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Aggregate Gradations for Concrete Pavement Mixtures

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Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. The June 2014 MAP Brief provides information relevant to Track 1 of the CP Road Map: Materials and Mixes for Concrete Pavements.

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"Moving Advancements into Practice"

MAP Brief October 2014

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Aggregate Gradations for Concrete Pavement Mixtures

Introduction

Most modern concrete mixtures have more than 70% of their volume composed of aggregate. Aggregate is typically an inexpensive ingredient that can reduce the amount of shrinkage and subsequent cracking. However, proportioning high aggregate volumes in a mixture is a complex subject. The gradation, volume, shape, and texture of aggregates make major contributions to the workability, paste content required, and mechanical properties of a concrete mixture. Each of these issues will be further discussed in detail in the sections below.

Workability

The workability requirements of a concrete mixture can drastically change depending on the application. The unique construction process of slip formed paving requires the workability of a mixture to be flowable enough under vibration for consolidation but still able to hold an edge after the vibration has stopped and the side forms are removed [1, 2]. This property of a concrete is called thixotropy, and is controlled by the paste properties of a mixture and the aggregate volume and gradation [3].

The aggregate gradation plays a major role in the constructability of a slip formed pavement. For example, if the aggregate gradation contains high amounts on any given sieve size, it negatively impacts the ability of a mixture to be consolidated under vibration [4]. Also, the material on the #8 through the #30 sieve plays an important role in the cohesion of the concrete or the ability for it to hold an edge [4, 5]. Mixtures lacking these sieve sizes are at greater risk of edge slumping and possibly segregation.

Finally, a mixture needs to have the right balance of mortar and coarse aggregate for the specified smoothness and the textured finish to reduce noise and improve skid resistance. While mixtures containing excessive material on the #8 through #200 can lead to stickiness, harsh surface finishing, and problems with poor consolidation, mixtures with low amounts retained on the #30 through #200 can create segregation [4]. In addition, many specifications limit the material on the #200 sieve and smaller, as it has a direct impact on the water required in a mixture due to fine particles being made of clay-like particles [6]. However, if these particles were not clays then it might be possible to use larger amounts.

Paste Content

Commonly, mixtures only use enough paste volume to achieve the required workability. One method for determining the paste content through a concrete mixture has been through the voids content of the aggregate [7]. Not only does the paste content play a role in cracking risk, but the paste content is a primary controller of cost, shrinkage, and heat generated in a mixture. These reasons demonstrate the importance of aggregate gradation for reducing the paste content of a mixture. However, the aggregate gradation with the minimum voids content does not necessarily lead to superior mixtures.

Mechanical Properties

Since aggregates make up a large volume of the concrete, the type of aggregate has a major impact on the mechanical properties of the concrete [3, 8, 9]. Aggregates largely control the stiffness and creep of a concrete mixture. However, these properties are more dependent on the aggregate type and volume than on the aggregate gradation.

One mechanical property of focus for concrete producers is the compressive and flexural strength of the concrete. This parameter is primarily controlled by the water/cementitious materials (w/cm) ratio of the paste and the type and volume of the aggregate. The aggregate gradation does play a minor role in determining the strength of concrete through modification of the amount of interfacial zone around aggregates, increased aggregate interlock, and relative stiffness of the paste to the aggregate.

How do I find a good gradation?

Much work has been done to take the information from a sieve analysis and develop methods and tools that help users better understand the gradation and provide insight in how the gradation affects concrete performance. However, not all of these tools have proved useful when applied in the field. A more detailed description of several approaches and their importance is discussed below.

Gap-Graded vs Well-Graded

Discussion has long circulated about the performance difference between gap-graded and well-graded aggregate systems [3, 4, 5, 8, 9, 10, 11, 12]. Both of these terms are broad expressions that do not have well defined meanings. Well-graded aggregate systems are interpreted as gradations with a uniform amount of material retained on adjacent sieve sizes. These mixtures can be used to produce workable mixtures with reduced paste contents and tend to obtain lower voids content of the combined aggregate gradation [9]. However, mixtures with the idealized grading do not always show superior performance [3, 4, 9, 10].

Gap-graded aggregate systems have low and high amounts retained on a given range of sieve sizes. Recent work has suggested that high amounts (> 20% retained) on a given sieve size has a significant impact on workability, while having low amounts did not drastically impact workability [4]. However, most of the literature agrees that a range of gradations can be used with little effect on the performance of the concrete [3, 4, 9, 10].

Maximum Nominal Aggregate Size

Historically, it has been suggested that one should use the gradation with the largest maximum nominal aggregate that is available and constructible in a concrete mixture. It is suggested that when the aggregate with maximum size of aggregate is used, then less water (or paste) will be required to achieve a given workability. While this may be commonly used in practice, the use of larger aggregate sizes does not guarantee improved workability [4]. The use of a larger maximum nominal aggregate size expands the number of sieves sizes and can help reduce high sieve size amounts for a gradation.

Coarseness Factor Chart

The Coarseness Factor Chart (figure 1) developed by Jim Shilstone, Sr. is an empirical approach to aggregate proportioning based on his experience in producing lean concrete mixtures with acceptable workability and reduced segregation [11, 12]. The Coarseness Factor Chart plots two different parameters that help divide a combined aggregate gradation into coarse, intermediate, and fine aggregate sections. The Coarseness Factor represents the ratio of coarse to intermediate aggregate and the Workability Factor represents the ratio of sand and cement to coarse and intermediate aggregate.

Coarseness Factor (CF) = (Q/R)*100
Q= cumulative % retained on the 3/8″ sieve
R= cumulative % retained on the no. 8 sieve

Workability Factor (WF) = W + (2.5(C-564)/94)
W= cumulative % passing the no. 8 sieve
C= cementitious material content (lbs. /yd^3)

The chart has been divided into five different zones that reportedly predict the workability of a mixture. Some states require that mixtures for slip formed pavements fall within a narrower

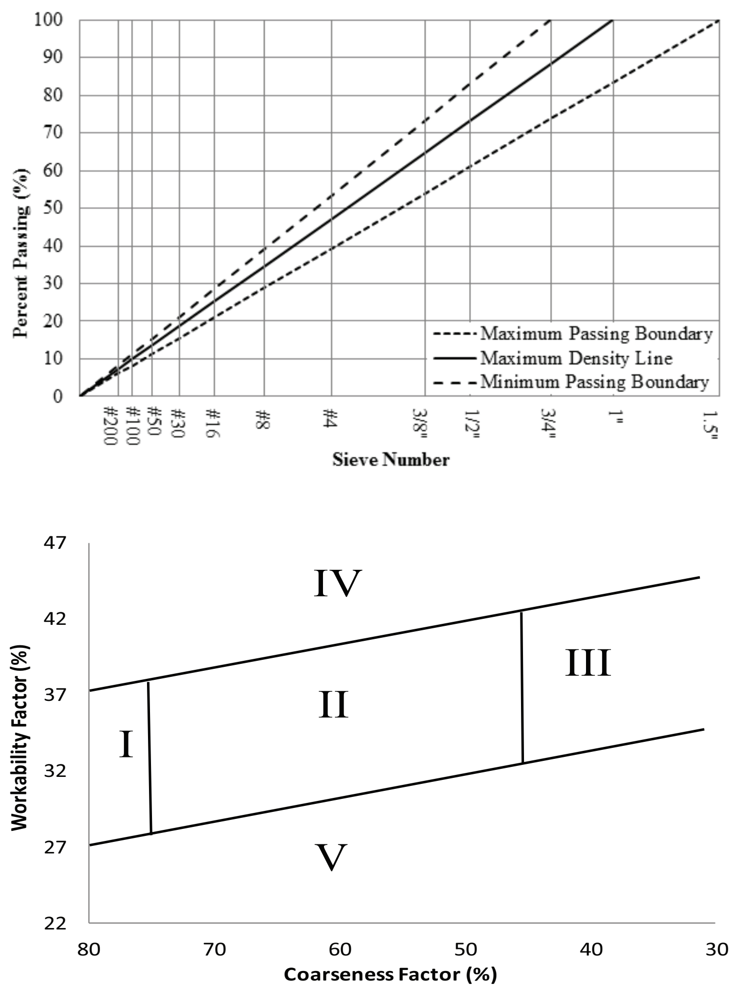

Figure 1. Power 45 Chart (top) and Coarseness Factor Chart (bottom)

region within Zone II [5]. While some contractors report improved constructability, others have found challenges with mixtures at the exact same locations [4, 13]. This suggests that other criteria control the workability of these mixtures.

Power 45 Curve

In this approach (shown in figure 1), the gradation is plotted on the cumulative percent passing chart with the sieve sizes raised to the power of 0.45 [3, 14, 15]. Although a range of exponents have been proposed based on the characteristics of the aggregates, the use of 0.45 is the most common value [16]. Theoretically, a system lying on a straight line from the smallest to largest particles will achieve a maximum density [14]. Experience has shown that it is not always possible to stay on or above the line for particles smaller than #30 [4, 13]. Others have reported that systems too close to the line produce mixtures that are not workable [5, 10, 13].

Individual Percent Retained Chart

Another graphical method for evaluating the distribution of a gradation is using the Individual Percent Retained Chart. This chart is commonly called the "8-18 chart" due to a minimum of 8% and a maximum of 18% required as gradation limits for sieves between 1" and #30; others have called it the "Haystack Chart" due to the results resembling a stack of hay [5]. This graph is useful as it allows the gradation to be plotted and the excessive or deficient amount of material to be easily observed. Recent research supported by field performance on the Individual Percent Retained Chart has led to the creation of the Tarantula Curve [4].

Tarantula Curve

A new set of limits for the Individual Percent Retained chart were developed by comparing the workability and aggregate gradation of more than 500 different mixtures with 8 different aggregate sources [4, 13]. Since the Slump Test has not been shown to adequately evaluate the workability of low flowable mixtures, a quick and inexpensive test was developed called the Box Test [2].

This test investigates the concrete's response to vibration while still being able to hold an edge after the vibration is stopped and the side forms are removed. Unconsolidated concrete is placed in a 1 ft^3 collapsible wood form and vibrated in a consistent manner. Next, the wood forms are removed and the sides of the concrete are inspected for excessive voids. If the sides have excessive voids, the mixture did not consolidate under the vibration and is not satisfactory. Also, the edges of the concrete can be inspected for edge slumping. Examples of satisfactory and unsatisfactory performance in the Box Test are shown in figure 2.

Based on comparing the workability impacts on aggregate gradation, a new set of limits for the Individual Percent Retained Chart were established with new upper and lower bounds that resemble the silhouette of a tarantula. The results also provide recommendations of the coarse sand amount needed for cohesion (the amount retained on the #8, #16, and #30 shall be greater than 15%) and fine sand for workability (between 24% and 34% retained on the #30 - #200). Also, a limit for the ASTM D 4791 flatness of the coarse aggregate has been proposed [4]. More information can be found at www.optimizedgraded.com.

When these results were compared to the gradations of hundreds of successfully placed lean concrete pavement mixtures in Minnesota and Iowa, there was agreement between the recommendations of the Tarantula Curve and the contractor-produced mixture designs. This suggests that, through trial and error, the contractors were finding mixtures with a number of different materials that closely matched the recommendations made by the Tarantula Curve (figure 3).

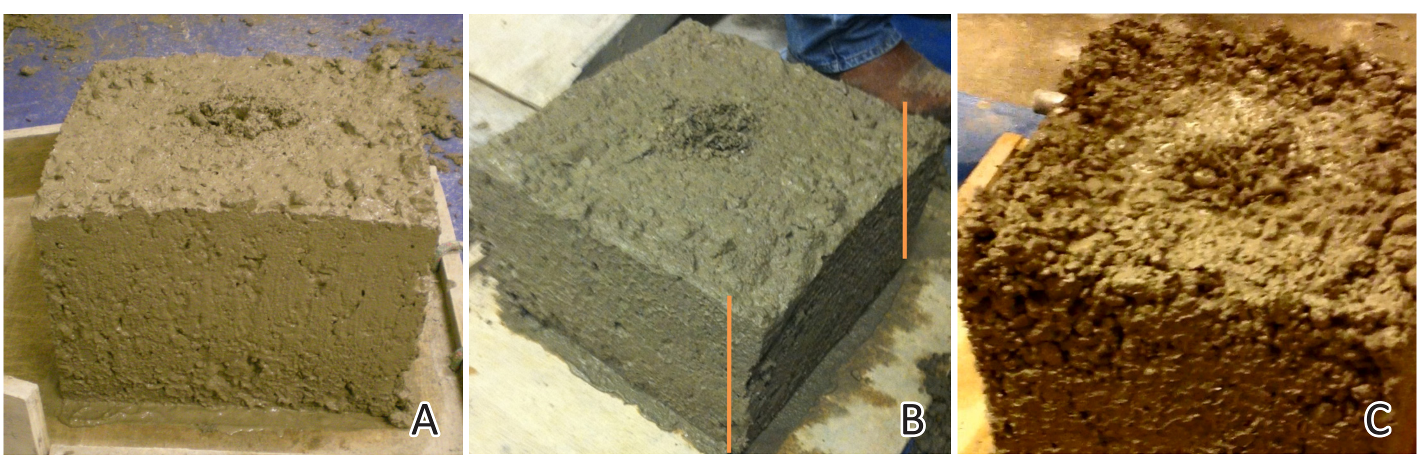

Figure 2. The mixture in image A showed good performance and the mixtures in image B and C did not. Image A shows a mixture that showed good consolidation and no edge slumping. Image B shows a mixture with good consolidation and poor edge slumping. Vertical lines have been added to highlight the edge slumping. Image C shows a mixture with poor consolidation.

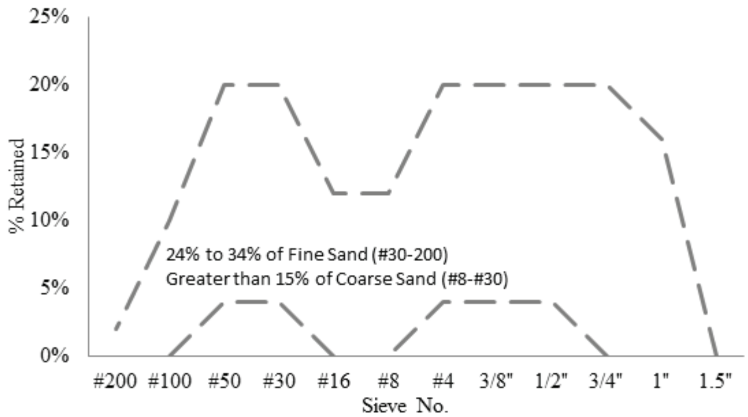

Figure 3 . The Tarantula Curve with the recommended limits of coarse and fine sand.

What if I cannot obtain the recommended gradation?

Concrete pavements have been placed with aggregate gradations that fall outside the recommended limits. Sometimes it may not be economically feasible to reject these gradations or find alternatives.

Due to the aggregate gradation, these mixtures may need higher amounts of paste for satisfactory workability or may require edge forms to minimize edge slumping. This will increase project cost, reduce constructability of the pavement, and lead to greater cracking of the concrete. These mixtures may be improved by blending different aggregate sources so that the resultant grading is closer to the suggested values.

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