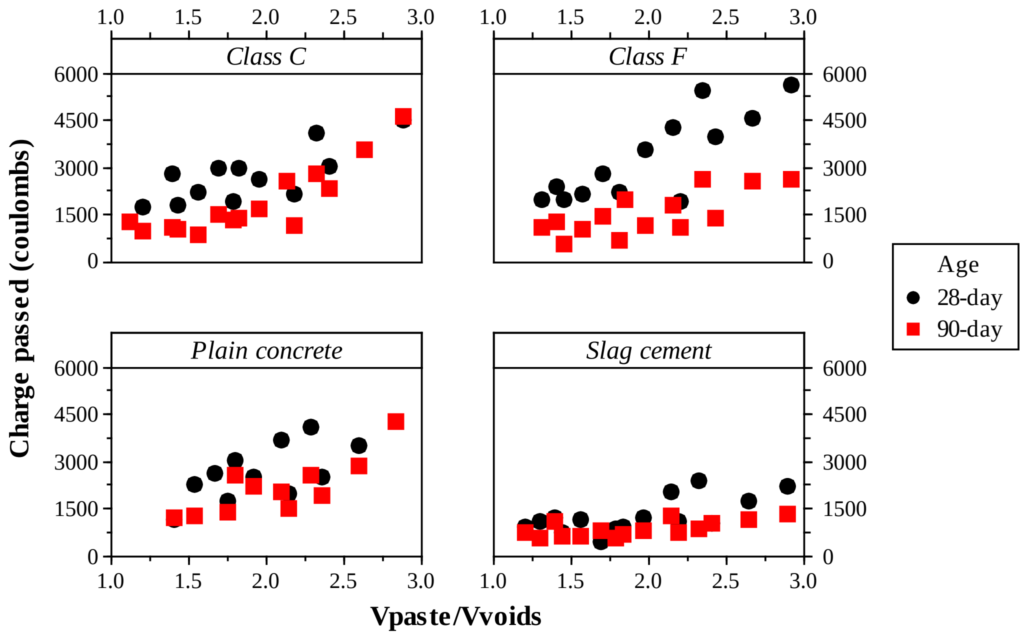

Figure 7 - The effect of paste volume on 28-day and 90-day chloride penetration

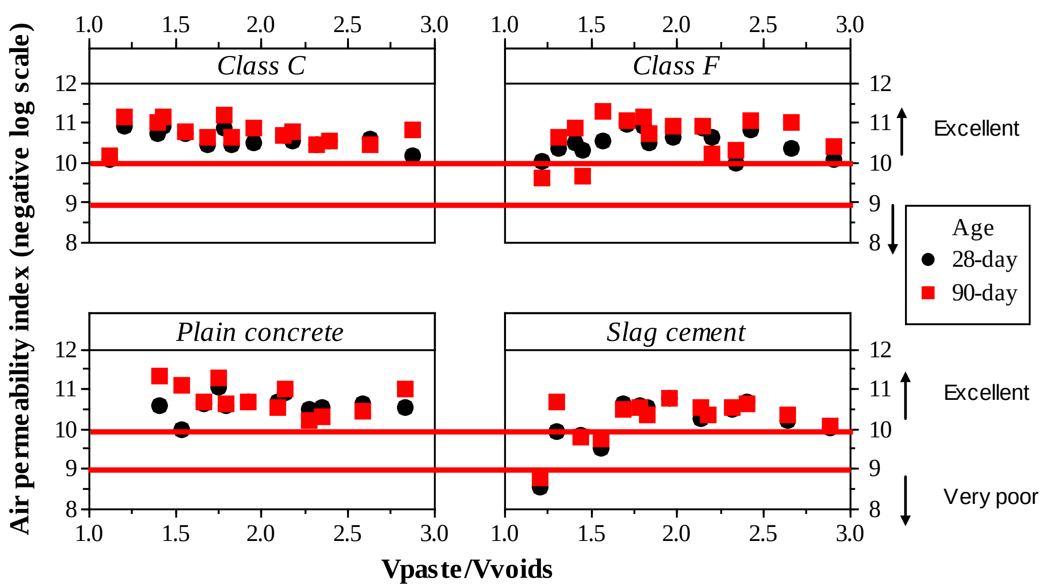

Figure 8 - The effect of paste volume on 28-day and 90-day air permeability

Hydration and the incorporation of SCM especially at later ages helped to fill some of the capillary voids and significantly increase the resistance against chloride ion penetration and air permeability, thus improved the durability. This result is not surprising, because increasing the testing age of the mixes incorporating SCM reduces the porosity of the concretes as a result of the continued pozzolanic reaction (Liu et al. 2012).

Increasing the paste volume increased the durability-indicating properties, which is consistent with the literature (Arachchige 2008). For a given cubic yard of concrete, increasing the paste volume means lower aggregate volume. Given the fact that, aggregates are likely to be denser than cement paste (especially at early ages) and have a lower permeability than cement paste, concretes with high paste volume tend to have higher permeability (Scrivener and Nemati 1996). Therefore, it is ideal to keep the paste volume as minimum as possible for durability prospective.

4. CONCLUSION AND RECOMMENDATIONS

The following conclusions can be drawn:

- For performance engineered mixtures, the initial step is choosing an aggregate system with high amount of aggregates which would result in the minimum voids content, hence minimum paste content requirement.
- The second step is to choose a paste system, which involves the selection of cementitious system, water-to-cementitious materials ratio (w/cm), air content, and chemical admixtures, based on the desired performance criteria.
- The final step of the proposed mix proportioning is determining the required paste volume for performance. Based on the overall tested properties, high paste volume is desired for workability perspective, whereas excessive paste volume adversely affects the strength and durability. While concrete with plain concrete may have difficulties having a balance in between these different properties, optimizing the mixes with incorporating SCM at various replacement level may help maintaining the properties at the desired level while minimizing the paste requirement and cost, thus being sustainable.
- The paste volume of 1.5 to 2 times more than voids between aggregates is found to be sufficient to meet the workability, strength and durability requirements for concrete pavements. Paste volume lower than 1.25 or higher than double of the voids between aggregates should be avoided.

To understand the applicability of this model, similar approach was conducted in 6 different projects in 3 labs. The results have showed that the trends were similar and pointed to a desirable range of Vpaste/Vvoids in the order of 1.75. The proposed model is mainly for concrete pavements, therefore, the performance criteria are set based on normal-strength concrete. Further research is needed to investigate the applicability of this approach on other types of concrete.

ACKNOWLEDGMENT

This study was funded by the Federal Highway Administration through Cooperative Agreement with the National Concrete Pavement Technology Center at Iowa State University. This study is a pooled fund project and Iowa Department of Transportation acts as the lead state. The opinions, findings, and conclusions presented here are those of the authors and do not necessarily reflect those of the research sponsors.

Reference to this paper should be made as follows: Taylor, P. C., Yurdakul, E., and Ceylan, H. (2014). "*Performance Engineered Mixtures for Concrete Pavements in the US*," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

REFERENCES

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

Arachchige A. D. M. (2008). "Influence of cement content on corrosion resistance." *Construction Materials*, Institution of Civil Engineers, 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*, Procedia Engineering, 14(2011), 2627-2634.

Bickley J. A., Hooton R. D., Hover K. C. (2006). "Performance specifications for durable concrete." *Concrete International*, 28(9), 51-57.

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

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

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

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 & Buildings*, Vol. 159. 361-363.

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

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.

Kennedy, C. T. (1940). "The design of concrete mixes." *Journal of the American Concrete Institute*, 36, 373-400.

Lemay L., Lobo C., and Obla K. (2013). "Sustainable concrete: The role of performance-based specifications." *Structures Congress*, 2693-2704.

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 USA.

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.

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

Obla K., Lobo C., and Lemay L. (2006). "Specifying concrete for durability-Performance-based criteria offer best solutions." *Concrete InFocus*, 4(4), 42-50.

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

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

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.

Taylor P. C., Kosmatka S. H., Voigt G. F. et al. (2006). "Integrated materials and construction practices for concrete pavement : a state-of-the-practice manual." Federal Highway Administration, Report No. FHWA HIF-07-004, Washington DC, USA.

Taylor, P.C. (2013). "Long-life concrete: how long will my concrete last? A synthesis of knowledge of potential durability of concrete," Supplement to TPF-5(159), *National Concrete Pavement Technology Center*, Ames, IA, USA.

Yaqub M., and Bukhari I. (2006). "Effect of size of coarse aggregate on compressive strength of high strength concrete." *31st Conference on Our World in Concrete & Structures*, 16 – 17 August 2006, Singapore.