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# TPF-5(291) FINAL REPORT:

# EVALUATING THE IMPACT OF MIX DESIGN ON PERFORMANCE

| **Prepared On Behalf Of** | **Date** | **Project Number** |
| --- | --- | --- |
| State Pooled Fund Study TPF-5(291) | October 2021 | 56A0418-008 (TPF 5(291))<br>219.03.10 (NCE) |


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# 1.0 BACKGROUND

The NCE team was awarded the Transportation Pooled Fund (TPF) Study 5(291) to investigate data from the Long-Term Pavement Performance (LTPP) Specific Pavement Study (SPS)-2 experiment for concrete pavement design factors, with the Washington State Department of Transportation as the Lead State. This pooled fund study included the investigation and proposal of a pavement preservation experiment utilizing existing test site conditions. Upon completion of the initial phase of the study, several SPS-2 Tech Days were conducted to broaden the pavement community's knowledge of the SPS-2 experiment and to garner input on analyses the community would find useful. The Pooled Fund Technical Advisory Committee (TAC) also provided recommendations for additional analyses.

As a result, five additional tasks were focused on SPS-2 test sections:

- Conducting a deterioration rate analysis
- Analyzing performance data
- Investigating sources of non-LTPP data
- Analyzing joint score and area of localized roughness (ALR) impacts on performance
- Updating previous SPS-2 analyses

Upon completion of these tasks, an additional 11 tasks were proposed. The purpose of this supplementary extension of TPF-5(291) was to conduct further analyses of existing data from the LTPP SPS-2 concrete pavement experiment. The focus of this set of tasks was to investigate the impact of non-experimental factors on pavement performance. The following tasks were completed:

- Identifying agency-specific trends
- Analyzing the impact of construction and materials issues
- Reviewing early SPS-2 failures
- Identifying lessons learned from state supplemental sections
- Analyzing the impacts of climate, traffic, and overall condition on deterioration rate
- Comparing SPS-8 and SPS-2 performance
- Assessing diurnal changes in roughness
- Evaluating service life
- Comparing mix-design performance
- Conducting Mechanistic Empirical Pavement Design Guide (MEPDG) sensitivity analysis of portland cement concrete/lean concrete base (PCC/LCB) bond
- Evaluating transverse joint opening width

This report presents the results of an investigation into the impact of specific concrete mix design factors on the performance of the SPS-2 test sections. Specific tasks included:

- Comparing aggregate grading to the Tarantula and Shilstone curve boundaries
- Evaluating the constructability of mixtures based on construction observations
- Evaluating correlation of the constructability to pavement performance (changes in roughness and development of distress)

## 2.0 METHODOLOGY

The goal of this study was to evaluate what, if any, impact the concrete mix design parameters for the SPS-2 experimental test sections had on the observed construction behavior and measured performance of those sections. To provide a comparison, a standard methodology was established for the investigation. It should be noted that all concrete mixture designs were acquired from the original construction reports for the LTPP SPS-2 experimental sections and these values are provided in Appendix A. Construction reports varied by state and detail level and it is possible changes could have been made from as-designed mixes to as-constructed mixes that were not captured completely in every report. This analysis is based on the as-designed data.

The first step was to calculate aggregate grading parameters to serve as indicators of the workability of the concrete mixtures. This included comparing the combined gradations of all aggregates to standard tools, including the 0.45 power chart, the workability chart, and the Tarantula curve. These indicators were compared to both constructability observations taken from the construction reports as well as measured performance of the test sections.

Measured performance criteria across three different metrics were quantified for each survey conducted: roughness (International Roughness Index, IRI), percent slabs cracked of jointed plain concrete pavement (JPCC), and faulting. Next, metrics established as recommended performance thresholds for pavement grading (Visintine et al. 2018) were used to establish performance levels. These performance levels and metrics are reproduced in Table 1 below.

***Table 1. Recommended Performance Thresholds for Pavement Grading (Visintine et al. 2018)***

| Condition Metric | Performance Level | Threshold |
|---|---|---|
| IRI | Good | <95 |
| IRI | Fair | 95-170 |
| IRI | Poor | >170 |
| Percent cracking, JPCC | Good | <5% |
| Percent cracking, JPCC | Fair | 5-15% |
| Percent cracking, JPCC | Poor | >15% |
| Faulting | Good | <0.10 |
| Faulting | Fair | 0.10-0.15 |
| Faulting | Poor | >0.15 |

Sites were classified as having poor performance if they met the criteria established for poor performance described in Table 1 across any of the three tested metrics for any year that measurements were taken. For example, if a test section obtained an IRI considered "poor" for only one year, this section would still be highlighted in the discussion. Additionally, performance comparisons were also made to the maximum directly measured performance rating obtained over the entire observational period of the test section.

Next, specific mix design parameters, including paste volume, water/cementitious materials ratio (w/cm), the amount of cementitious material, use and amount of supplementary cementitious materials, and density were also compared against construction observations and test section performance. Due to the variation of concrete mix designs used for the supplemental test sections, only the SPS-2 core experiment test sections were evaluated in this task. The SPS-2 experiment was designed to be a study on the impact of different levels of design factors on rigid pavements. Fourteen SPS-2 projects were constructed in different states consisting of 12 core test sections and a varying number of supplemental sections. The 12 core test sections were a half-factorial of the combination of four distinct design factors:

- Pavement thickness
  - 8-inch thin pavement
  - 11-inch thick pavement
- Base type
  - Dense graded aggregate base (DGAB)
  - Lean concrete base (LCB)
  - Permeable asphalt treated base (PATB)
- PCC design strength
  - 550 pounds per square inch (psi) – low-strength
  - 900 psi – high-strength
- Lane width
  - 12-foot standard-width lanes
  - 14-foot widened-width lanes

Additionally, there was a design factor drainage, where DGAB and LCB pavements were undrained and PATB pavements were drained. However, this was the extent of experimental design factors with defined levels.

For comparison, the concrete mix designs produced by each agency were divided between low-strength (target 14-day modulus of rupture of 550 pounds per square inch [psi]) and high-strength mixtures (target 14-day modulus of rupture of 900 psi) to evaluate trends between the two different concrete mixture types. In this report, test sections are referenced by their agency number using the LTPP state numbering convention given in Table 2.

***Table 2. LTPP State Codes***

| State | State Code |
|---|---|
| Arizona | 04 |
| Arkansas | 05 |
| California | 06 |
| Colorado | 08 |
| Delaware | 10 |
| Iowa | 19 |
| Kansas | 20 |
| Michigan | 26 |

| | |
|---|---|
| Nevada | 32 |
| North Carolina | 37 |
| North Dakota | 38 |
| Ohio | 39 |
| Washington | 53 |
| Wisconsin | 55 |

# 3.0 COMPARISON OF AGGREGATE GRADATIONS

The constructability and workability of a concrete mixture can largely be attributed to the aggregate gradation, or distribution of particle sizes of coarse and fine aggregates. Mixtures with proportionately more fine aggregates tend to be markedly less workable with noted increased stiffness, while mixtures with a higher proportion of coarse aggregates or even gap-graded aggregates (lacking an even distribution of intermediate-size aggregates) are prone to segregation during construction.

In addition to workability and constructability concerns, the aggregate gradation can contribute greatly to the overall durability of a concrete mixture. Densely graded aggregate occupies more total volume of a concrete mixture, as a distribution of aggregate sizes fills void spaces. This allows for a lower cementitious material content to be used, which can be directly correlated to a decrease in drying shrinkage (Page and Page 2007). Drying shrinkage is a direct result of the cement paste itself contracting; therefore, a lower paste content will result in less drying shrinkage. Drying shrinkage contributes to decreased ride quality as moisture gradients result in slab warping and slab cracking, and may affect concrete durability by allowing water and chemicals to easily infiltrate through the compromised concrete surface.

Due to the importance of defining and evaluating the aggregate gradation, multiple common methods exist to evaluate and compare the particle size distributions, including the 0.45 power chart, the workability factor chart, and the Tarantula curve. For this analysis, core-section concrete mixtures of the SPS-2 experiment (low- and high-strength mixtures for each state agency) were evaluated against these criteria. Additionally, when applicable, performance trends from individual test sections were compared to these aggregate parameters.

## 3.1 Comparison of Aggregate Gradations Using the 0.45 Power Chart

The 0.45 power chart provides a method of examining the aggregate gradation by plotting the percent retained across the entire aggregate distribution against the sieve size, raised to the 0.45 power. This tool is used frequently in asphalt applications to evaluate densely graded blends of aggregates. In this plot, the maximum density line is a straight line plotted from the origin to the maximum aggregate size. Therefore, the closer the aggregate gradation is plotted to the line, the denser the aggregate gradation. Aggregate gradations that plot significantly above the maximum density line generally skew toward higher coarse-aggregate content, while aggregate gradations that plot significantly below the maximum density line generally include finer aggregate gradations.

### 3.1.1 LOW-STRENGTH MIXTURES

In the following charts, the maximum density line for each plot is shown as a dashed red line. For clarity, groups of state mixtures were plotted based on maximum aggregate size:

- Figure 1 – Low-Strength mixtures with a maximum aggregate size of 2 inches
- Figure 2 – Low-Strength mixtures with a maximum aggregate size of 1½ inches
- Figure 3 – Low-Strength mixtures with a maximum aggregate size of 1 inch
- Figure ***4*** – Low-Strength mixtures with a maximum aggregate size of ¾ inch

California (06), Nevada (32), and Wisconsin (55) were compared for low-strength mixes with a maximum aggregate size of 2 inches.

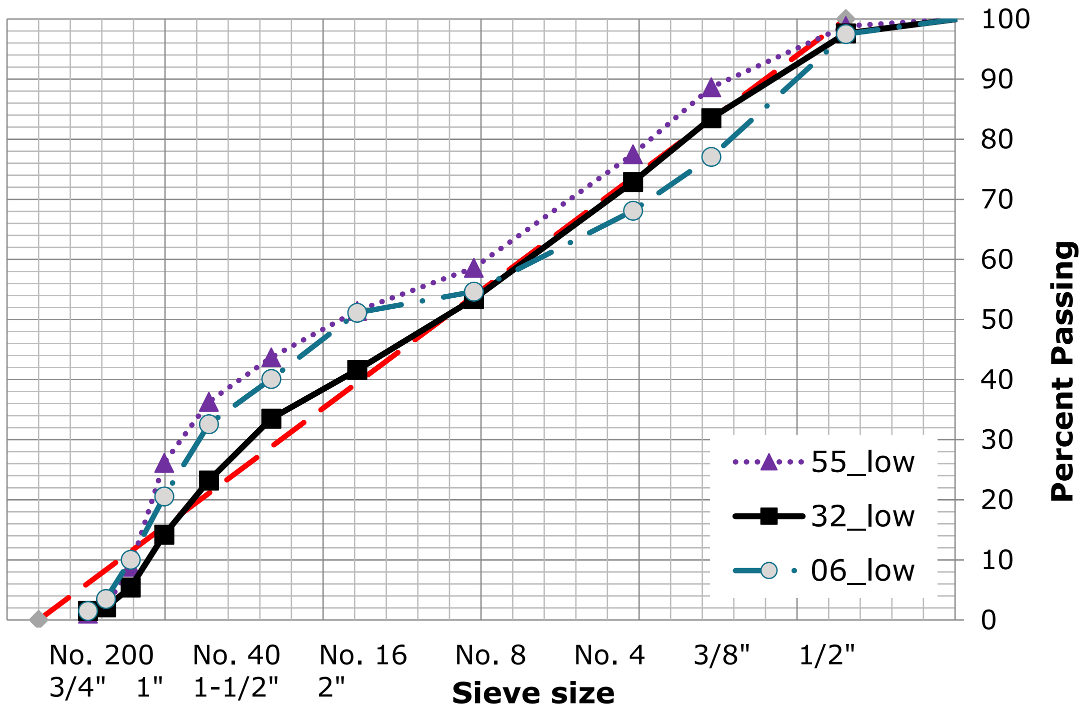


***Figure 1. 0.45 Power Chart for SPS-2 Low-Strength Concrete Mixtures with a Maximum Aggregate Size of 2-inches***

The Nevada (32) mixture appeared to have the most densely graded aggregates, while Wisconsin (55) had the least dense aggregate gradation of the of the three mixtures. The Wisconsin (55) data plotted above the maximum density line, indicating a coarse gradation. Despite these slight irregularities, all three state gradations aligned reasonably close to the maximum density line.

Colorado (08), Delaware (10), North Carolina (37), Ohio (39), and Washington (53) were compared for low-strength concrete mixtures with a maximum aggregate size of 1½ inches.

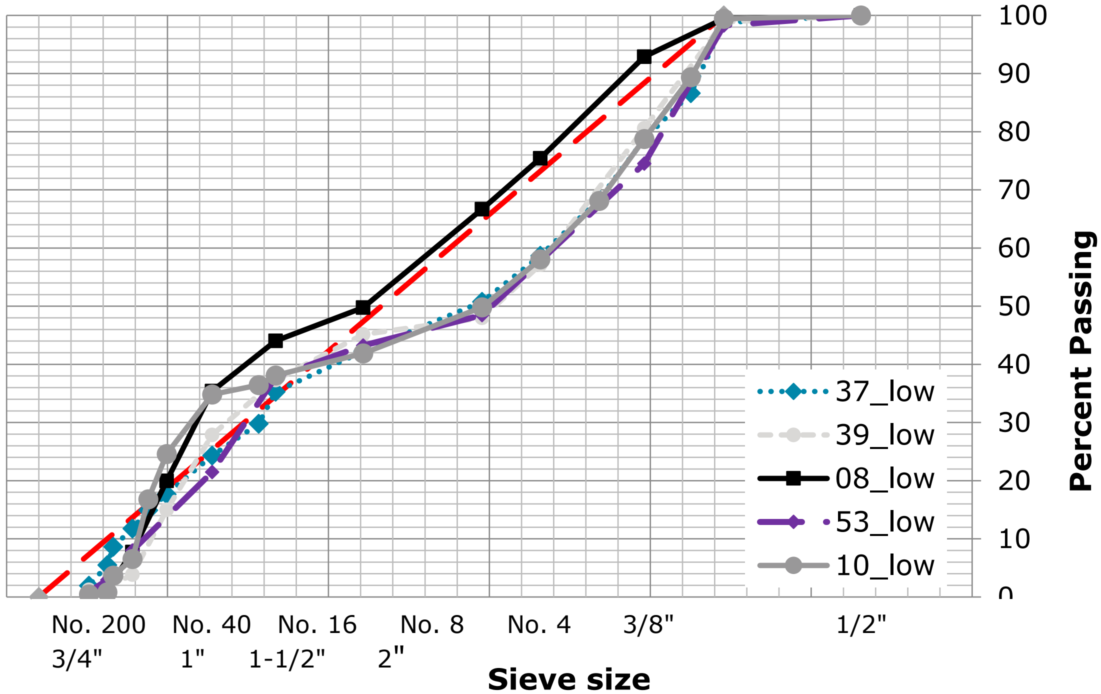


***Figure 2. 0.45 Power Chart for SPS-2 Low-Strength Concrete Mixtures with a Maximum Aggregate Size of 1½ inches***

For this dataset, there was some variation in density shown. Of these gradations, Colorado (08) appeared to have the most densely graded aggregate while the other four gradations shown here, including Delaware (10), North Carolina (37), Ohio (39), and Washington (53), had more significant variation from the maximum density line, all plotting below it. This indicates that these mixtures had a relatively higher fine aggregate content and therefore had the potential to be less workable.

The surface of the low-strength mixture in Washington (53) was noted to be especially coarse on the surface with excessive slump, indicating a wet but coarse mixture. This mixture exhibited a significant deviation (below the maximum density line in Figure 2), indicating a finer gradation and lower aggregate density.

Delaware (10) also noted difficulty in placing the low-strength mixture in its construction report, stating that the mix had excessively high stiffness. This aggregate gradation deviated below the maximum density line, similarly to Washington's (53) low-strength mix.

Significantly, construction reports for Colorado (08) specifically stated that finishing went smoothly and reported no difficulty with the mix workability for the low-strength sections. The Colorado (08) sections most-closely followed the 0.45 maximum density line of the 1½-inch low-strength mixtures examined here.

Arizona (04), Iowa (19), Michigan (26), and North Dakota (38) were compared for low-strength concrete mixtures with a maximum aggregate size of 1 inch.

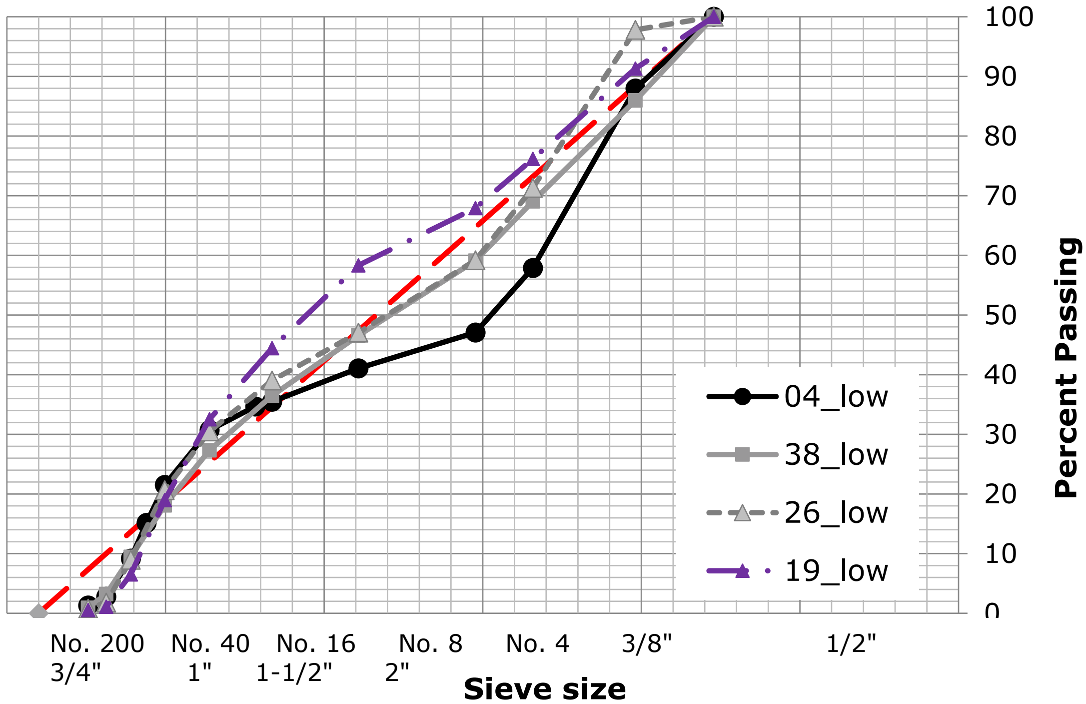


***Figure 3. 0.45 Power Chart for SPS-2 Low-Strength Concrete Mixtures with a Maximum Aggregate Size of 1 inch***

Of the four aggregate gradations, Iowa (19) plotted mostly above the maximum density line, indicating a coarse gradation, while Arizona (04) plotted below the maximum density line, indicating a finer gradation. Michigan (26) and North Dakota (38) plotted very closely to the maximum density line, indicating a relatively well-graded mixture. Despite the marked deviation from the maximum density line, the construction report for Arizona (04) did not note any issues with workability.

Finally, Arkansas (05) and Kansas (20) were compared for low-strength concrete mixtures with a maximum aggregate size of ¾ inch.

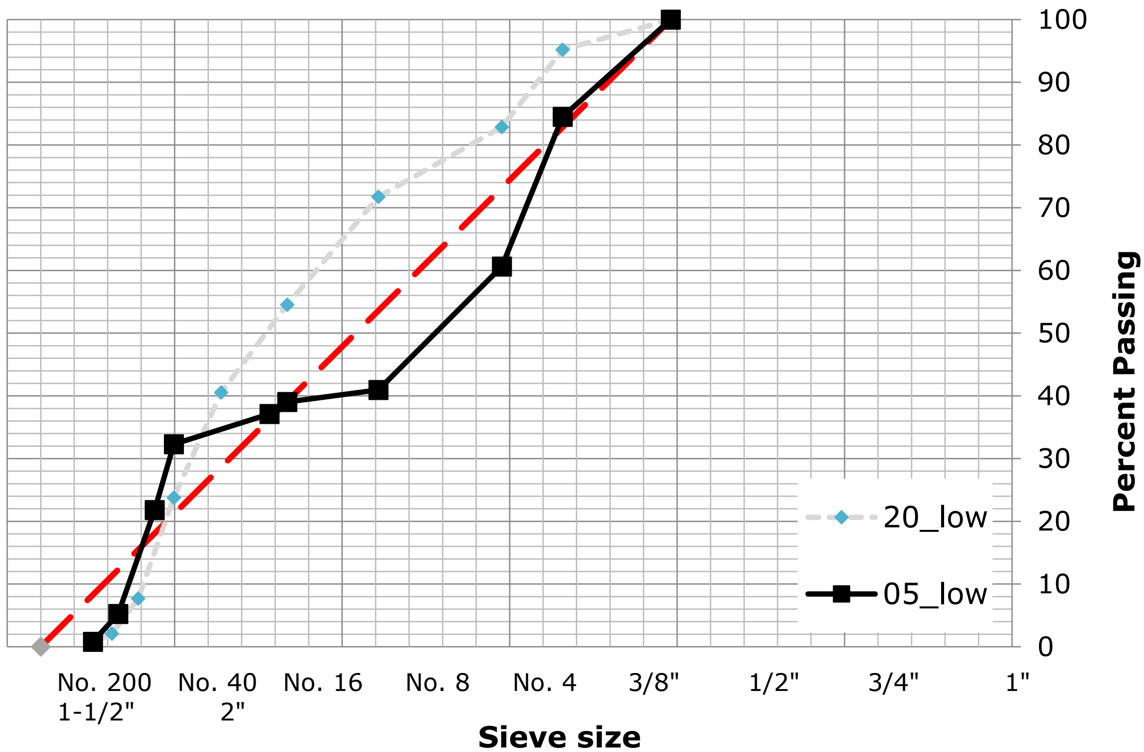


***Figure* 4. *0.45 Power Chart for SPS-2 Low-Strength Concrete Mixtures with a Maximum Aggregate Size of ¾ inch***

Both the Arkansas (05) and Kansas (20) gradations deviated significantly from the maximum density line, indicating potential gap-grading in the aggregate gradations.

Based on the low-strength concrete mixtures, Arkansas (05) and Kansas (20) had the most variation from the maximum density line, while Colorado (08), Nevada (32), and Michigan (26) had aggregate gradations plotting most closely to the maximum density line.

### 3.1.2 HIGH-STRENGTH MIXTURES

The high-strength mixtures (target modulus of rupture of 900 psi) were also grouped by the maximum aggregate size, as shown in the following charts. The maximum density line for each plot is given as a dashed red line.

- Figure 5 – High-Strength mixtures with a maximum aggregate size of 2 inches
- Figure 6 – High-Strength mixtures with a maximum aggregate size of 1½ inches
- Figure 7 – High -strength mixtures with a maximum aggregate size of 1 inch
- Figure 8 – High strength mixtures with a maximum aggregate size of ¾ inch

California (06) and Wisconsin (55) were compared for high-strength mixes with a maximum aggregate size of 2 inches.

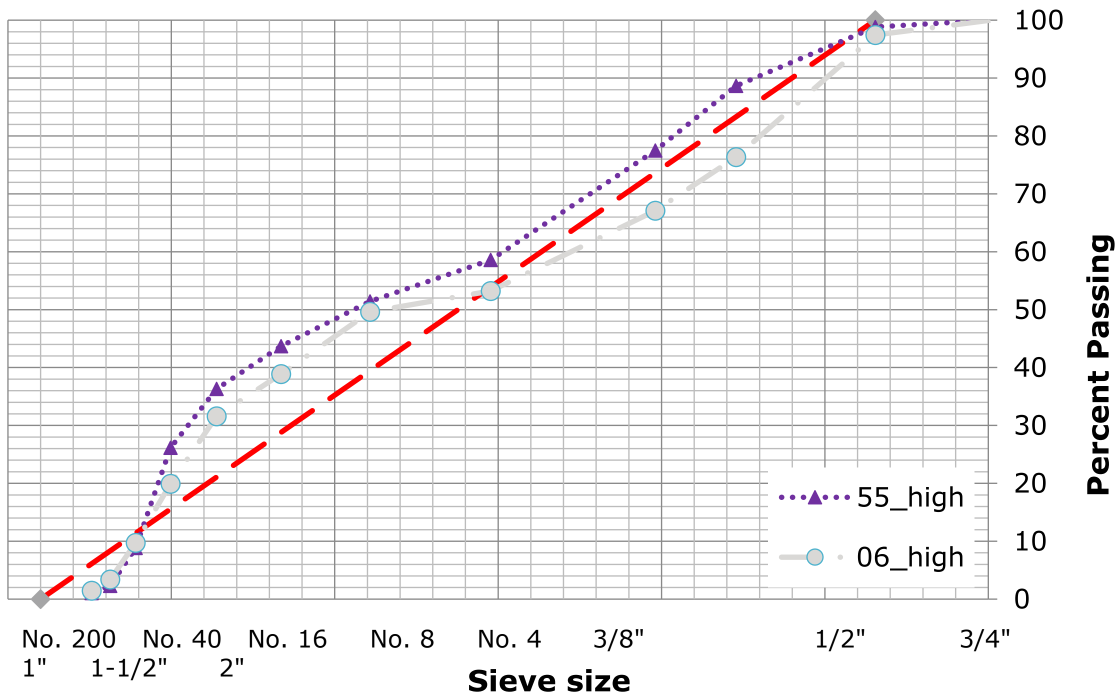


***Figure 5. 0.45 Power Chart for SPS-2 High-Strength Concrete Mixtures with a Maximum Aggregate Size of 2-inches***

Some deviations from the maximum density line for the Wisconsin (55) and California (06) mixtures were observed; however, the California gradation crossed the maximum density line, indicating a denser gradation.

Colorado (08), Delaware (10), North Carolina (37), Ohio (39), and Washington (53) were compared for high-strength concrete mixtures with a maximum aggregate size of 1½ inches.

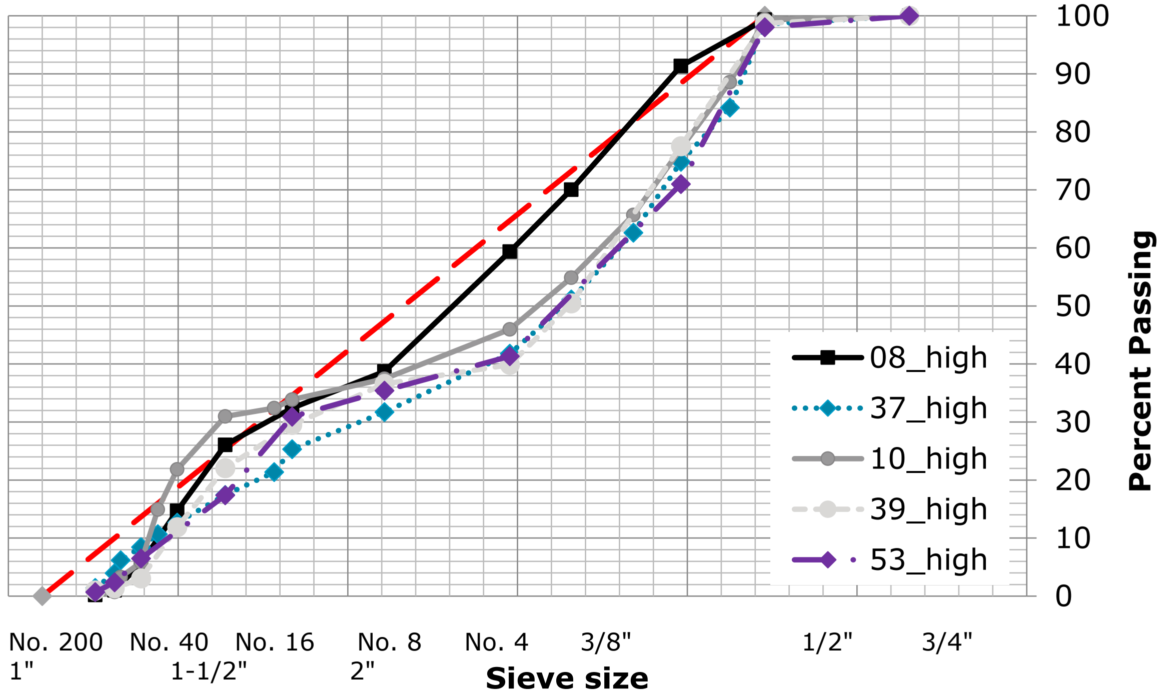


***Figure 6. 0.45 Power Chart for SPS-2 High-Strength Concrete Mixtures with a Maximum Aggregate Size of 1 ½ inches***

Colorado (08) gradations plotted most closely to the maximum density line, as was true for the low-strength mixtures. Again, North Carolina (37), Ohio (39), Delaware (10), and Washington (53) plotted below the maximum density line, indicating gradations that skew toward fine aggregates, which could potentially lead to lower workability and decreased density.

Some construction reports noted workability issues with placing the high-strength mixtures. Delaware (10) noted difficulty placing their high-strength mixture due to high stiffness, and it was also noted that several high-strength sections in North Carolina (37) were difficult to finishing due to mix stiffness. Interestingly, both these aggregate gradations deviated similarly from the maximum density line.

The surface of the high-strength mixture in Washington (53) was noted to be smoother than the lower-strength mix; however, there was a decrease in workability that required more hand-finishing of edges. The Washington (53) gradation also deviated from the maximum density line similar to Delaware (10) and North Carolina (37).

Significantly, the construction report for Colorado (08) specifically stated that finishing went smoothly with no report of any difficulty with the mix workability for the high-strength sections. The aggregate gradation for Colorado (08) plotted most closely to the maximum density line.

Arizona (04), Iowa (19), Michigan (26), Nevada (32), and North Dakota (38) were compared for high-strength concrete mixtures with a maximum aggregate size of 1 inch.

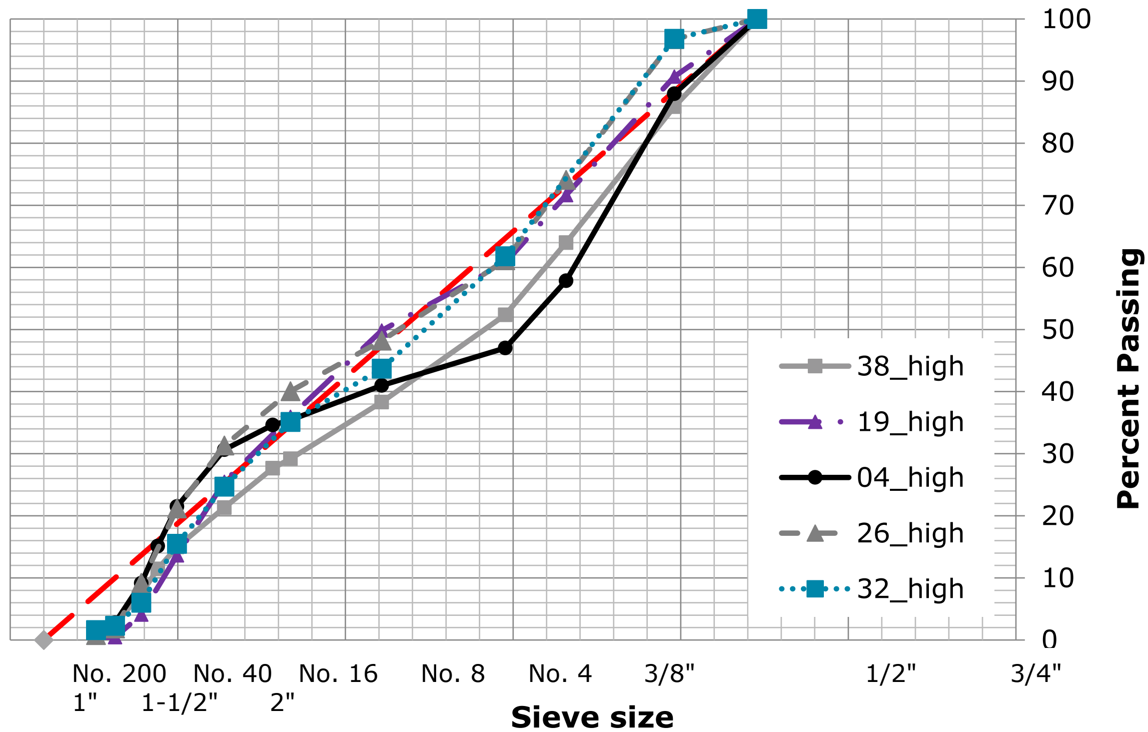


***Figure 7. 0.45 Power Chart for SPS-2 High-Strength Concrete Mixtures with a Maximum Aggregate Size of 1 inch***

For these mixtures, Arizona (04) again deviated most prominently from the maximum density line, followed by North Dakota (38) while Nevada (32), Michigan (26), and Iowa (19) plotted very closely to the maximum density line.

Finally, Arkansas (05) and Kansas (20) were compared for high-strength concrete mixtures with a maximum aggregate size of ¾ inch.

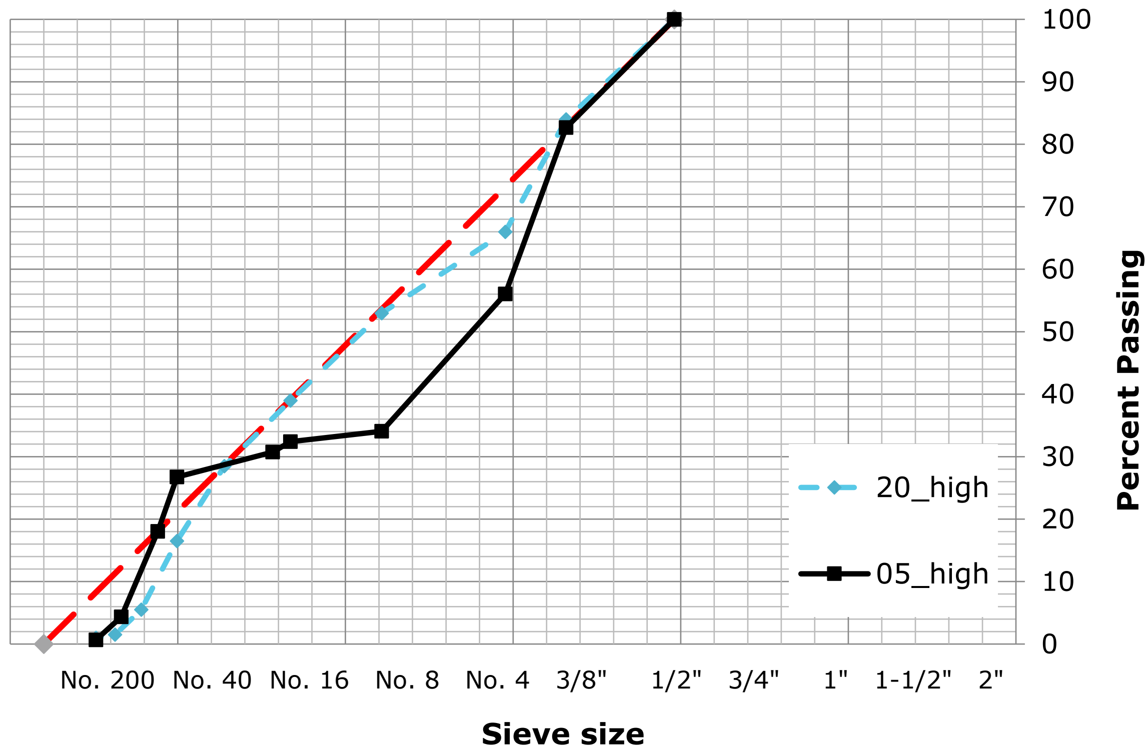


***Figure 8. 0.45 Power Chart for SPS-2 High-Strength Concrete Mixtures with a Maximum Aggregate Size of ¾ inch***

Compared to its low-strength mixture, Kansas (20) appeared to have a much denser aggregate gradation, while Arkansas (05) again appeared to have an irregular gradation veering significantly from the maximum density line.

Interestingly, Arkansas (05) exhibited one of the highest deviations from the maximum density line of the gradations evaluated and also had many test sections exhibit significant distress and early failures, as outlined previously in Dufalla and Senn (2021). However, Michigan (26) and Nevada (32) had some of the most consistently dense gradations when plotted against the maximum density lines and the test sections in both these states also exhibited extreme early failures. This could indicate that performance issues with these test sections were most likely due to factors outside of the aggregate gradation.

## 3.2 Comparison of Aggregate Gradations Based on Coarseness Factor - Workability Factor Chart

The coarseness factor – workability factor chart plots a concrete mixture's calculated coarseness factor against the workability factor, providing an indication of the workability of the concrete mixture based largely on aggregate gradations. Developed by Shilstone (1990), the coarseness factor is defined as the percent of the combined aggregate retained on the No. 8 sieve that is also retained on the 3/8-inch sieve and is given in Equation 1. The workability factor is the percent of the combined aggregate that passes the No. 8 sieve and includes a correction for workability to include cement content beyond a standard 6-sack concrete mix (564 pounds/cubic yard) and is given in Equation 2.

$$Coarseness\ Factor\ (CF) = \left(\frac{Cumulative\ \%\ Retained\ on\ the\ 3/8"\ sieve}{Cumulative\ \%\ Retained\ on\ the\ No.8\ sieve}\right) \times 100 \qquad (1)$$

$$Workability\ Factor\ (WF) = \%\ Total\ aggregate\ passing\ the\ No.8\ sieve + \frac{Total\ cementitious\ materials\ content\ \left(in\ \frac{lbs}{CY}\right) - 564\ \frac{lbs}{CY}}{94} \qquad (2)$$

The coarseness factor and workability factor are then plotted together on the standardized Coarseness Factor – Workability Factor Chart to determine the placement of the mixture within one of the five established workability zones:

- Zone I indicates that the aggregate gradation is coarse and gap graded.
- Zone II indicates a well-graded, dense aggregate mixture.
- Zone III indicates an aggregate gradation graded less than the ¾-inch sieve.
- Zone IV indicates a sticky mixture with excessive fines content .
- Zone V indicates a rocky aggregate mixture that tends to behave non-plastically.

Zone II is considered an ideal aggregate grading for concrete pavements. The coarseness factor – workability factor chart for the low-strength concrete mixtures is given in Figure 9 and in Figure 10 for the high-strength concrete mixtures.

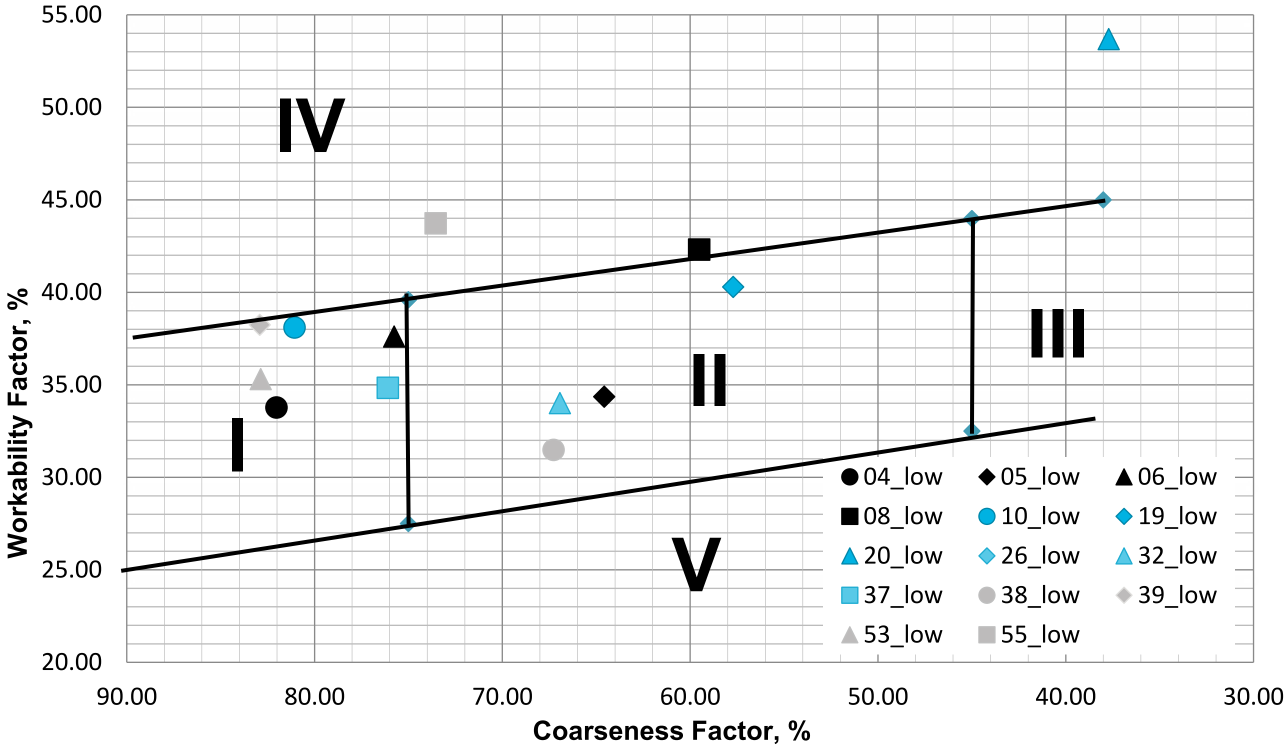


***Figure 9. Coarseness Factor – Workability Factor Chart for Low-Strength (550 psi) Concrete Mixtures***

The low-strength aggregate gradations predominately plotted in three zones: Zone I (Gap Graded – Coarse), Zone II (Well-Graded), and Zone IV (Excessive Fines – Sticky). No gradations from the low-strength mixtures fell in Zone V (Rocky) or Zone III (Well-Graded for ¾-minus gradations). Most gradations fell within Zone I (Gap Graded – Coarse). Significantly, the gradations in Zone II included the low-strength mixtures from Michigan (26), Nevada (32), and Arkansas (05), which were found previously to exhibit significant early failure. This observation supplements the early failure discussion given previously in Dufalla and Senn (2021), indicating that the significant early failures and overall lower performance of these three SPS-2 state agency test sections were likely not a result of the aggregate gradations, which are shown here as nearly optimal.

The surface of the 550 psi mixture in Washington (53) was noted to be especially coarse on the surface with excessive slump, indicating a wet but coarse mixture. It can be seen from Figure 9 that the low-strength mixture for Washington (53) had one of the highest coarseness factors of all low-strength mixtures, plotting in Zone I (Gap Graded – Coarse). It was noted in the construction report that additional forms were required due to the softness of the mix.

Additionally, the low-strength Delaware (10) mixture was noted to be difficult to place in the construction report due to excessively high stiffness. This aggregate gradation also plotted well within the boundaries of Zone I (Gap Graded – Coarse).

Significantly, the thorough construction reports for Arizona (04) and Colorado (08) specifically stated that finishing went smoothly and none reported any difficulty with mix workability for the low-strength sections. Arizona (04) plotted similarly to Delaware (10) and Washington (53) in Zone I, while Colorado (08) plotted very differently in Zone IV (Excessive Fines – Sticky). This may indicate that, despite the potential to segregate, adequate finishing and workability are possible using a mixture with excessive fines if favorable conditions and correct construction techniques are applied.

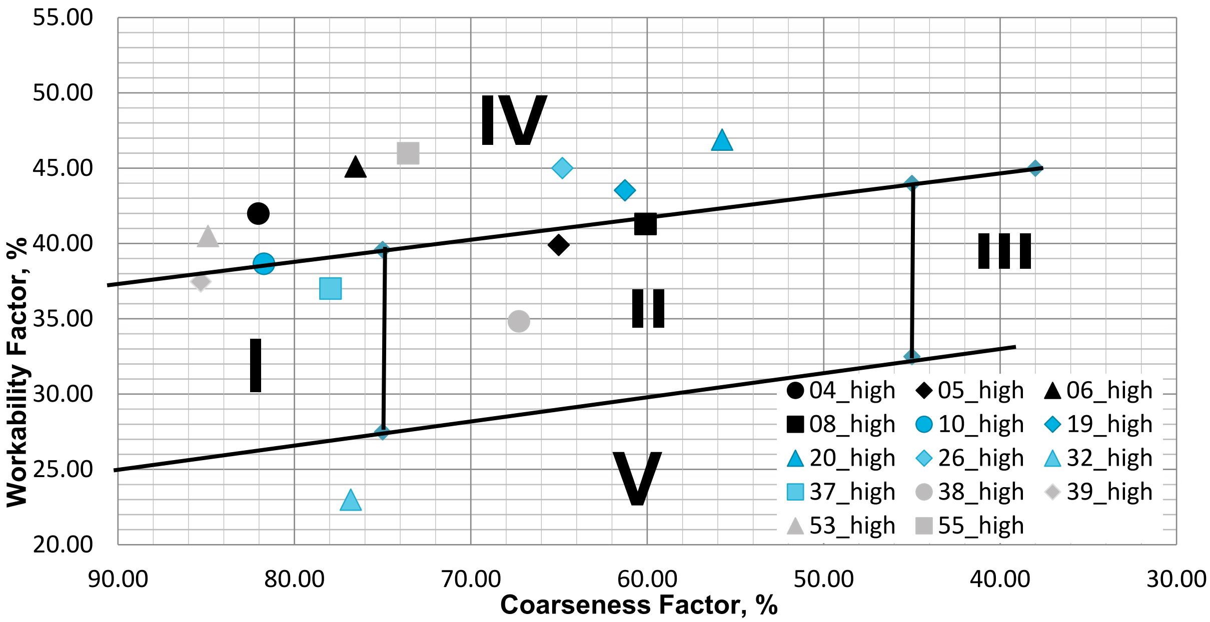


***Figure 10. Coarseness Factor – Workability Factor Chart for High-Strength (900 psi) Concrete Mixtures***

The high-strength mixtures, shown in Figure 10, primarily plotted in three zones: Zone I (Gap Graded – Coarse ), Zone II (Well-Graded) and Zone IV (Excessive Fines – Sticky). One gradation – the high-strength mixture for Nevada (32) test sections – is plotted in Zone V. Significantly, both North Dakota (38) and Arkansas (05) plotted in the well-graded zone for both high- and low-strength mixtures.

Some construction reports noted workability issues with placing the high-strength mixtures, including Delaware (10), which reported difficulty placing due to high stiffness, and several sites in North Carolina (37), which reported difficulty in finishing due to mix stiffness. Interestingly, both of these mixtures were plotted within Zone I (Gap Graded – Coarse).

The surface of the high-strength Washington (53) section was noted to be smoother than the low-strength section; however, there was a decrease in workability that required more hand-finishing of edges. The Washington (53) gradation plotted within Zone IV (Excessive Fines – Sticky).

Significantly, the thorough construction reports for Arizona (04) and Colorado (08) specifically stated that finishing went smoothly and no difficulty was reported with the mix workability for the high-strength sections. The aggregate gradation for Colorado (08) plotted within the optimal Zone II for a well-graded aggregate while Arizona (04) plotted within Zone IV (Excessive Fines – Sticky).

Many mixtures shifted from Zone I (Gap Graded – Coarse) to Zone IV (Excessive Fines – Sticky) in the transition from low-strength mixtures to high-strength mixtures. A summary of the aggregate gradations plotted in each zone for both low- and high-strength mixtures is shown in Table 3.

***Table 3. Summary of Coarseness Factor – Workability Factor Chart Results for Low- and High-Strength Concrete Mixtures***

| Zone | Description | Low-Strength Mixtures | High-Strength Mixtures |
|---|---|---|---|
| Zone I | Coarse gap-graded aggregate mix that tends to segregate | 04 (Arizona)<br>06 (California)<br>10 (Delaware)<br>37 (North Carolina)<br>39 (Ohio)<br>53 (Washington) | 37 (North Carolina)<br>39 (Ohio) |
| Zone II | Well graded mix in sizes between 2-inch and ¾-inch maximum aggregate size | 05 (Arkansas)<br>19 (Iowa)<br>26 (Michigan)<br>32 (Nevada)<br>38 (North Dakota) | 05 (Arkansas)<br>08 (Colorado)<br>38 (North Dakota) |
| Zone III | ¾-inch minus aggregate mixtures | None | |
| Zone IV | Excessive fines mixtures – sticky | 08 (Colorado)<br>20 (Kansas)<br>55 (Wisconsin) | 04 (Arizona)<br>06 (California)<br>10 (Delaware)<br>19 (Iowa)<br>20 (Kansas)<br>26 (Michigan)<br>53 (Washington)<br>55 (Wisconsin) |
| Zone V | Non-plastic mixtures – rocky | | 32 (Nevada) |

The shift between low-strength mixtures (most commonly plotted in Zone I) and high-strength mixtures (most commonly plotted in Zone IV) resulted from most agencies increasing the proportion of fine aggregate, which would likely cause a drop in workability between the two mixtures. While mixtures in Zone I tend to segregate, they are not unworkable, whereas aggregate gradations plotted in Zone IV do have a marked decrease in workability.

Gradations for each individual test section were used to calculate the coarseness factor and workability factor for each mixture. The performance of each of these test sections was then defined based on the criteria outlined previously in Table 1. Each test section was assigned a performance rating (Good, Fair, or Poor) based on the provided criteria and based on its lowest performance in each of the three performance criteria: roughness (measured as IRI), percent slabs cracked, and wheel-path faulting. The results of this evaluation are given in Figure 11, Figure 12, and Figure 13.

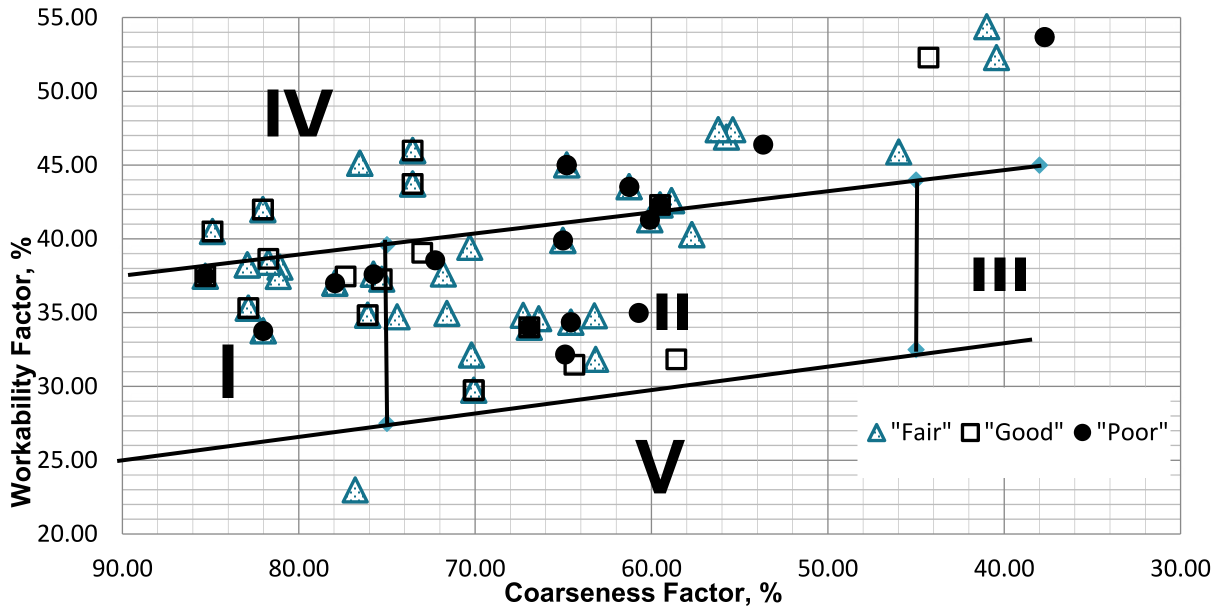


***Figure 11. Coarseness Factor – Workability Factor Chart Based on Measured Roughness Performance of All Test Sections***

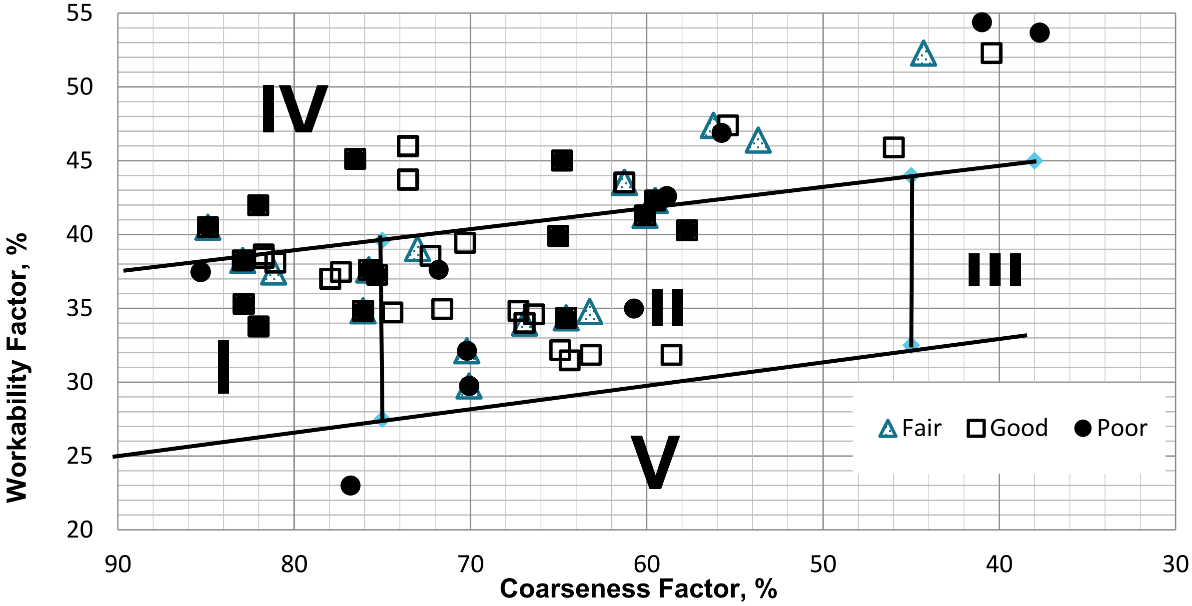


***Figure 12. Coarseness Factor – Workability Factor Chart Based on Measured Cracking Performance of All Test Sections***

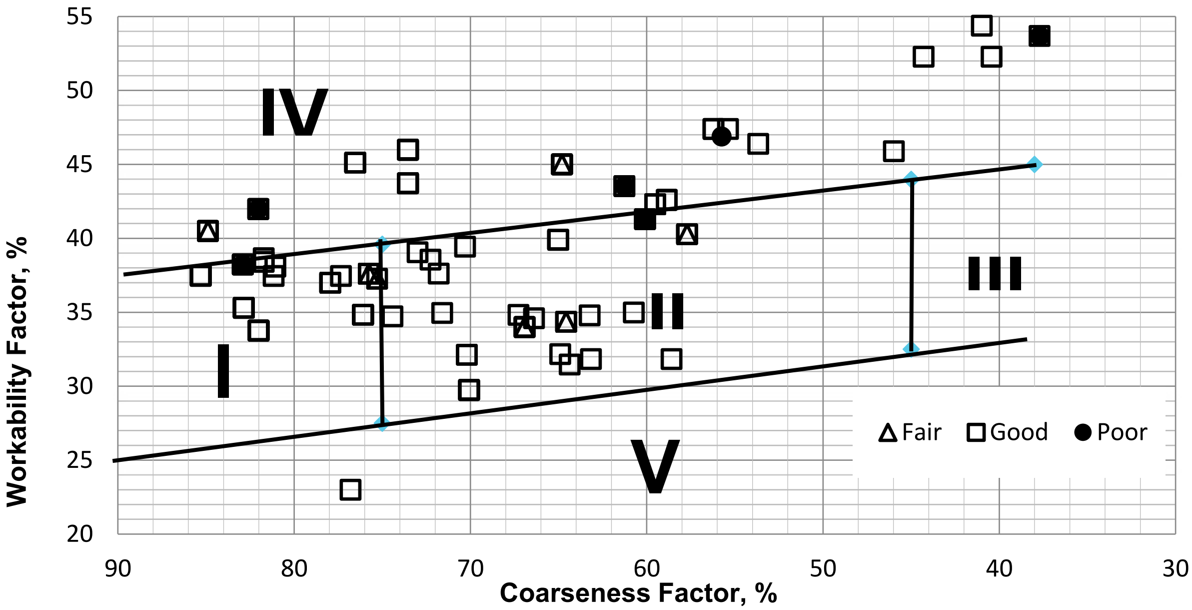


***Figure 13. Coarseness Factor – Workability Factor Chart Based on Measured Wheel-Path Faulting Performance of All Test Sections***

There is significant scatter observed in the data. However, several trends can be observed. A summary of how many test sections were categorized by each performance metric organized by specific performance criteria are shown in Table 4.

***Table 4. Summary of Coarseness Factor – Workability Factor Chart Results for Low and High-Strength Concrete Mixtures***

| Performance Criteria | Performance Rating | Plotted CF-WF Zone | Number of Sections | Percent of Sections in this Zone by Performance Rating |
|---|---|---|---|---|
| IRI | Good | Zone I | 16 | 52% |
| | | Zone II | 13 | 42% |
| | | Zone IV | 2 | 6% |
| | | Zone V | 0 | 0% |
| | Fair | Zone I | 48 | 44% |
| | | Zone II | 55 | 50% |
| | | Zone IV | 0 | 6% |
| | | Zone V | 7 | 0% |
| | Poor | Zone I | 4 | 17% |
| | | Zone II | 16 | 67% |
| | | Zone IV | 3 | 12.5% |
| | | Zone V | 1 | 4% |
| Cracking | Good | Zone I | 34 | 40% |
| | | Zone II | 46 | 55% |
| | | Zone IV | 4 | 5% |
| | | Zone V | 0 | 0% |
| | Fair | Zone I | 6 | 24% |
| | | Zone II | 15 | 60% |
| | | Zone IV | 4 | 16% |
| | | Zone V | 0 | 0% |
| | Poor | Zone I | 29 | 51% |
| | | Zone II | 23 | 40% |
| | | Zone IV | 4 | 7% |
| | | Zone V | 1 | 2% |
| Faulting | Good | Zone I | 63 | 43% |
| | | Zone II | 75 | 51% |
| | | Zone IV | 10 | 7% |
| | | Zone V | 0 | 0% |
| | Fair | Zone I | 4 | 40% |
| | | Zone II | 5 | 50% |
| | | Zone IV | 0 | 0% |
| | | Zone V | 1 | 10% |
| | Poor | Zone I | 2 | 25% |
| | | Zone II | 4 | 50% |
| | | Zone IV | 2 | 25% |
| | | Zone V | 0 | 0% |

First, it can be seen from the above data that most test sections that exhibited "Good" roughness performance (as measured by IRI) were in Zone I (Gap Graded – Coarse), while most test sections exhibiting "Fair" or "Poor" roughness performance were plotted in Zone II (Well-Graded), considered an ideal aggregate gradation.

However, most test sections that exhibited "Good" and "Fair" cracking performance were plotted within Zone II (Well-Graded) while most test sections exhibiting "Poor" cracking performance were plotted in Zone I (Gap Graded – Coarse). Finally, most test sections achieving "Good," "Fair," or "Poor" performance against faulting were plotted within Zone II (Well-Graded). Therefore, it was difficult to observe trends between the plotted Zone and the final performance.

The Coarseness Factor – Workability Factor does indicate certain characteristics by aggregate zone, such as tendency to segregate, and could correlate to performance, the chart is best used providing an indication of the workability of the fresh concrete itself. Therefore, while there were not significant relationships found between the Coarseness Factor – Workability Factor zones, there were corroborating relationships between the observed workability of these mixtures and their location on the Coarseness Factor – Workability Factor chart. No concrete mixtures whose aggregate gradation plotted in Zone II had any observed difficulties in finishing, per the original construction reports. Several sections with noted difficulties, however, plotted in either Zone I (Gap Graded – Coarse) or Zone IV (Excessive Fines – Sticky).

## 3.3 Comparison of Aggregate Gradations Based on Tarantula Curve

Oklahoma DOT commissioned a study to further optimize aggregate gradations for slipform pavements. Their goal was to find a balance between a suitably dense concrete matrix for durability concerns and a workable mix. This extended testing resulted in a modified, combined grading percent retained chart, known as the Tarantula Curve, intended to replace the previously popular 8 -18 chart, which set limits on the percent retained on each sieve between 8% and 18% to minimize the uniformity of a mixture's aggregate size. The Tarantula curve (Cook et al. 2015) provides modified boundaries for a restricted percent retained plot as well as checks for the coarse and fine sand portions. These boundaries provide an indication of whether suitable mixture workability can be achieved with a lower paste content. For aggregate gradations that plot outside of the boundaries provided, workability can be increased with an increased paste volume; however, increased paste volume can make the concrete more susceptible to shrinkage cracking throughout its lifespan.

The aggregate gradations for low-strength concrete mixtures are given in Figure 14 and Figure 15, with the Tarantula curve boundaries included as red dashed lines. The three primary restrictions on the Tarantula curve are:

- To limit the fine material, between the No. 50 and No. 30 sieves, to improve workability
- To limit the intermediate material between the No. 8 to the No. 16 sieve, to decrease finishing problems
- To decrease the coarse material above the No. 4 sieve, to increase workability and decrease the likelihood of segregation

The boundaries of the Tarantula curve were developed and applied to concrete mixture issues regarding workability and constructability rather than performance metrics.

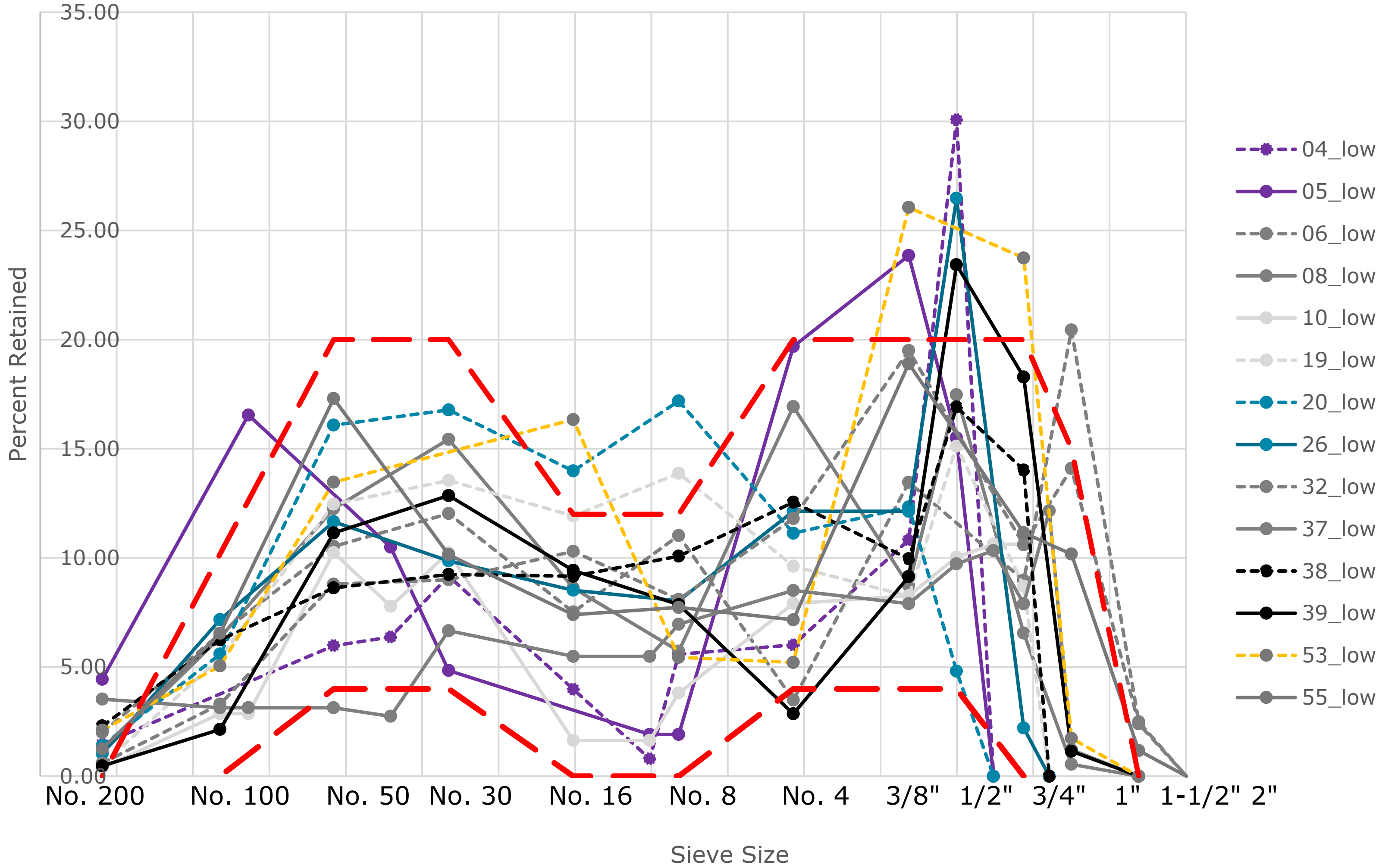


***Figure 14. Tarantula Curve for Low-Strength Mixture Aggregate Gradations***

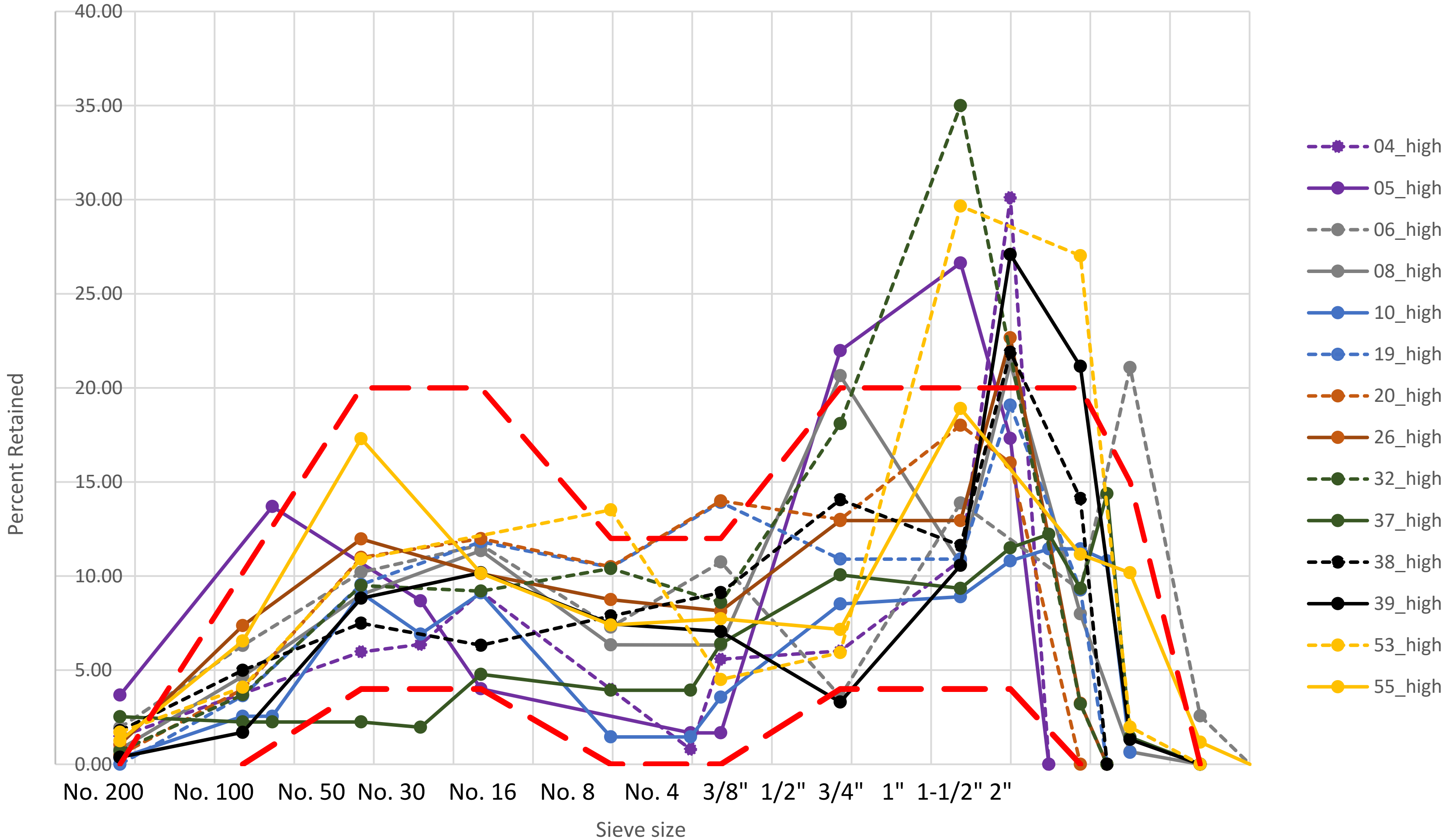


***Figure 15. Tarantula Curve for High-Strength Mixture Aggregate Gradations***

In both plots, the majority of aggregate gradations fell within the requirements of the Tarantula curve with notable exceptions for material between the 3/8-inch and 1-inch sieves. For low-strength mixtures, Arizona (04), Arkansas (05), Michigan (26), Ohio (39) and Washington (53) contained fine aggregate contents outside of the allowable boundaries of the Tarantula curve. Iowa (19), Kansas (20), and Washington (53) also contained too much of the intermediate sized material between the No. 4 and No. 16 sieves as recommended for the Tarantula curve.

For the high-strength mixtures, again the most common deviation from the Tarantula curve was excessive material between the 3/8-inch and 1-inch sieves; Arizona (04), Arkansas (05), Michigan (26), Nevada (32), North Carolina (37), North Dakota (38), Ohio (39) and Washington (53) all fell outside of the boundaries of the Tarantula curve for this material. As was true for the low-strength mixtures, Iowa (19), Kansas (20), and Washington (53) contained too much intermediate-sized aggregates between the No. 4 and No. 16 sieve.

However, to provide an indication of workability, the amount of paste should be considered for the mixtures that were extremely outside of the limits of the plot. These outliers and their paste volumes are given in Table 5.

***Table 5. Aggregate Gradations with Substantial Deviation from Tarantula Curve***

| State code | Mix Type | Paste Volume |
|---|---|---|
| 04 (Arizona) | Low-Strength | 24% |
| | High-Strength | 33% |
| 05 (Arkansas) | Low-Strength | 20% |
| | High-Strength | 33% |
| 26 (Michigan) | Low-Strength | 20% |
| 32 (Nevada) | High-Strength | 32% |
| 39 (Ohio) | Low-Strength | 26% |
| | High-Strength | 33% |
| 53 (Washington) | Low-Strength | 23% |
| | High-Strength | 34% |

Aggregate gradations falling outside of the Tarantula curve are prone to workability issues, which may be supplemented by increasing paste volume. As shown in Table 5, the high-strength mixtures had higher paste volume than the low-strength mixtures, which would likely cover workability issues resulting from the aggregate gradation. The impact of paste volume is discussed in Section 5.1.

## 3.4 Summary of Mix Constructability

Information from the previously presented aggregate analyses can be combined to evaluate the constructability and performance of the concrete mixtures. The three methods of comparing the workability and density of aggregate gradations used – the 0.45 power chart, the Coarseness Factor – Workability Factor Chart, and the Tarantula curve, provided good consistency between density and workability observations between these mixtures.

Comparison with the 0.45 power chart revealed some interesting trends of the mixtures that were corroborated with observations from the original construction reports. There was noted and significant deviation from the maximum density line for the Washington (53), Delaware (10), and North Carolina (37) test sections, all of which reported difficulty in the workability of these mixtures in the original construction reports. Interestingly, the aggregate gradation for Colorado (08) plotted very closely to the maximum density line and it was noted in the construction report that these mixtures finished easily and without problems. These trends were reflected somewhat similarly across the other methods of comparing aggregate gradations. Table 6 summarizes the results of these analyses for the SPS-2 mixtures by state.

***Table 6. Summary of Aggregate Gradation Parameters for SPS-2 Mixtures***

| State | Mix Type | 0.45 Power Chart | Coarseness Factor Chart | Tarantula Curve | Workability Issues |
|---|---|---|---|---|---|
| Arizona (04) | 550 psi | Moderate deviation | Zone I | Excessive 3/8″ – 1″ material | Excellent finishing |
| | 900 psi | Moderate deviation | Zone IV | Excessive 3/8″ – 1″ material | Excellent finishing |
| Arkansas (05) | 550 psi | Significant deviation | Zone II | Excessive 3/8″ – 1″ material | |
| | 900 psi | Significant deviation | Zone II | Excessive 3/8″ – 1″ material | |
| California (06) | 550 psi | Moderate deviation | Zone I | Excessive +1″ material | |
| | 900 psi | Moderate deviation | Zone IV | Excessive +1″ material | |
| Colorado (08) | 550 psi | Dense | Zone IV | | Excellent finishing |
| | 900 psi | Dense | Zone II | Excessive 3/8″ – 1″ material | Excellent finishing |
| Delaware (10) | 550 psi | Moderate deviation | Zone I | | Difficulty finishing mixes |
| | 900 psi | Moderate deviation | Zone IV | Excessive 3/8″ – 1″ material | Difficulty finishing mixes |
| Iowa (19) | 550 psi | Moderate deviation | Zone II | Excessive No. 8 to No. 16 material | |
| | 900 psi | Dense | Zone IV | Excessive 3/8″ – 1″ material | |
| Kansas (20) | 550 psi | Significant deviation | Zone IV | Excessive No. 8 to No. 16 material | |
| | 900 psi | Dense | Zone IV | Excessive 3/8″ – 1″ material | |
| Michigan (26) | 550 psi | Dense | Zone II | Excessive 3/8″ – 1″ material | |
| | 900 psi | Dense | Zone IV | Excessive 3/8″ – 1″ material | |
| Nevada (32) | 550 psi | Dense | Zone II | | |
| | 900 psi | Dense | Zone V | | |
| North Carolina (37) | 550 psi | Moderate deviation | Zone I | Insufficient sub-50 material | |
| | 900 psi | Moderate deviation | Zone I | Insufficient sub-50 material | Difficulty finishing mix |
| North Dakota (38) | 550 psi | Dense | Zone II | | |
| | 900 psi | Moderate deviation | Zone II | Excessive 3/8″ – 1″ material | |
| Ohio (39) | 550 psi | Moderate deviation | Zone I | Excessive 3/8″ – 1″ material | |
| | 900 psi | Moderate deviation | Zone I | Excessive 3/8″ – 1″ material | |
| Washington (53) | 550 psi | Moderate deviation | Zone I | Excessive 3/8″ – 1″ material | Difficulty finishing mixes |
| | 900 psi | Moderate deviation | Zone IV | Excessive No. 8 to No. 16 material | Difficulty finishing mixes |
| Wisconsin (55) | 550 psi | Moderate deviation | Zone IV | | |
| | 900 psi | Moderate deviation | Zone IV | Excessive 3/8″ – 1″ material | |

# 4.0 COMPARISON OF MIX DESIGN PARAMETERS

While observations of the density of the aggregate gradations provided some insight into the constructability and workability of the concrete mixtures, other mix design parameters might provide a stronger indication of the performance of the mixtures themselves. Parameters including the paste volume, the density of the concrete mixture, the w/cm ratio, the total cementitious materials content, and the use of supplementary cementitious materials in each mixture were examined and correlated to the performance indicators (roughness, percent slabs cracked, and wheel-path faulting). All concrete mix design data, acquired from the original construction reports for the SPS-2 experiments, and factors calculated from this data and discussed in this test section are given in the Appendix.

## 4.1 Comparison of Paste Volume

The paste volume of concrete mixtures describes the volume of paste (cementitious materials and water) to the total volume of the concrete mixture. It is increasingly being recognized that a higher paste volume generally indicates an increased susceptibility to shrinkage and consequently, shrinkage cracking. It has been found that reducing the paste volume of a mixture can decrease the shrinkage of a concrete mixture. Previously, Ley and Weiss (2015) recommended that a concrete paste volume should be restricted to a maximum of 28% to reduce the free shrinkage of the concrete. The paste volume for each SPS-2 concrete mixture was calculated and is compared in Table 7.

***Table 7. Summary of Calculated Paste Volumes by State Mix Design***

| State | Paste Volume (%) | |
|---|---|---|
| | Low-Strength Mixes (550 psi) | High-Strength Mixes (900 psi) |
| Arizona (04) | 24.1% | 32.6% |
| Arkansas (05) | 20.4% | 33.2% |
| California (06) | 31.6% | 41.6% |
| Colorado (08) | 24.4% | 33.6% |
| Delaware – 1 (10) | 27.6% | 32.3% |
| Delaware – 2 (10) | 25.7% | 29.7% |
| Iowa (19) | 21.2% | 35.4% |
| Kansas (20) | 25.8% | 34.1% |
| Michigan (26) | 19.6% | 31% |
| Nevada (32) | 20.2% | 31.8% |
| North Carolina (37) | 26.6% | 38.4% |
| North Dakota (38) | 17.6% | 30.6% |
| Ohio (39) | 26.4% | 33.4% |
| Washington (53) | 23% | 34.3% |
| Wisconsin (55) | 24.3% | 23.5% |
| **Average** | **23.9%** | **33.0%** |

The data indicate that the low-strength mixtures had smaller paste volumes than the high-strength mixtures. The strategy for concrete design by many agencies during the time of the SPS-2 construction indicated that higher strength was often achieved by increasing the cement content, which in turn, generally increases the paste volume. The result is that the average paste volume of the low-strength mixtures was 23.9%, well under the recommended maximum of 28%, and the average paste volume for high-strength mixtures was 33%, which exceeded the recommended maximum value. The impact of the paste volume on the IRI, percent slabs cracked and wheel-path faulting of each test section is given in Figure 16, Figure 17, and Figure 18, respectively.

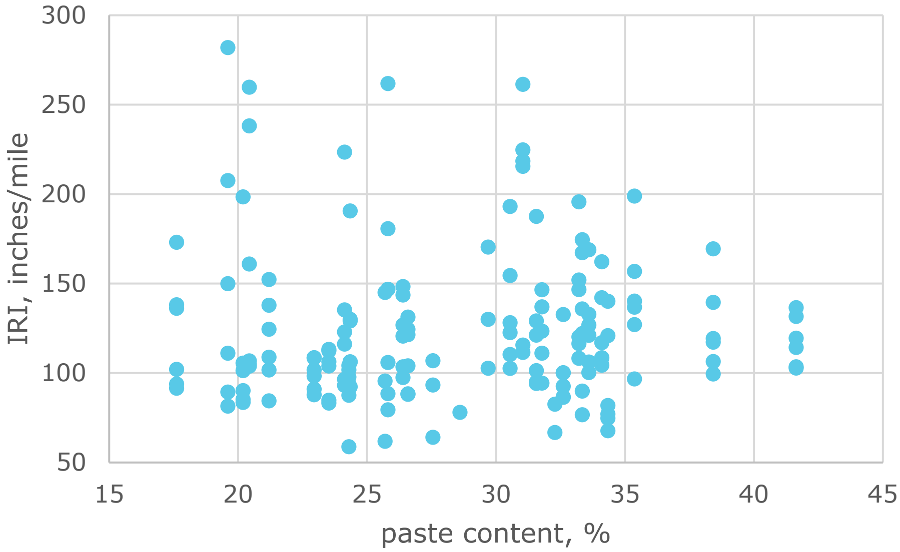


***Figure 16. Paste Content vs. IRI for all SPS-2 Test Sections***

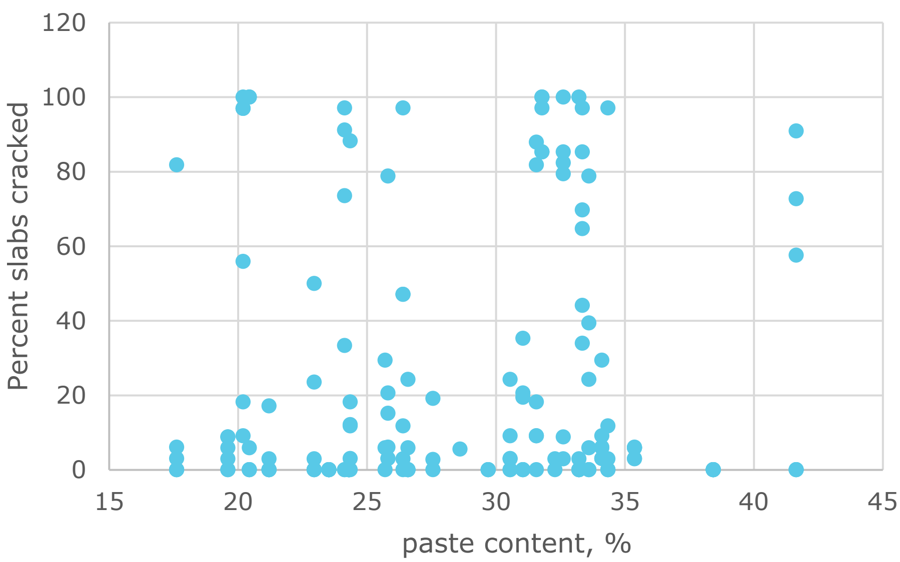


***Figure 17. Paste Content vs. Percent Slabs Cracked for all SPS-2 Test Sections***

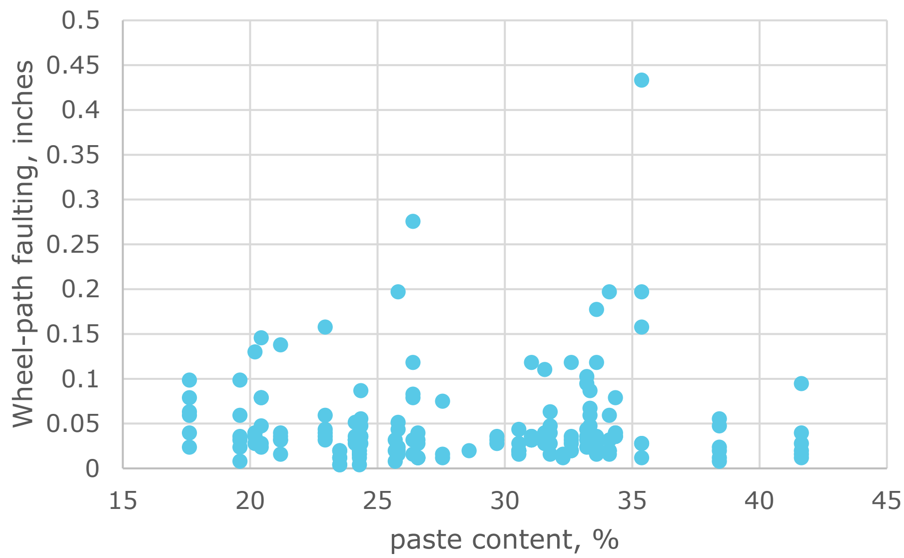


***Figure 18. Paste Content vs. Wheel-Path Faulting for all SPS-2 Test Sections***

While there is considerable scatter within the data, there are more sites exhibiting 100% slabs cracked with a higher paste volume than test sections with a lower paste volume. To observe these trends more clearly, the performance of each test section was assigned to qualitative performance parameters using the criteria outlined previously in Table 1. This assigned each test section a rating of "Good", "Fair," or "Poor" based on its measured performance; the results are shown in Figure 19, Figure 20, and Figure 21.

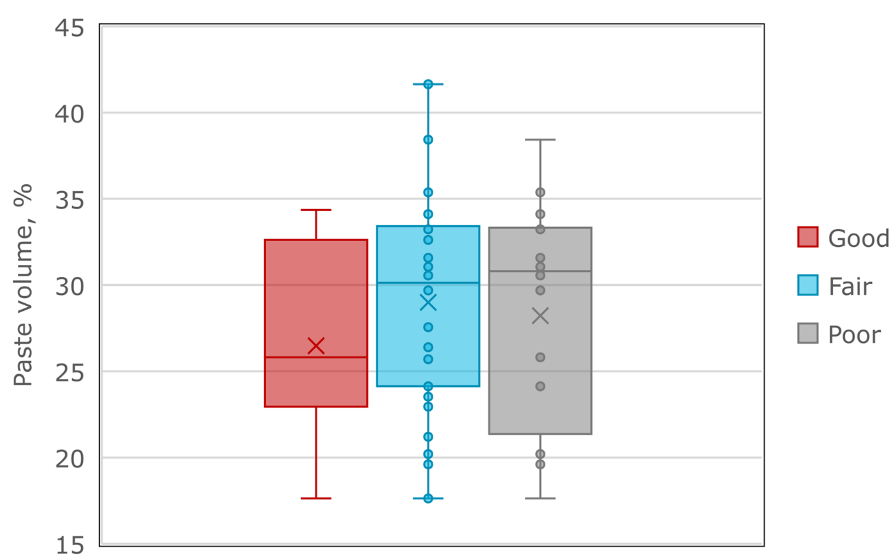


***Figure 19. IRI Performance vs. Paste Volume***

Despite the observed scatter, it can be seen from the box-and-whisker plot that the median paste volume across sections receiving a "Poor" rating with respect to roughness (measured at IRI) is higher than the median paste volume for test sections receiving a "Fair" rating for roughness. The sections receiving a "Good" rating for roughness on average had the lowest paste volume of all test sections.

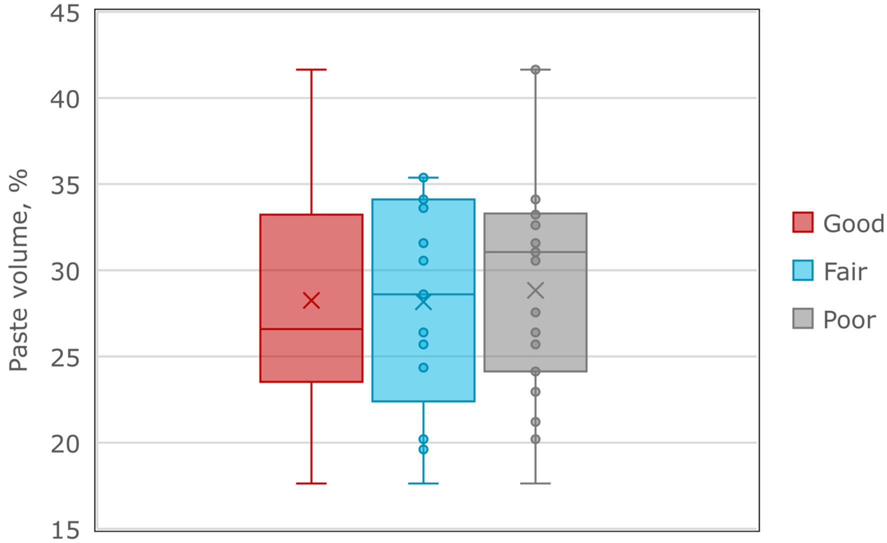


***Figure 20. Slab Cracking Performance vs. Paste Volume***

While there is considerable scatter in the distribution, again it can be seen the trends observed between roughness and paste volume remained consistent for cracking performance and paste volume. Test sections receiving a performance rating of "Poor" for slab cracking had the highest average paste volume while the average of all test sections receiving a "Fair" rating for percent slabs cracked was less, and test sections rated "Good" for percent slabs cracked had the lowest average paste volume of all test sections.

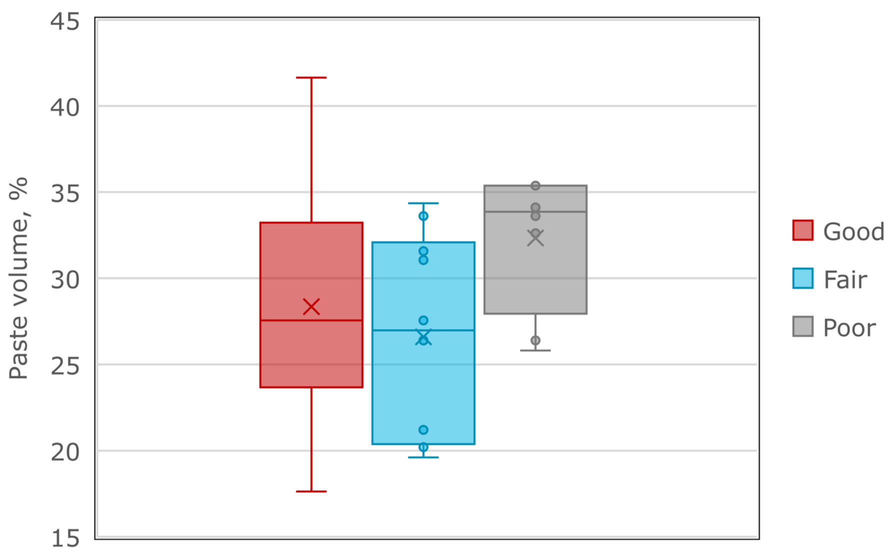


***Figure 21. Wheel-Path Faulting Performance vs. Paste Volume***

Test sections with a performance rating of "Poor" for wheel-path faulting had a higher median paste volume than those test sections receiving a "Fair" or "Good" rating. Therefore, it can be seen across all three performance parameters that the median paste volume for test sections with a "Poor" rating was higher than the median paste volume for test sections receiving a "Good" or "Fair" performance rating across the three performance metrics, indicating some correlation between the paste volume and the SPS-2 test section performance.

## 4.2 Comparison of Density

The density, or unit weight, of a concrete mixture describes the compactness of a mixture and can provide a rough indication of the voids, or even durability of a mixture. The density for each mixture in the core SPS-2 experiment is summarized in Table 8.

***Table 8. Summary of Concrete Density by State Mix Design***

| State | Concrete Density (lbs/ft$^3$) | |
|---|---|---|
| | Low-Strength Mixes (550 psi) | High-Strength Mixes (900 psi) |
| Arizona (04) | 146.5 | 153.2 |
| Arkansas (05) | 144.6 | 143.8 |
| California (06) | 152.2 | 144.8 |
| Colorado (08) | 143.9 | 146.5 |
| Delaware (10) | 144.0 | 150.7 |
| Iowa (19) | 142.9 | 146.9 |
| Kansas (20) | 139.3 | 142.9 |
| Michigan (26) | 144.4 | 148.5 |
| Nevada (32) | 142.6 | 141.0 |
| North Carolina (37) | 146.9 | 145.9 |
| North Dakota (38) | 146.3 | 147.6 |
| Ohio (39) | 140.0 | 145.7 |
| Washington (53) | 148.7 | 147.8 |
| Wisconsin (55) | 145.7 | 148.1 |
| **Average** | **144.9** | **146.7** |

On average, the high-strength mixtures generally had a higher density than the low-strength mixtures. Similar to paste volume, this is a logical conclusion given that high-strength mixtures generally had a much higher cementitious material content. The average density for low-strength mixtures was 144.9 lbs/CF and for high-strength mixtures was 146.7 lbs/CF. The impact of the density on the IRI, percent slabs cracked and wheel-path faulting of each test section is given in Figure 22, Figure 23, and Figure 24.

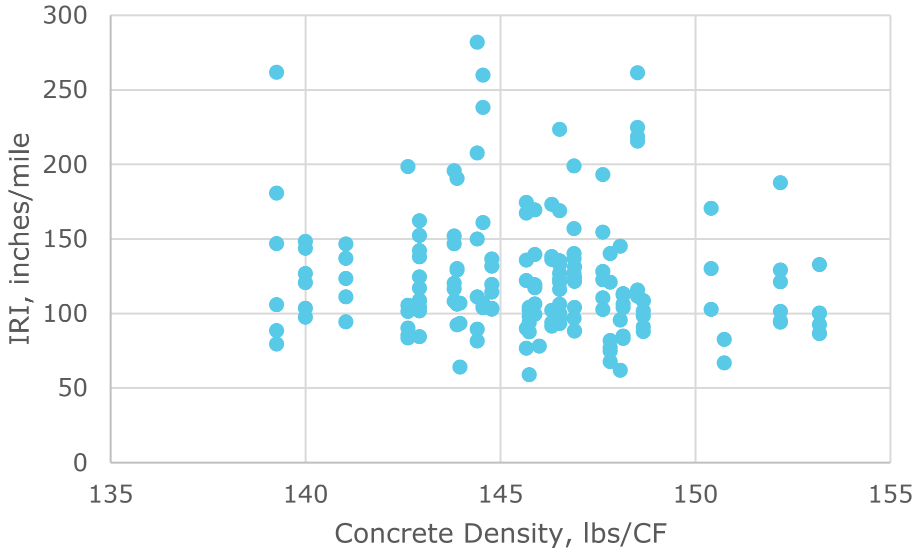


***Figure 22. Concrete Density vs. IRI for all SPS-2 Test Sections***

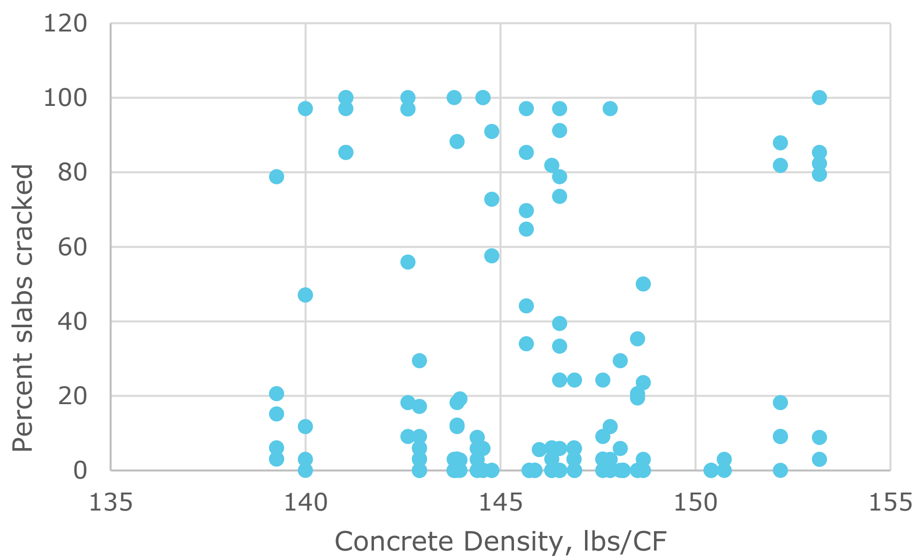


***Figure 23. Concrete Density vs. Percent Slabs Cracked for all SPS-2 Test Sections***

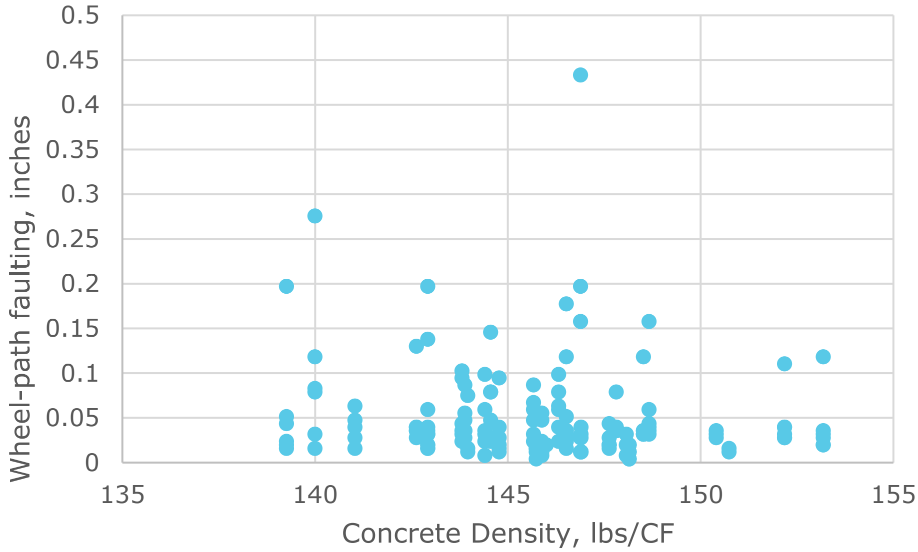


***Figure 24. Concrete Density vs. Wheel-Path Faulting for all SPS-2 Test Sections***

Again, there is observed scatter within the data; however, it appears that sites exhibiting higher wheel-path faulting and roughness had a lower concrete density. In order to observe these trends more clearly, the performance of each test section was assigned to qualitative performance parameters using the criterial outlined previously in Table 1 developed by Visintine et al. (2018). This assigned each test section a rating of "Good", "Fair," or "Poor" based on its measured performance. These results are given in the box and whisker plots shown in Figure 25, Figure 26, and Figure 27.

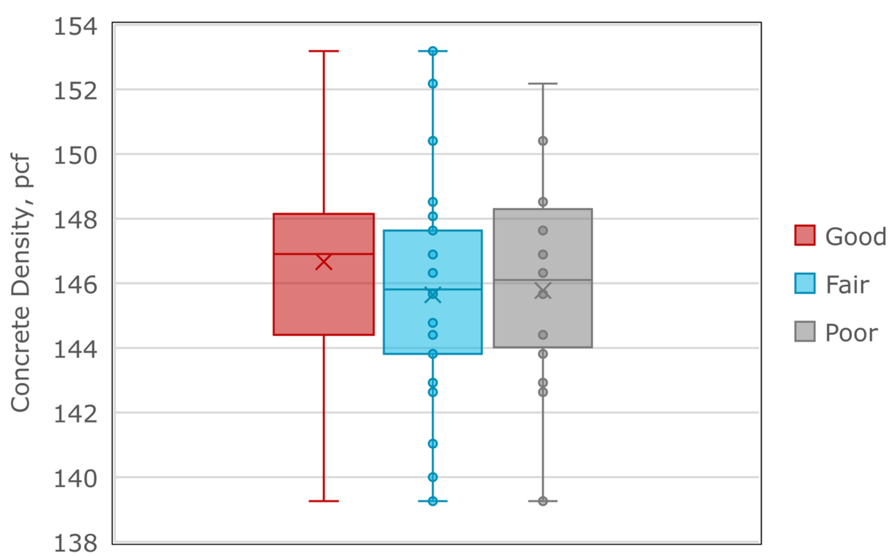


***Figure 25. IRI performance vs. Concrete Density***

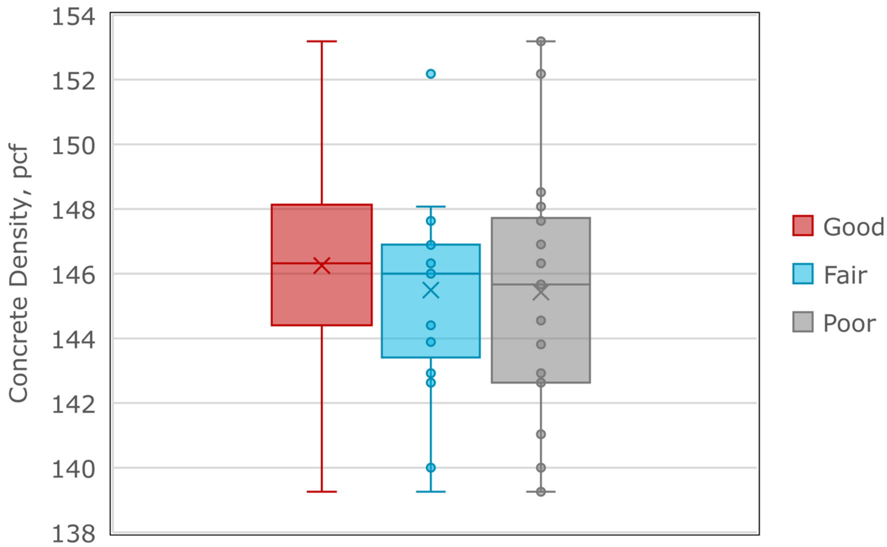


***Figure 26. Cracking Performance vs. Concrete Density***

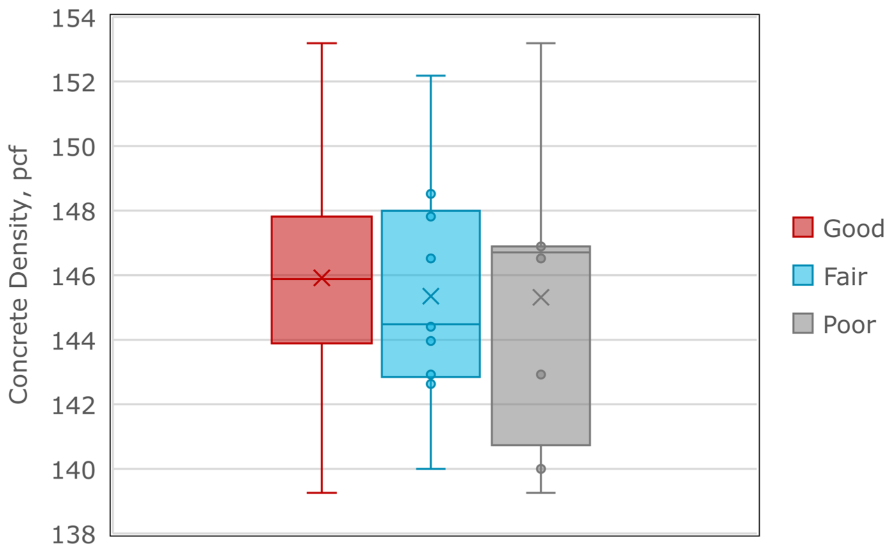


***Figure 27. Wheel-Path Faulting Performance vs. Concrete Density***

As shown, there is still significant scatter between the plots and most median density values are so close that there were no observable differences between test sections.

## 4.3 Comparison of Water/Cementitious Materials Ratio

The w/cm ratio describes the ratio of the weight of water divided by the weight of total cementitious materials, including cement and any supplementary cementitious materials used. The w/cm ratio has long been correlated with concrete performance. It is a fundamental principle that for a given mixture, as the w/cm ratio increases, the compressive strength decreases and permeability increases, resulting in poorer durability of concrete mixtures. The w/cm ratios for all SPS-2 concrete mixtures are compared in Table 9.

***Table 9. Summary of Water/Cementitious Materials Ratios by State Mix Design***

| State | Water/Cementitious Materials Ratio | |
|---|---|---|
| | Low-Strength Mixes (550 psi) | High-Strength Mixes (900 psi) |
| Arizona (04) | 0.46 | 0.36 |
| Arkansas (05) | 0.55 | 0.32 |
| California (06) | 0.51 | 0.44 |
| Colorado (08) | 0.47 | 0.29 |
| Delaware (10) | 0.45 | 0.36 |
| Iowa (19) | 0.53 | 0.36 |
| Kansas (20) | 0.50 | 0.35 |
| Michigan (26) | 0.56 | 0.38 |
| Nevada (32) | 0.49 | 0.32 |
| North Carolina (37) | 0.47 | 0.29 |
| North Dakota (38) | 0.45 | 0.32 |
| Ohio (39) | 0.40 | 0.31 |
| Washington (53) | 0.49 | 0.31 |
| Wisconsin (55) | 0.41 | 0.29 |
| **Average** | **0.48** | **0.34** |

As assumed, the low-strength mixtures had a significantly higher w/cm ratios than the high-strength mixtures, having an average w/cm ratio of 0.48 compared to 0.34. For concrete paving mixtures subjected to freeze-thaw environments, a w/cm ratio under 0.45 is recommended to reduce permeability and increase strength. The impact of the w/cm ratio on the IRI, percent slabs cracked, and wheel-path faulting of each test section is given in Figure 28, Figure 29, and Figure 30.

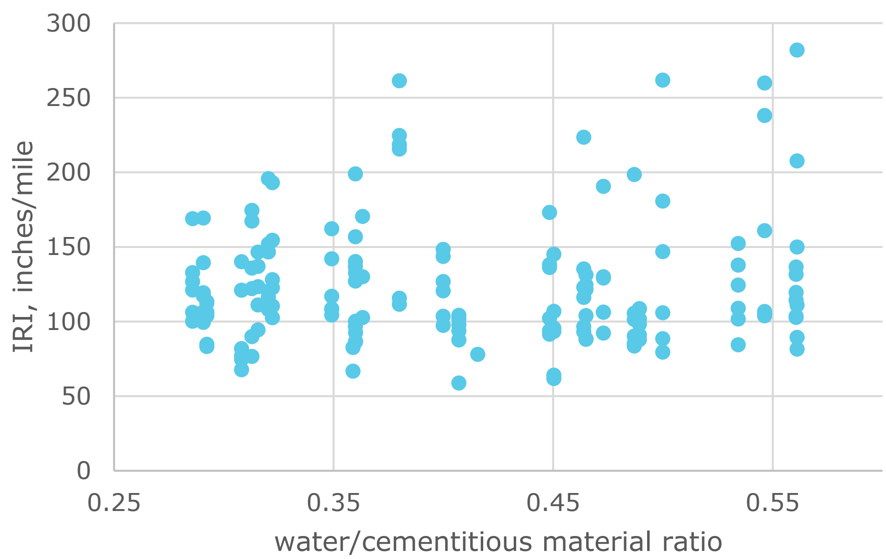


***Figure 28. Water/Cementitious Materials Ratio vs. IRI for all SPS-2 Test Sections***

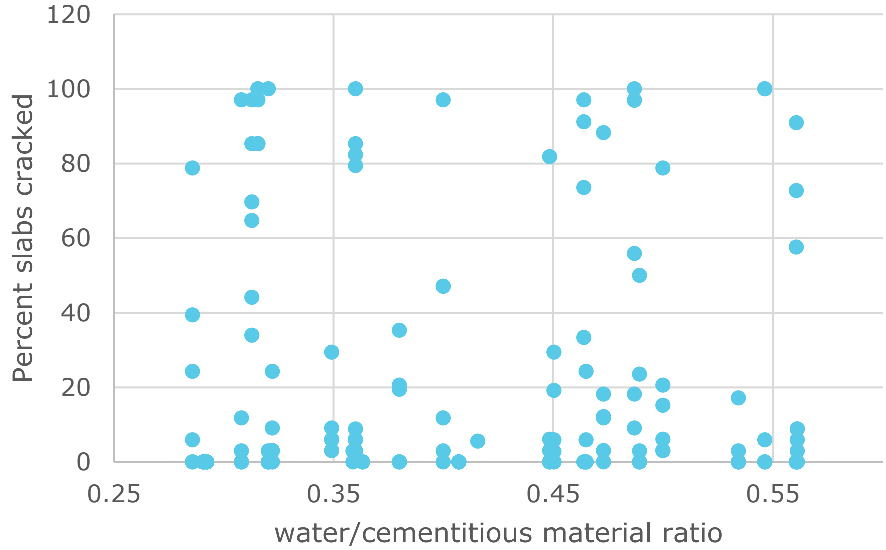


***Figure 29. Water/Cementitious Materials Ratio vs. Percent Slabs Cracked for all SPS-2 Test Sections***

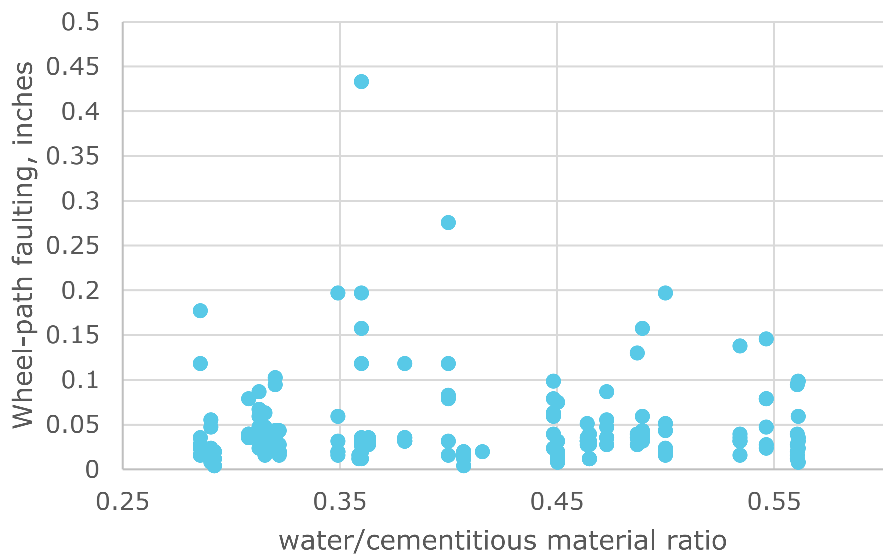


***Figure 30. Water/Cementitious Materials Ratio vs. Wheel-Path Faulting for all SPS-2 Test Sections***

There is observed scatter within the data, yet there appears to be a slight trend between the w/cm ratio and the increased roughness. However, there were many sites with 100% slabs cracked and a low w/cm ratio, which may be attributed to low workability of the mixture and difficulty placing or constructing the mixture itself. The low water/cementitious material mixtures could also have undergone autogenous shrinkage, which would be more likely for low water/cementitious materials ratio concrete. This would have increased the likelihood of early-age cracking. To observe these trends more clearly, the performance of each test section was assigned to qualitative performance parameters using the criterial outlined previously in Table 1. This assigned each test section a rating of "Good", "Fair," or "Poor" based on its measured performance. These results are given in the plots shown in Figure 28, Figure 29, and Figure 30.

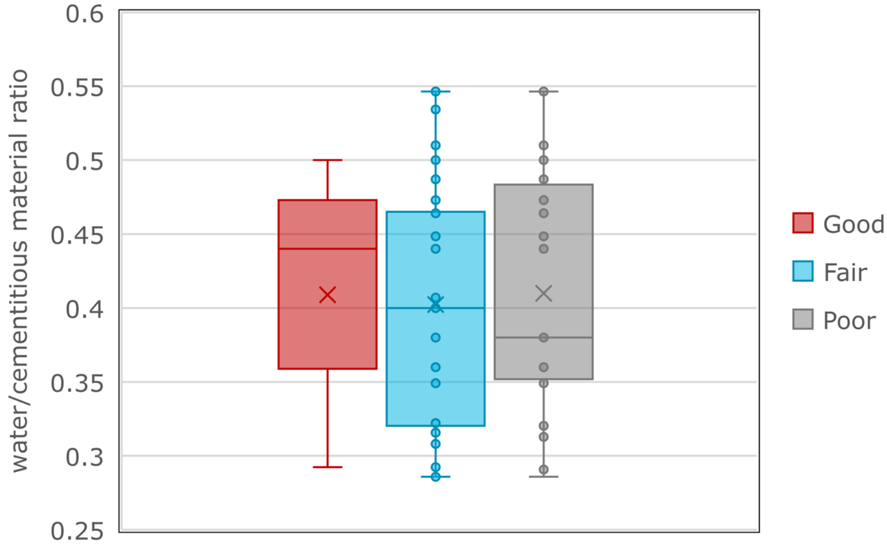


***Figure 31. SPS-2 IRI Performance vs. Water/Cementitious Materials Ratio***

Interestingly, more of the test sections rated "Poor" appeared to have a lower w/cm ratio. This could be explained by the low workability and difficulty finishing in many of the higher-strength mixtures with a low w/cm ratio, which would have a greater effect on surface roughness and the possible susceptibility to autogenous shrinkage.

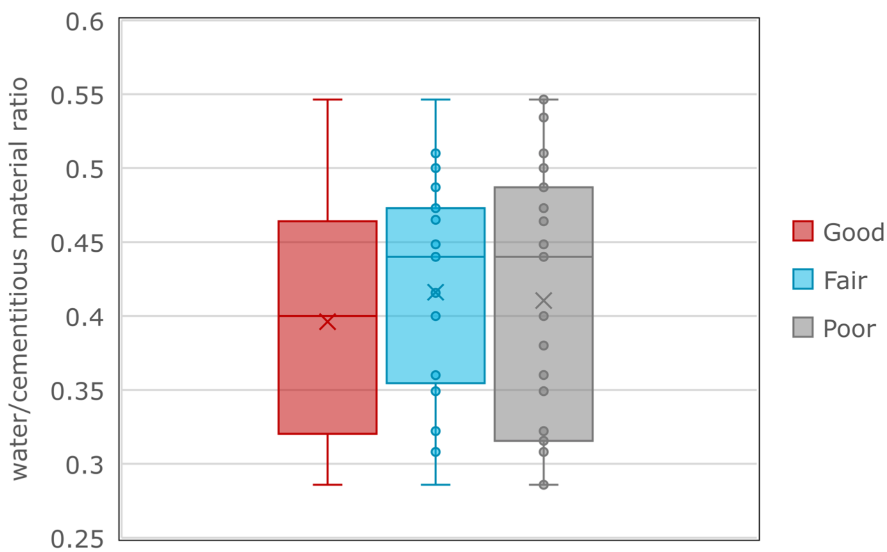


***Figure 32. SPS-2 Cracking Performance vs. Water/Cementitious Materials Ratio***

Test sections with a "Good" rating for cracking had a median lower w/cm ratio than those receiving a "Fair" or "Poor" rating in cracking performance.

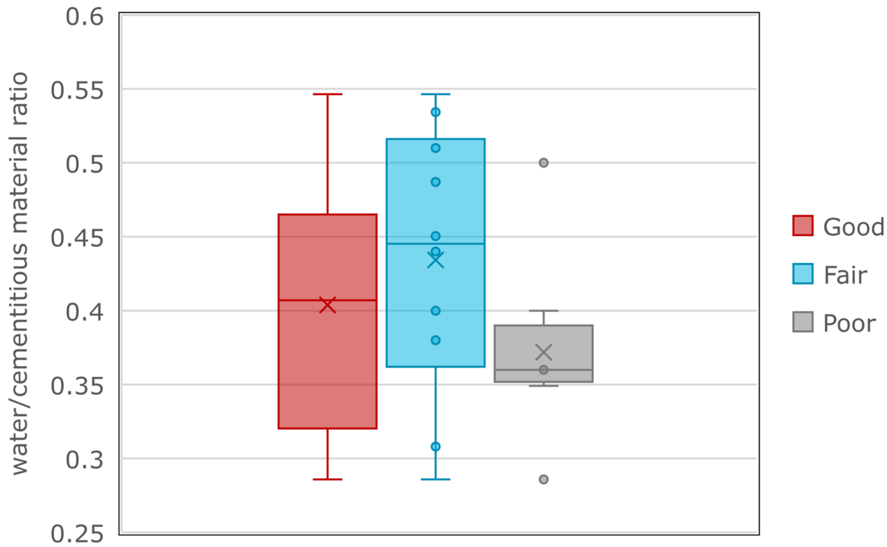


***Figure 33. SPS-2 Faulting Performance vs. Water/Cementitious Materials Ratio***

Finally, test sections receiving a "Poor" rating for wheel-path faulting had a lower median w/cm ratio, which could similarly be attributed to the issues with finishing and constructability of the low w/cm mixtures rather than the low w/cm ratio itself.

## 4.4 Comparison of Cementitious Materials Content and Use of Supplementary Cementitious Materials

Since the development of the SPS-2 experiment, increasing evidence has suggested than an increased cementitious materials content can cause increased shrinkage and decreased workability. Previously, Araiza et al. (2011) suggested that optimally, a maximum cementitious materials content of 600 lbs/CY could be applied to concrete mixtures for optimal performance. The cement content, supplementary cementitious materials content, and total cementitious materials content, in lbs/CY, for each SPS-2 concrete mixture is compared in for low-strength mixes and high-strength mixes in Table 10 and Table 11, respectively.

***Table 10. Summary of Cementitious Materials Content by State Mix Design for Low-Strength Mixtures***

| State | Content in lbs/CY of concrete | | |
|---|---|---|---|
| | Cement | Supplementary Cementitious Material | Total Cementitious Material |
| Arizona (04) | 400 | 100 | 500 |
| Arkansas (05) | 330 | 58 | 388 |
| California (06) | 352 | 117.9 | 470 |
| Colorado (08) | 399 | 100 | 499 |
| Delaware (10) | 367 | 197 | 564 |
| Iowa (19) | 347 | 61 | 408 |
| Kansas (20) | 532 | 0 | 532 |
| Michigan (26) | 376 | 0 | 376 |
| Nevada (32) | 423 | 0 | 423 |

| State | Content in lbs/CY of concrete | | |
|---|---|---|---|
| | Cement | Supplementary Cementitious Material | Total Cementitious Material |
| North Carolina (37) | 421 | 126 | 547 |
| North Dakota (38) | 319.6 | 56.4 | 376 |
| Ohio (39) | 510 | 90 | 600 |
| Washington (53) | 423 | 47 | 470 |
| Wisconsin (55) | 565 | 0 | 565 |
| **Average** | **412** | **87** | **480** |

***Table 11. Summary of Cementitious Materials Content by State Mix Design for High-Strength Mixtures***

| State | Content in lbs/CY of Concrete | | |
|---|---|---|---|
| | Cement | Supplementary Cementitious Material | Total Cementitious Material |
| Arizona (04) | 811 | 0 | 811 |
| Arkansas (05) | 719 | 127 | 846 |
| California (06) | 799 | 0 | 799 |
| Colorado (08) | 749 | 150 | 899 |
| Delaware (10) | 487 | 257 | 744 |
| Iowa (19) | 723 | 127 | 850 |
| Kansas (20) | 862 | 0 | 862 |
| Michigan (26) | 750 | 0 | 750 |
| Nevada (32) | 846 | 0 | 846 |
| North Carolina (37) | 772 | 232 | 1004 |
| North Dakota (38) | 660 | 116 | 776 |
| Ohio (39) | 750 | 113 | 863 |
| Washington (53) | 925 | 0 | 925 |
| Wisconsin (55) | 650 | 0 | 650 |
| **Average** | **750** | **102** | **830** |

As shown, the average cementitious content was much higher for the high-strength mixtures than the low-strength mixtures, with low-strength mixtures having an average total cementitious materials content of 480 lbs/CY compared to 830 lbs/CY for the high-strength mixtures. In addition, more low-strength test sections utilized supplementary cementitious materials (10 out of 14) than the high-strength mixtures (7 out of 14). The impact of the cement content on the IRI, percent slabs cracked, and wheel-path faulting of each test section is illustrated in Figure 34, Figure 35, and Figure 36.

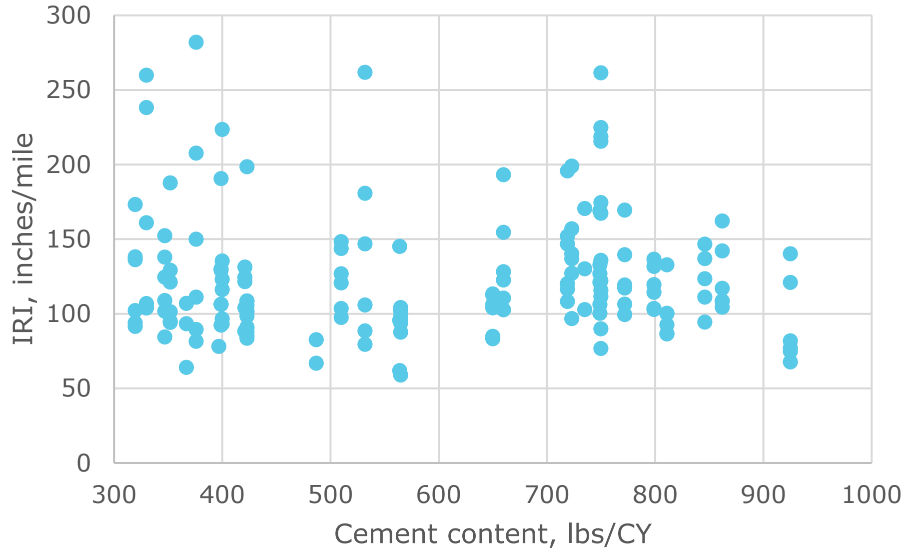


***Figure 34. IRI vs. Cement Content for all SPS-2 Test Sections***

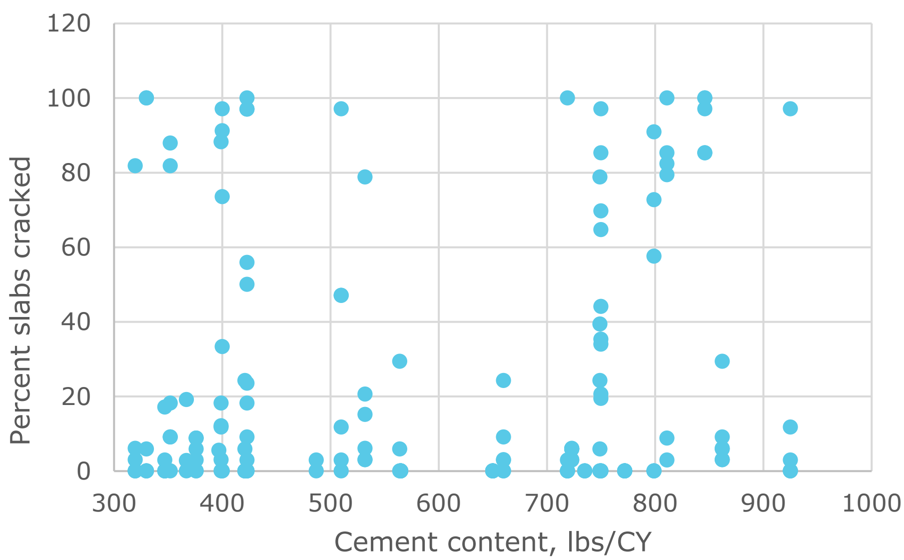


***Figure 35. Cracking vs. Cement Content for all SPS-2 Test Sections***

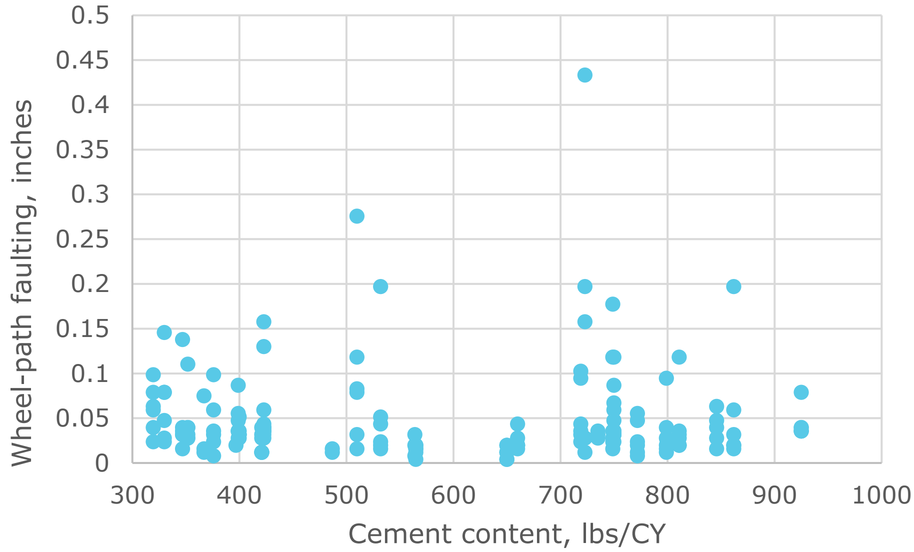


***Figure 36. Wheel-Path Faulting vs. Cement Content for all SPS-2 Test Sections***

There is observed scatter within the data. The performance of each test section was assigned to qualitative performance parameters using the criterial outlined previously in Table 1. This assigned each test section a rating of "Good", "Fair," or "Poor" based on its measured performance. These results are given in the plots shown in Figure 37, Figure 38, and Figure 39.

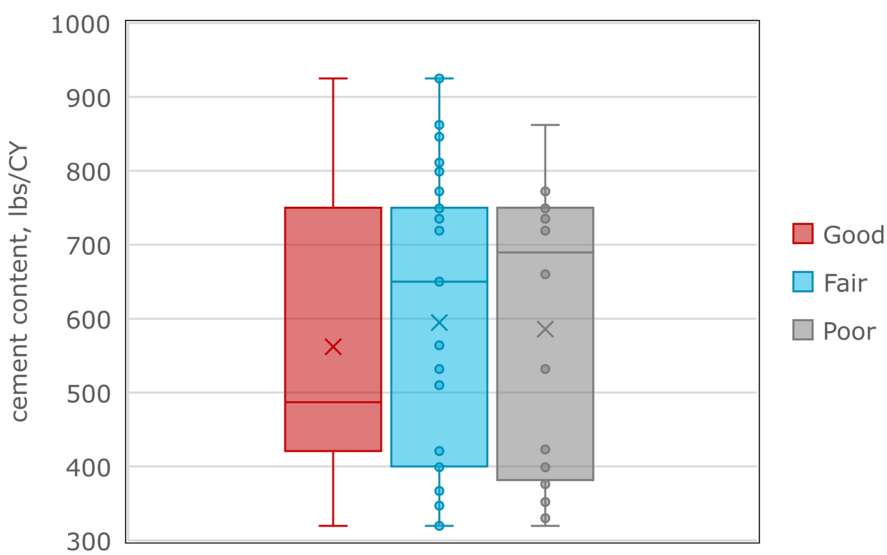


***Figure 37. IRI Performance vs. Cement Content for all SPS-2 Test Sections***

The test sections receiving a "Poor" rating for roughness had a much higher median cement content than test sections receiving a "Fair" rating. Test sections receiving a "Good" rating for roughness had by far the lowest median cement content.

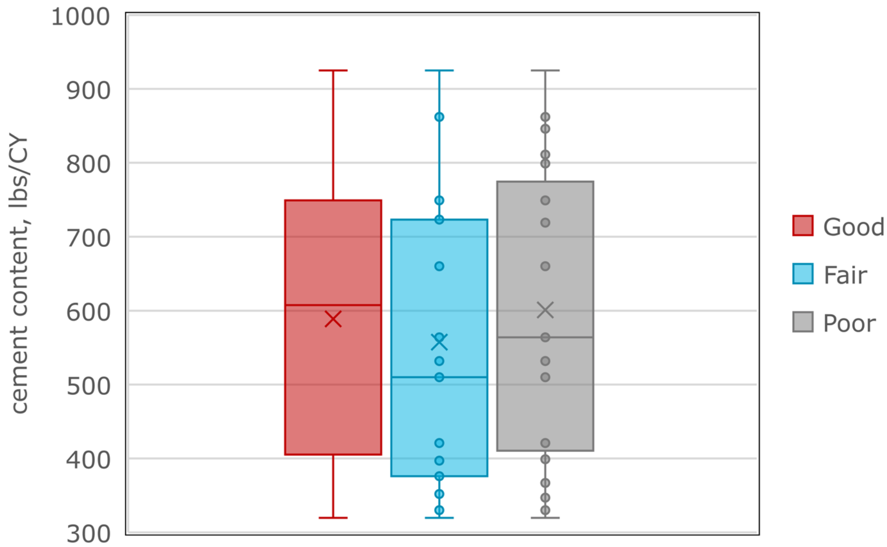


***Figure 38. Percent Slabs Cracked Performance vs. Cement Content for all SPS-2 Test Sections***

However, when considering percent slabs cracked, the median cement content of test sections receiving a "Poor" rating was slightly lower than test sections receiving a "Good" rating.

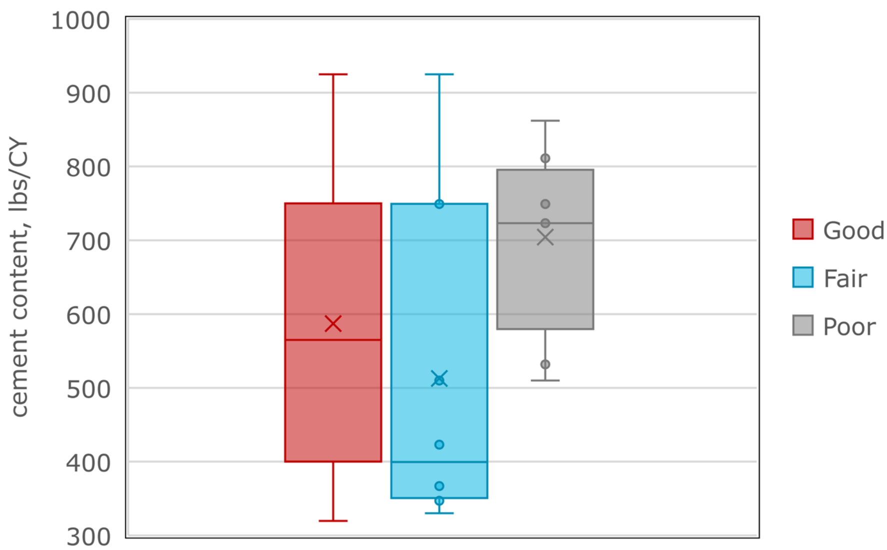


***Figure 39. Wheel-Path Faulting Performance vs. Cement Content for all SPS-2 Test Sections***

Test sections receiving a "Poor" rating with respect to wheel-path faulting had a much higher cement content than test sections receiving a "Good" or "Fair" rating.

The impact of the amount of supplementary cementitious materials in the concrete mixtures on the roughness, cracking, and wheel-path faulting is shown in Figure 40, Figure 41, and Figure 42.

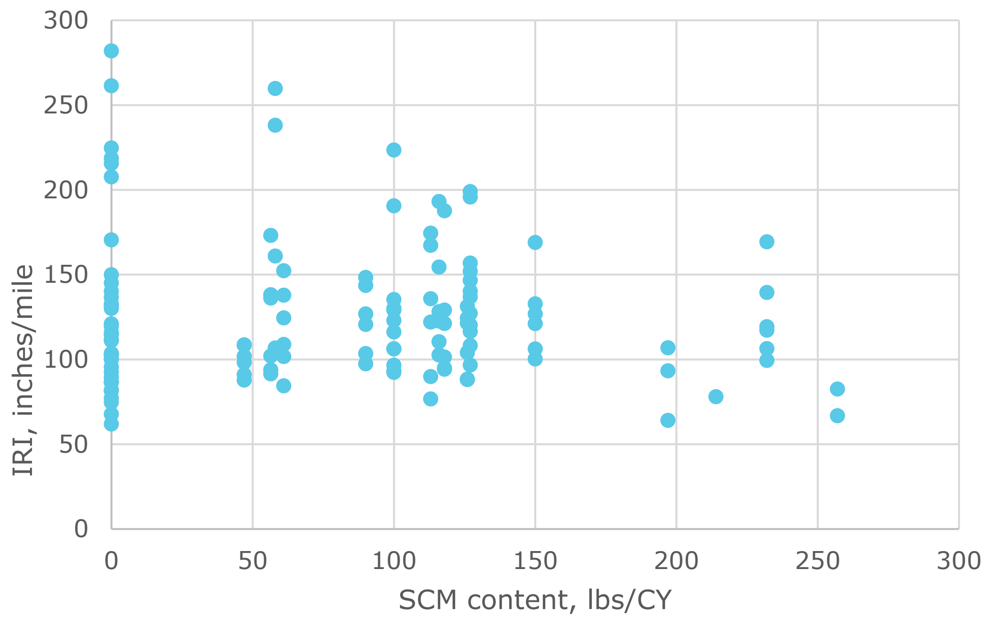


***Figure 40. IRI vs. Supplementary Cementitious Materials Content for all SPS-2 Test Sections***

While there is scatter in the presented data, there appeared to be a decrease in the roughness, or elimination of extreme roughness, as the amount of supplementary cementitious materials increased for the SPS-2 test sections.

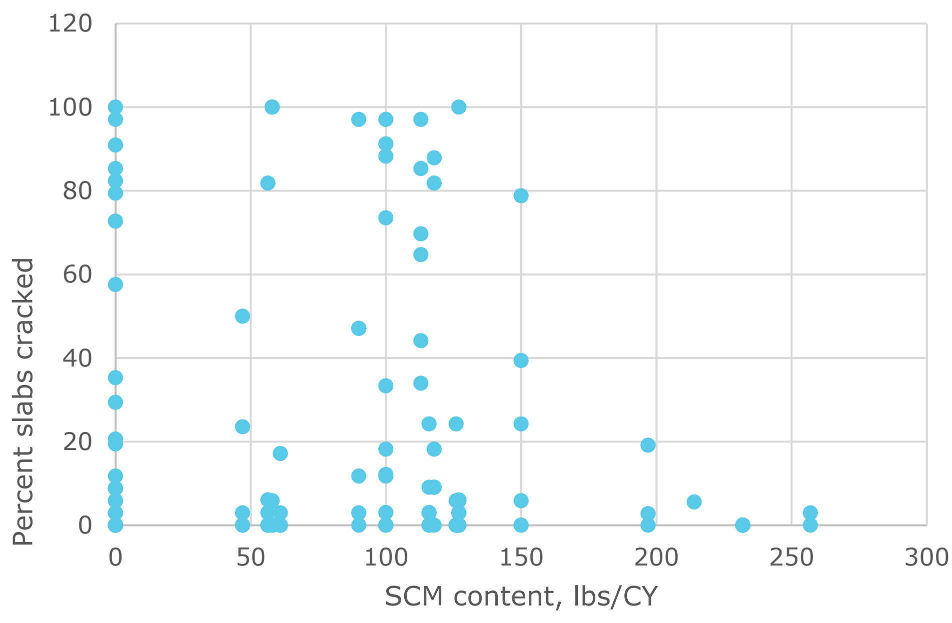


***Figure 41. Percent Slabs Cracked vs. Supplementary Cementitious Materials Content for all SPS-2 Test Sections***

Similarly, there was a decreasing trend in the percent slabs cracked as the supplementary cementitious materials content increased across all SPS-2 test sections.

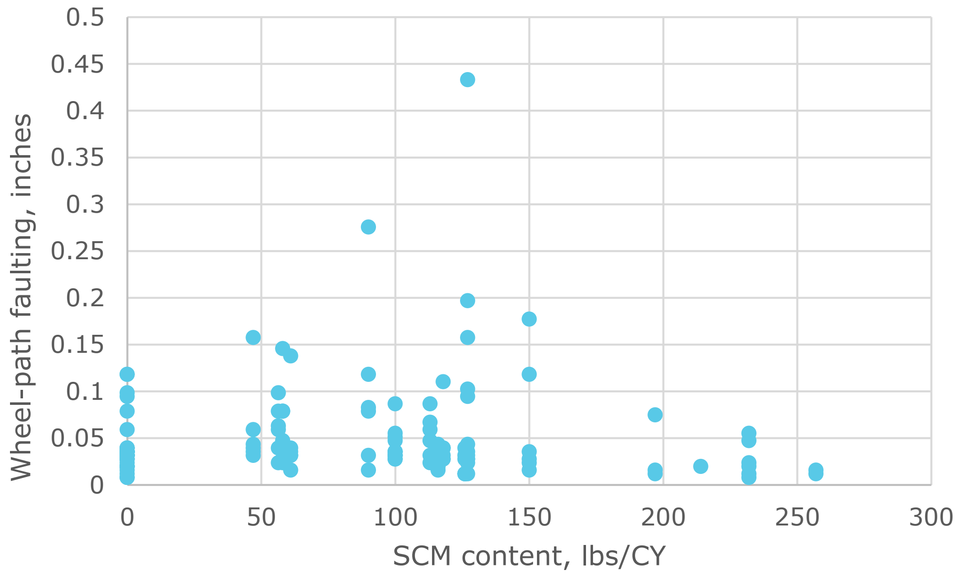


***Figure 42. Wheel-Path Faulting vs. Supplementary Cementitious Materials Content for all SPS-2 Test Sections***

Finally, there was a general decrease in wheel-path faulting measurements as the supplementary cementitious content increased. While there were several distinct trends presented in the previous three plots, the data were again presented utilizing the Visintine et al. (2018) classifications for performance to more clearly observe these trends, as shown in Figure 43, Figure 44, and Figure 45.

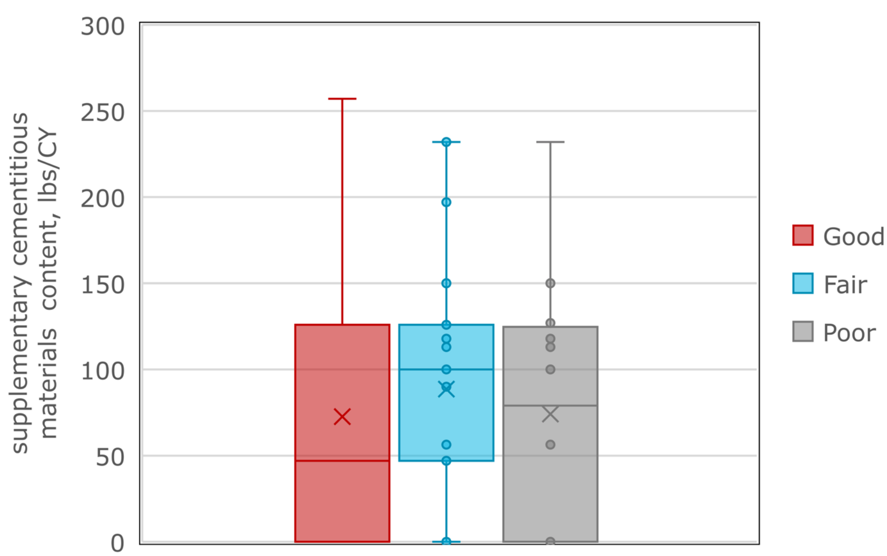


***Figure 43. IRI Performance vs. Supplementary Cementitious Materials Content for all SPS-2 Test Sections***

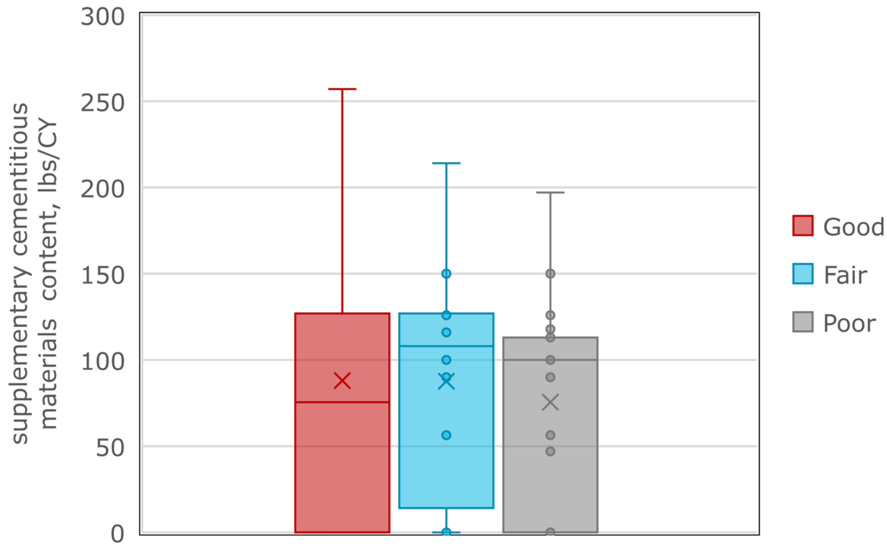


***Figure 44. Cracking Performance vs. Supplementary Cementitious Materials Content for all SPS-2 Test Sections***

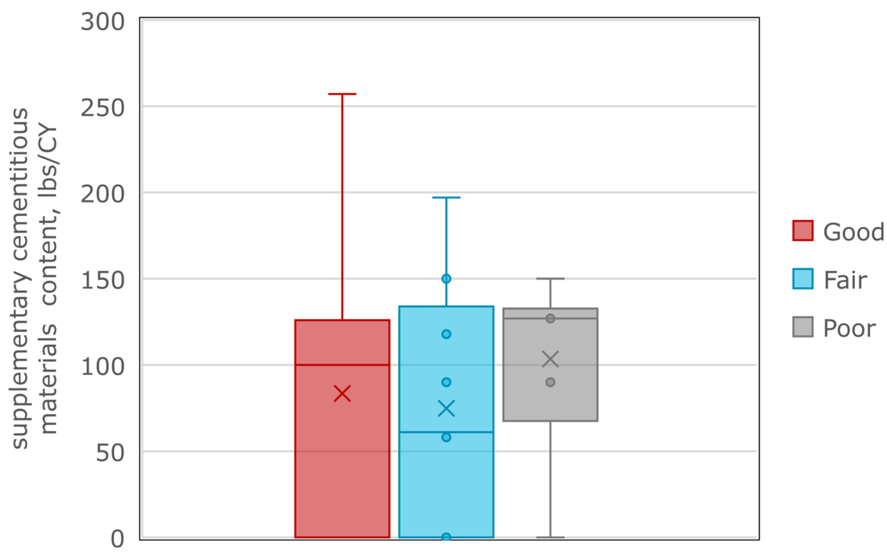


***Figure 45. Wheel-Path Faulting Performance vs. Supplementary Cementitious Materials Content for all SPS-2 Test Sections***

Based on the box and whisker plots, test sections rated "Good" across all three performance metrics had lower median supplementary cementitious materials content than test sections receiving a "Poor" rating. This could be because the more high-strength sections did not contain any supplementary cementitious materials. The impact of the total cementitious materials content, including both cement and supplementary cementitious material, against IRI, percent slabs cracked and wheel-path faulting are shown in Figure 46, Figure 47, and Figure 48.

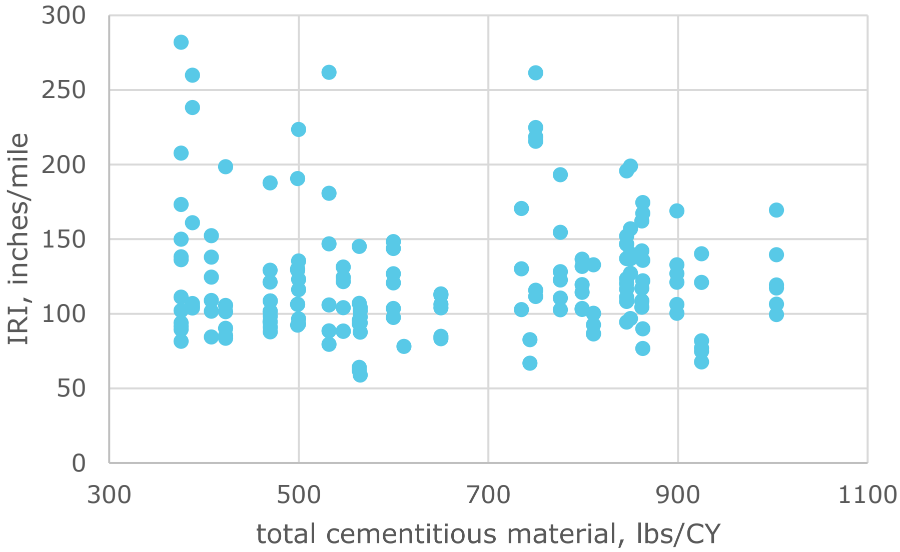


***Figure 46. IRI vs. Total Cementitious Materials Content for all SPS-2 Test Sections***

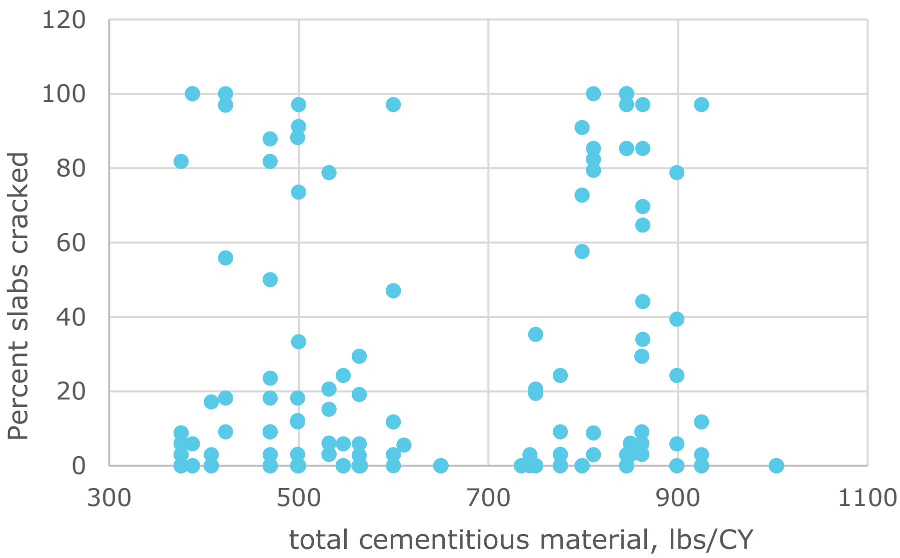


***Figure 47. Percent Slabs Cracked vs. Total Cementitious Materials Content for all SPS-2 Test Sections***

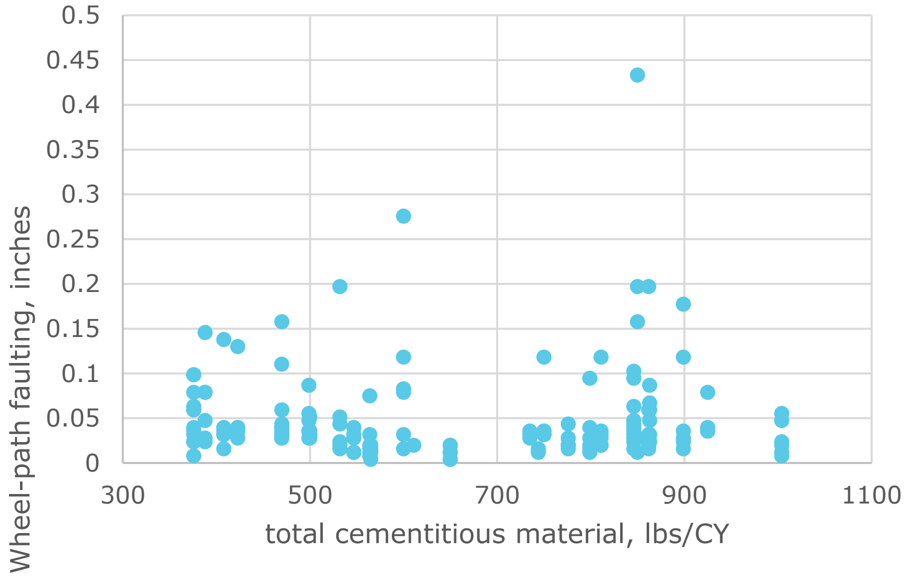


***Figure 48. Wheel-Path Faulting vs. Total Cementitious Materials Content for all SPS-2 Test Sections***

There appears to be significant scatter in this data with no apparent trends; however, the performance of each test section was again assigned to qualitative performance parameters using the criterial outlined previously in Table 1. This assigned each test section a rating of "Good", "Fair," or "Poor" based on its measured performance . The results are given in the plots shown in Figure 49, Figure 50, and Figure 51.

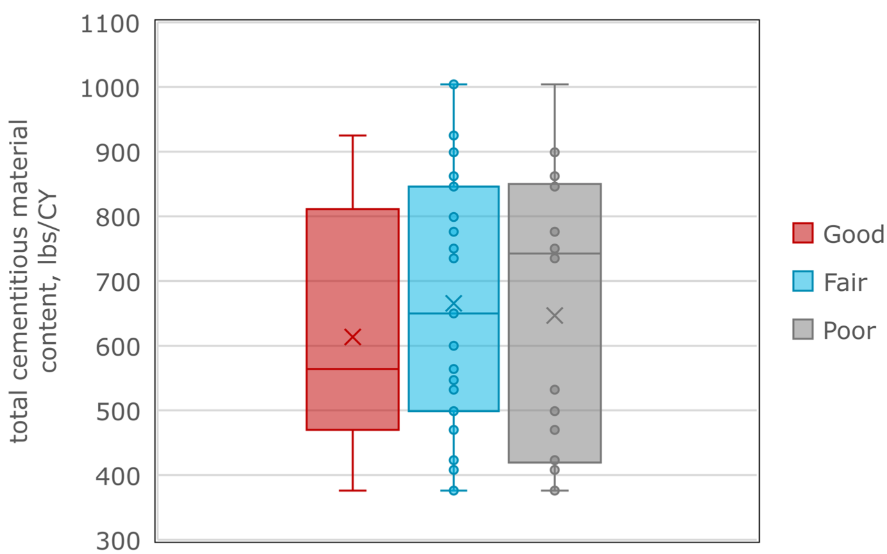


***Figure 49. IRI Performance vs. Total Cementitious Materials Content for all SPS-2 Test Sections***

Test sections receiving a "Poor" rating for roughness had a much higher median total cementitious materials content than test sections receiving a "Fair" rating and test sections receiving a "Good" rating had the lowest median total cementitious materials content at 575 lbs/CY.

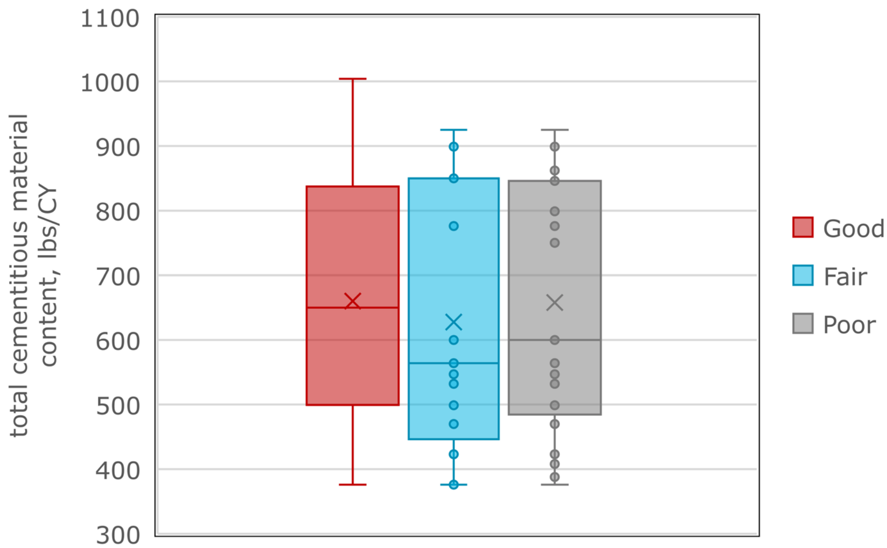


***Figure 50. Cracking Performance vs. Total Cementitious Materials Content for all SPS-2 Test Sections***

However, for cracking, test sections receiving a "Good" rating had the highest median total cementitious materials content.

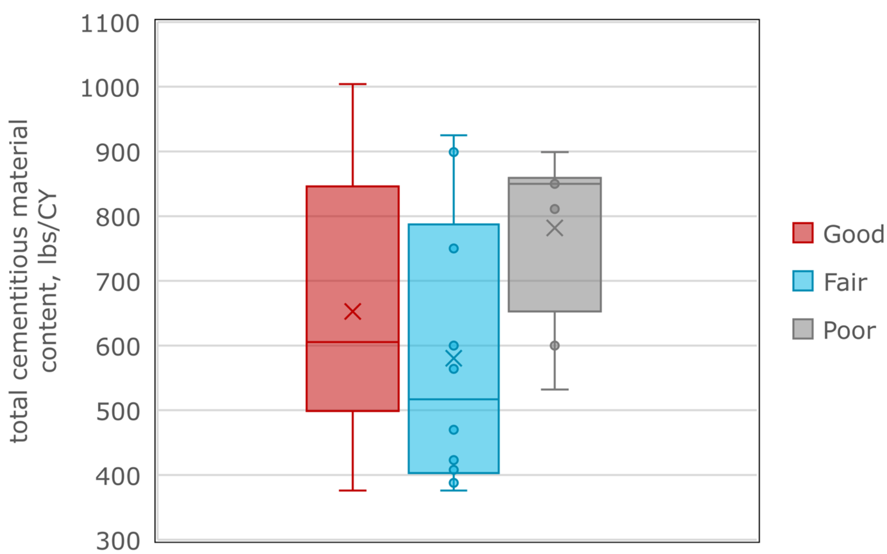


***Figure 51. Wheel-Path Faulting Performance vs. Total Cementitious Materials Content for all SPS-2 Test Sections***

Finally, test sections with a "Poor" rating with respect to wheel-path faulting had the highest median total cementitious materials content.

## 4.5 Summary of Mix Design Parameters

There were several mix design parameters that varied significantly between mixtures, and these variations potentially had an effect on performance. The median paste volume of test sections with a "Good" or "Fair" rating was lower than those with a "Poor" rating across the three performance metrics. While some of the trends were contradictory, there was a general trend between the presence of supplementary cementitious materials and increased performance, such that the test sections with extreme IRI and faulting did not typically contain any supplementary cementitious materials.

While it would be expected the w/cm ratio would align well with performance, this relationship was found to be scattered, likely due to the significantly decreased workability of the high-strength mixtures, which also generally had a lowered w/cm ratio. Generally, there was no significant relationship between the density of the material and the performance.

While there were some trends observed, there was enough scatter present to indicate that other factors outside of the mix design likely controlled the performance of the SPS-2 test sections.

# 5.0 CONCLUSIONS

This task evaluated both aggregate gradation variables (which primarily contribute to the workability and constructability of concrete mixtures) and key mix design parameters (which can contribute to the final performance of concrete mixtures). Relationships across different concrete mix designs used for the core experimental sections in the SPS-2 experiment were investigated and trends between these parameters and the ultimate performance of the SPS-2 test sections were observed.

Factors investigated related to aggregate gradations were the 0.45 power chart, the Coarseness Factor – Workability Factor chart, and the Tarantula curve. These were used to evaluate the density and ease of constructability and workability of the low-strength (550 psi) and high-strength (900 psi) concrete mixtures used in the SPS-2 experiment. There were some key agreements between these three metrics and observations from the mixtures themselves, fully summarized previously in Table 6. The 0.45 power chart, primarily used to evaluate the density of aggregate gradations, revealed some interesting trends, which included that some SPS-2 test sections with lowered performance, such as Arkansas, had significant deviation from the maximum density line, indicating an irregularly graded aggregate blend. Some mixtures indicated a very good fit with the maximum density line, including Colorado, Michigan, and Nevada, which did not have marked problems due to finishing. Michigan and Nevada did experience premature cracking but did not exhibit issues with workability.

Evaluations of the aggregate gradations on the Coarseness Factor – Workability Factor chart revealed the aggregate gradations for most test sections fell within one of three gradation zones: Zone I (Coarse-Gap Graded), Zone II (Well-Graded) and Zone IV (Excessive Fines – Sticky). Generally, more low-strength mixtures utilized a Zone I aggregate gradation while most high-strength mixtures utilized a Zone IV gradation. There was some agreement here between states with dense gradations plotted within Zone II, including Michigan, Nevada, and North Dakota, which had a lack of noted issues with finishing or general mix workability. However, test sections with noted finishing or construction issues due to mix workability did fall within either Zone I or Zone IV on the Coarseness Factor – Workability Factor chart.

Finally, aggregate blends were evaluated on the Tarantula Curve, which provides restrictions across the coarse, intermediate, and fine aggregate fractions. Some gradations did exceed the boundaries recommended in the Tarantula Curve due to excessive coarse material, which was especially common for high-strength mixtures. Mixtures exceeding the boundaries of the Tarantula Curve have decreased workability with an increased potential for segregation. Again, many of the same test sections previously outlined exceeded these limits.

When all three aggregate gradation evaluation methods were considered together, only the low-strength mixtures from Nevada and North Dakota indicated dense, workable gradations across all three criteria.

Next, mix design parameters including paste volume, mix density, w/cm ratio, and cementitious materials content with supplementary cementitious materials content were compared and evaluated against known test section performance parameters. These are summarized in Table 12. The median value of each property is given across test sections achieving the indicated performance rating for each of the three performance measures: roughness, and percent slabs cracked, and faulting. For example, the median paste volume of test sections achieving a "Good" rating with respect to roughness was 25.8%.

***Table 12. Summary of Cementitious Materials Content by State Mix Design for Low-strength Mixtures***

| SPS-2 Mix Design Factors | Performance Rating | Hardened Concrete Properties - Pavement Performance Measure Median – Worst Observed Condition | | |
|---|---|---|---|---|
| | | Roughness | Percent Slabs Cracked | Faulting |
| Paste Volume | Good | 25.8 | 26.6 | 27.6 |
| | Fair | 30.1 | 28.6 | 27.0 |
| | Poor | 30.8 | 31.0 | 33.9 |
| Density | Good | 146.9 | 146.3 | 145.9 |
| | Fair | 145.8 | 146.0 | 144.5 |
| | Poor | 146.1 | 145.7 | 146.7 |
| w/cm Ratio | Good | 0.45 | 0.40 | 0.41 |
| | Fair | 0.40 | 0.45 | 0.47 |
| | Poor | 0.38 | 0.44 | 0.36 |
| Cement Content | Good | 487 | 608 | 565 |
| | Fair | 650 | 510 | 400 |
| | Poor | 690 | 564 | 723 |
| SCM Content | Good | 47 | 76 | 100 |
| | Fair | 100 | 108 | 61 |
| | Poor | 79 | 100 | 127 |
| Total Cementitious Material Content | Good | 564 | 650 | 605.5 |
| | Fair | 650 | 564 | 516.9 |
| | Poor | 742.5 | 600 | 850 |

Test sections receiving ratings of "Good" across the three performance parameters of roughness, slab cracking, and wheel-path faulting did have lower median paste volumes than other test sections, indicating an inversely correlated relationship between paste volume and concrete pavement performance. However, median values across concrete density proved to be more consistent across test sections without distinct trends between concrete density and ultimate concrete performance. As this was likely controlled more by aggregate type, it could provide a good indication that there was not significant variation of aggregate densities across SPS-2 test sections.

It was also observed that test sections receiving a rating of "Good" in roughness generally had a higher median w/cm ratio than test sections with a "Fair" or "Poor" rating. This could be due to the increased likelihood of autogenous shrinkage for concrete mixtures with a w/cm ratio below 0.40. However, test sections receiving a "Good" rating with regard to cracking had a lower median w/cm ratio than test sections with "Fair" or "Poor" ratings. Despite widespread industry knowledge that better performance is generally expected from lower w/cm ratios, the better performance for roughness for higher w/cm mixtures indicates that there could have been enough of an issue with final workability that the final surface roughness was affected. Another possibility is that the w/cm ratio was sufficiently low that autogenous shrinkage could have been a problem.

Finally, test sections receiving a "Good" rating in roughness had a lower median cement content and total cementitious materials content. Trends across the supplementary cementitious materials content were more difficult to discern due to the limited number of test sections. However, test sections receiving a "Good" rating for cracking generally had higher median cement content, suggesting an optimal value between the lower value to achieve good roughness performance and a higher value to achieve good cracking performance.

Some key conclusions include:

- A ***lower paste volume*** was observed to improve the performance of test sections with respect to ***cracking*** and ***roughness***. A significant difference in performance was not observed with respect to faulting.
- A ***lower w/cm ratio*** was observed to improve the performance of test sections with respect to ***cracking***. A ***higher w/cm ratio*** was observed to improve the performance of test sections with respect to ***roughness***. A ***midpoint w/cm ratio*** was observed to improve the performance of test sections with respect to ***faulting***.
- A ***higher total cementitious materials content*** was observed to decrease the performance of test sections with respect to ***roughness*** and ***faulting*** but increase performance with respect to ***cracking***.

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# Appendix A

## Summary of Concrete Mixture Designs and Calculated Mix Factors for each SPS-2 section

***Table A1. Summary of Low-Strength (550 psi) Mixture Designs by State***

| | AZ (04) | AR (05) | CA (06) | CO (08) | DE-1 (10) | DE-2 (10) | IA (19) | KS (20) | MI (26) | NV (32) | NC (37) | ND (38) | OH (39) | WA (53) | WI (55) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cement, lbs/CY | 400 | 330 | 352 | 399 | 367 | 564 | 347 | 532 | 376 | 423 | 421 | 320 | 510 | 423 | 565 |
| Fly ash, lbs/CY | 100 | 58 | 117.9 | 100 | 197 | 0 | 61 | 0 | 0 | 0 | 126 | 56 | 90 | 47 | 0 |
| Water, lbs/CY | 232 | 212 | 239.9 | 236 | 254 | 254 | 218 | 266 | 211 | 206 | 254 | 169 | 240 | 230 | 230 |
| Fine aggregate, lbs/CY | 1285 | 1333 | 1171 | 1430 | 1257 | 1281 | 1752 | 2071 | 1485 | 1198 | 1241 | 1399 | 1260 | 1395 | 1240 |
| Coarse aggregate, lbs/CY | 1939 | 1970 | 2104 | 1720 | 1812 | 1899 | 1481 | 891 | 1827 | 2024 | 1924 | 2007 | 1680 | 1919 | 1900 |
| w/cm | 0.46 | 0.55 | 0.51 | 0.47 | 0.45 | 0.45 | 0.53 | 050 | 0.56 | 0.49 | 0.46 | 0.45 | 0.40 | 0.49 | 0.41 |
| Paste volume | 0.24 | 0.20 | 0.24 | 0.24 | 0.28 | 0.26 | 0.21 | 0.26 | 0.20 | 0.20 | 0.27 | 0.18 | 0.26 | 0.23 | 0.24 |
| Density, pcf | 146.5 | 144.6 | 147.6 | 143.9 | 143.9 | 148.1 | 142.9 | 139.3 | 144.4 | 142.6 | 146.9 | 146.3 | 140 | 148.7 | 145.7 |

***Table A2. Summary of High-Strength (900 psi) Mixture Designs by State***

| | AZ (04) | AR (05) | CA (06) | CO (08) | DE-1 (10) | DE-2 (10) | IA (19) | KS (20) | MI (26) | NV (32) | NC (37) | ND (38) | OH (39) | WA (53) | WI (55) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cement, lbs/CY | 811 | 719 | 799 | 749 | 487 | 397 | 723 | 862 | 750 | 846 | 772 | 660 | 750 | 925 | 650 |
| Fly ash, lbs/CY | 0 | 127 | 0 | 150 | 257 | 214 | 127 | 0 | 0 | 0 | 232 | 116 | 113 | 0 | 0 |
| Water, lbs/CY | 292 | 271 | 349 | 257 | 267 | 254 | 306 | 301 | 285 | 267 | 292 | 250 | 270 | 285 | 190 |
| Fine aggregate, lbs/CY | 1207 | 924 | 914 | 935 | 1114 | 1239 | 1278 | 1347 | 1370 | 1055 | 743 | 960 | 950 | 948 | 1260 |
| Coarse aggregate, lbs/CY | 1826 | 1842 | 1748 | 1865 | 1945 | 1838 | 1532 | 1349 | 1605 | 1640 | 1900 | 2000 | 1850 | 1833 | 1900 |
| w/cm | 0.36 | 0.32 | 0.44 | 0.29 | 0.36 | 0.42 | 0.36 | 0.35 | 0.38 | 0.32 | 0.29 | 0.32 | 0.31 | 0.31 | 0.29 |
| Paste volume | 0.33 | 0.33 | 0.36 | 0.34 | 0.32 | 0.29 | 0.35 | 0.34 | 0.31 | 0.32 | 0.38 | 0.31 | 0.33 | 0.34 | 0.24 |
| Density, pcf | 153.2 | 143.8 | 141.1 | 146.5 | 150.7 | 146 | 146.9 | 142.9 | 148.5 | 141 | 145.9 | 147.6 | 145.7 | 147.8 | 148.1 |

***Table A3. Summary of Combined Aggregate Gradations for Low-Strength (550 psi) Mixture Designs by State***

| Sieve size | AZ (04) | AR (05) | CA (06) | CO (08) | DE-1 (10) | DE-2 (10) | IA (19) | KS (20) | MI (26) | NV (32) | NC (37) | ND (38) | OH (39) | WA (53) | WI (55) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2″ | 100 | | 100 | 100 | 100 | 100 | | | | 100 | | | | | 100 |
| 1 ½″ | 100 | | 97.5 | 99.5 | 100 | 100 | | | | 97.6 | 100 | | 100 | 100 | 98.8 |
| 1″ | 100 | | 77.1 | 92.9 | 99.41 | 99.4 | 100 | | 100 | 83.5 | 98.8 | 100 | 98.9 | 98.3 | 88.6 |
| ¾″ | 88 | 100 | 68.1 | | 89.37 | 89.25 | 91.3 | 100 | 97.8 | 72.9 | 86.6 | 86 | 80.6 | 74.5 | 77.5 |
| ½″ | 57.9 | 84.5 | | 75.4 | 78.74 | 78.5 | 76.2 | 95.2 | 71.3 | | 78.7 | 69.1 | 57.1 | | |
| 3/8″ | 47.1 | 60.6 | 54.6 | 66.7 | 68.12 | 67.75 | 67.9 | 82.9 | 59.2 | 53.4 | 68.4 | 59.1 | 48 | 48.5 | 58.6 |
| No. 4 | 41.1 | 41 | 51.1 | 49.8 | 58.08 | 57.6 | 58.3 | 71.7 | 47 | 41.6 | 58.7 | 46.6 | 45.1 | 43.3 | 51.4 |
| No. 8 | 35.5 | 39 | 40.1 | 44 | 49.81 | 49.24 | 44.4 | 54.5 | 39 | 33.5 | 50.8 | 36.5 | 37.3 | 37.8 | 43.7 |
| No. 10 | 34.7 | 37.1 | | | 41.9 | 41.24 | | | | | 42.2 | | | | |
| No. 16 | 30.7 | | 32.6 | 35.4 | 38.09 | 37.46 | 32.5 | 40.6 | 30.5 | 23.2 | 35.3 | 27.3 | 27.9 | 21.5 | 36.3 |
| No. 30 | 21.5 | 32.3 | 20.6 | 20 | 36.45 | 35.85 | 19 | 23.8 | 20.6 | 14.2 | 29.8 | 18.1 | 15 | | 26.2 |
| No. 40 | 15.1 | 21.8 | | | 34.81 | 34.24 | | | | | 24.3 | | | | |
| No. 50 | 9.2 | | 10 | 7.7 | 24.57 | 24.17 | 6.5 | 7.7 | 9 | 5.4 | 17.6 | 9.4 | 3.9 | 8 | 8.9 |
| No. 80 | | 5.2 | | | 16.79 | 16.52 | | | | | 14.9 | | | | |
| No. 100 | 2.8 | | 3.5 | 1.4 | 6.55 | 6.45 | 1.1 | 2.1 | 1.8 | 2.1 | 11.8 | 3.2 | 1.7 | 2.9 | 2.3 |
| No. 200 | 1.3 | 0.8 | 1.5 | 0.3 | 3.69 | 3.63 | 0.5 | 0.7 | 0.8 | 1.5 | 8.6 | 0.9 | 1.2 | 0.8 | 1.1 |

***Table A4. Summary of combined aggregate gradations for high-strength (900 psi) mixture designs by state***

| Sieve size | AZ (04) | AR (05) | CA (06) | CO (08) | DE-1 (10) | DE-2 (10) | IA (19) | KS (20) | MI (26) | NV (32) | NC (37) | ND (38) | OH (39) | WA (53) | WI (55) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2″ | 100 | | 100 | 100 | 100 | 100 | | | | | | | | | 100 |
| 1 ½″ | 100 | | 97.4 | 99.3 | 100 | 100 | | | | | 100 | | 100 | 100 | 98.8 |
| 1″ | 100 | | 76.4 | 91.3 | 99.36 | 99.1 | 100 | | 100 | 100 | 98.6 | 100 | 98.7 | 98 | 88.6 |
| ¾″ | 88 | 100 | 67.1 | | 88.56 | 91.04 | 90.7 | 100 | 96.8 | 96.8 | 84.2 | 85.9 | 77.5 | 71 | 77.5 |
| ½″ | 57.9 | 82.7 | | 70 | 77.11 | 83.27 | 71.6 | 84 | 74.1 | | 74.8 | 64 | 50.4 | | |
| 3/8″ | 47 | 56 | 53.2 | 59.4 | 65.67 | 75.51 | 60.7 | 66 | 61.2 | 61.8 | 62.6 | 52.4 | 39.9 | 41.3 | 58.6 |
| No. 4 | 41 | 34.1 | 49.6 | 38.7 | 54.86 | 67.39 | 49.8 | 53 | 48.2 | 43.7 | 51.1 | 38.3 | 36.6 | 35.4 | 51.4 |
| No. 8 | 35.4 | 32.4 | 38.9 | 32.4 | 45.95 | 54.6 | 35.9 | 39 | 40.1 | 35.1 | 41.8 | 29.2 | 29.5 | 30.9 | 43.7 |
| No. 10 | 34.6 | 30.7 | | | 37.43 | 41.82 | | | | | 31.7 | 27.7 | | | |
| No. 16 | 30.6 | | 31.6 | 26 | 33.87 | 37.81 | 25.5 | 28.5 | 31.3 | 24.7 | 25.3 | 21.3 | 22.1 | 17.4 | 36.3 |
| No. 30 | 21.5 | 26.7 | 19.9 | 14.7 | 32.41 | 35.84 | 13.6 | 16.5 | 21.2 | 15.5 | 21.4 | 15 | 11.9 | | 26.2 |
| No. 40 | 15.1 | 18 | | | 30.95 | 34.07 | | | | | 17.4 | 11.4 | | | |
| No. 50 | 9.2 | | 9.7 | 5.7 | 21.85 | 24.12 | 4.1 | 5.5 | 9.2 | 6 | 12.7 | 7.5 | 3.1 | 6.5 | 8.9 |
| No. 80 | | 4.3 | | | 14.93 | 14.5 | | | | | 10.7 | | | | |
| No. 100 | 2.8 | | 3.4 | 1 | 5.83 | 5.23 | 0.5 | 1.5 | 1.8 | 2.3 | 8.4 | 2.5 | 1.4 | 2.4 | 2.3 |
| No. 200 | 1.3 | 0.7 | 1.5 | 0.2 | 3.28 | 2.82 | 0.5 | 1 | 0.8 | 1.6 | 6.2 | 0.7 | 1 | 0.7 | 1.1 |