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Tech Brief

BLENDED AGGREGATES FOR CONCRETE MIXTURE OPTIMIZATION

Best Practices for Jointed Concrete Pavements

INTRODUCTION

Historically, aggregate gradation has been controlled by specifications that call out envelopes for individual fractions, typically the coarse aggregate and the fine aggregate. The shortcoming of this approach is that the gradation of the overall system is not addressed. While it is sensible to stockpile coarse and fine fractions separately to prevent segregation, it is the combined system that is critical in the final mixture.

The combined grading of aggregates used in concrete mixtures for paving applications can have a direct impact on workability, and indirectly on mixture performance. The measurement of what comprises a good combined gradation is the topic of this tech brief.

Mixtures that must be heavily vibrated because the workability is poor run the risk of segregation and creation of low-durability vibrator trails due to the air void system being compromised (Taylor 2006). Too often, additional water is used to compensate for poor workability, thus increasing the water-to-cementitious materials ratio (w/cm) and compromising potential durability and strength.

Mixtures that have well graded aggregate and are responsive to vibration can lead to significant savings during construction because less effort is required to consolidate and finish the slab and are likely to last longer because less abuse has been applied to the surface to create the required finish.

Another significant benefit of designing a well-graded aggregate system is that the paste content of the mixture can be managed and potentially reduced. Concrete mixtures containing excess paste (i.e., more than is needed for placing and finishing) exhibit numerous undesirable characteristics, including the following:

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Figure 1. Slipformed pavement edge of an optimized mixture (no hand finishing required)

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- Increased shrinkage, which can result in cracking
- Higher permeability leading to critical saturation of the paste fraction (i.e., lower resistance to freeze-thaw deterioration)
- Higher heat of hydration
- Increased cost

Portland cement concrete mixtures used for slipformed pavements should be designed to meet all performance objectives (strength, durability, thickness, smoothness, etc.) and delivered with a workability that produces a nearly vertical edge and minimizes the need for excessive vibration and/or hand finishing (Figure 1). A well graded aggregate system is one tool that can be used to help achieve this aim.

Reducing the paste content of a concrete paving mixture (within limits) through careful management of the aggregate system is therefore desirable for improved performance and at the same time for improved sustainability.

BACKGROUND

Until the 1990s, the gradation of the total aggregate system was rarely considered. However, efforts by Shilstone (1990) led to development of the workability factor chart (Figure 2) among other tools. This empirical work was based on field experimentation with a focus on reducing segregation in mixtures.

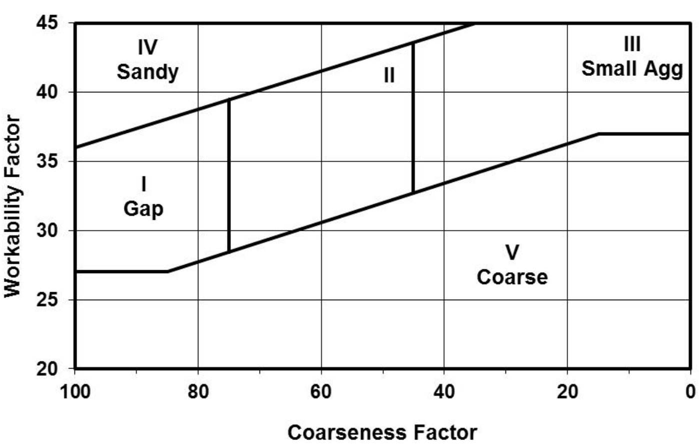


Figure 2. Shilstone workability factor chart

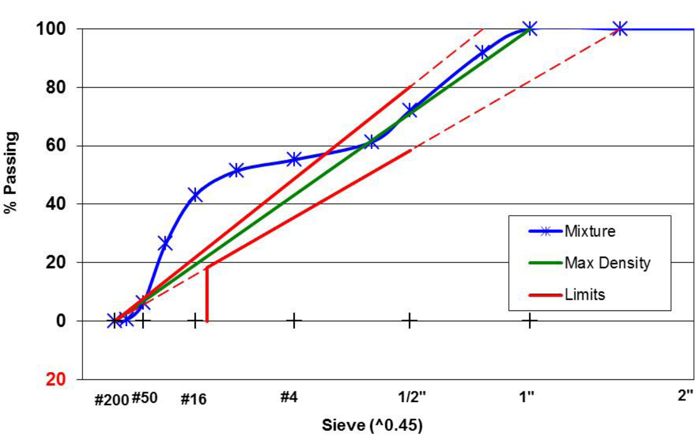


Figure 3. Power 45 gradation curve

The horizontal axis of the workability factor chart is the so-called coarseness factor, which is the mass of the coarse sized (>3/8 in.) aggregate divided by the sum of the masses of the coarse and intermediate (>#8 and <3/8 in.) sizes. A coarseness factor of 100 describes a grading with no intermediate aggregate, and such a mixture may be considered gap-graded. A value of 0 describes a mixture with no coarse aggregate.

The vertical axis is the "workability factor," which is the percent of the combined aggregate that passes the 2.36-mm (#8) sieve plus an adjustment for the amount of cementitious material in a mixture. The chart is divided into several zones with Zone II reported as that desirable for 3/4 in. to 2 in. aggregate nominal maximum sizes in paving mixtures.

Experience has shown that staying within the Zone II box may improve the probability that a workable mixture is achieved; however, it is still possible to produce concrete with poor characteristics inside the box, and good performance is still possible outside the box. Data by Ley has indicated poor correlation between workability and information provided by this chart.

A second tool is to compare the combined gradation on a cumulative passing plot in which the horizontal axis is raised to the power of 0.45. This is based on numerical modeling indicating that maximum density of aggregates is achieved when the plotted combined gradation falls on the line (Kennedy et al. 1994) (Figure 3).

It has been reported that some variation off the ideal line is indeed desirable because too dense a system becomes unworkable.

The third tool used to date has been the Haystack (percent retained) chart in which the amount of material retained on any given sieve was kept within the range of 8 to 18%.

All three of these tools provide slightly different information. Experience has shown that none of these approaches is ideal.

Recent work by Ley has reported that an approach based on the Haystack chart seems to provide promise of achieving reliably workable mixtures. The work was based on re-sieving a given set of materials to adjust the amount retained on one sieve size, by increments, and then to assess the workability of a mixture with fixed proportions (Ley and Cook 2014).

Workability was measured using the Box Test (Ley et al. 2012). The Tarantula curve (Figure 4) provides an envelope in which a desirable amount of material retained on each sieve is reported. The curve varies from the Haystack in that for most fractions, the upper and lower bounds are broadened, except for those on the #8 and #16 sieves that are reduced.

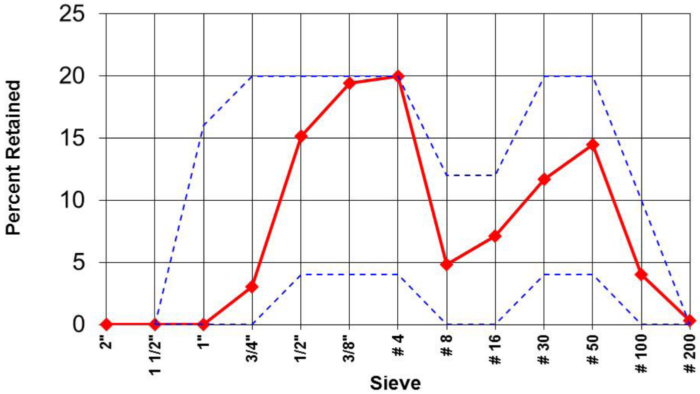


Figure 4. Tarantula curve

The curve has been independently validated by concrete pavement contractors. For example, historical sieve analysis data from the Minnesota Department of Transportation (MnDOT), which implemented the Shilstone approach to combined grading in the 1990s, shows that over time, concrete mixtures have evolved to fit within the recommended limits of the Tarantula curve (Figures 5 and 6) (Ley et al. 2014).

These graphs demonstrate that, with no knowledge of the Tarantula curve, contractor-developed mixtures were refined over time by trial and error to parallel the later-developed Tarantula curve. Similar results have been reported from mixtures in Iowa, North Dakota, and South Africa.

In addition, test sections slipformed in Texas with mixtures containing aggregate gradations falling within the Tarantula curve showed excellent response to vibration with very low cementitious materials content (~450 pcy) (Cook et al. 2013).

IMPLEMENTATION

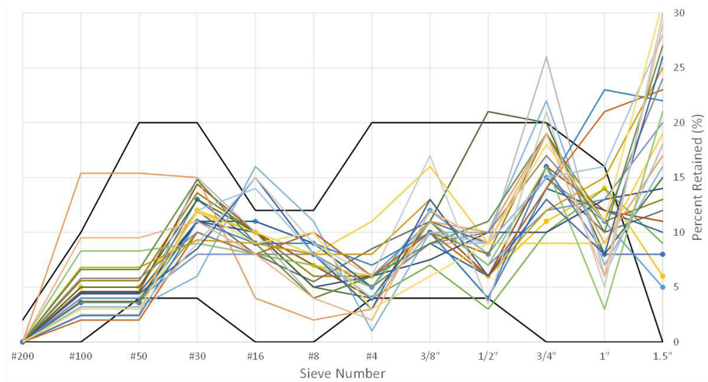
1. Mixture Proportioning

As noted in the two companion tech briefs, which cover Materials-Related Distress (Taylor and Wang 2015 and Sutter 2015), you should select aggregates to be durable in the environment to which they will be exposed. Avoid materials that are susceptible to D-cracking, and avoid those at risk of alkali aggregate reaction or include suitable mitigation systems (such as fly ash) in the mixture as recommended in AASHTO PP65 (2010).

A spreadsheet like the one available from Oklahoma State University at www.optimizedgraded.com can be used to assess whether any given selected combination of aggregates falls within the Tarantula envelope.

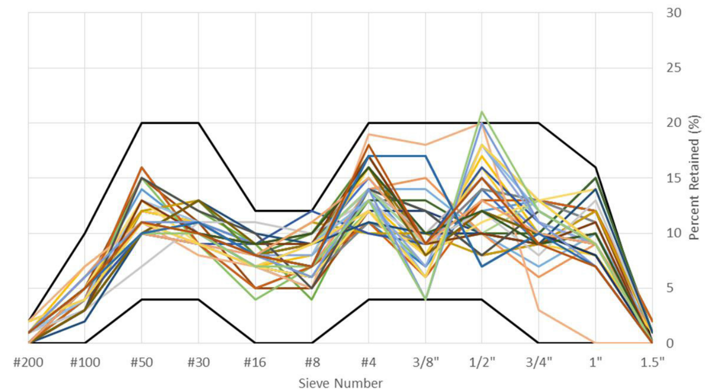
The National Concrete Pavement Technology (CP Tech) Center at Iowa State University has developed a new approach to mixture proportioning based on the work of Koehler and Fowler (2006). The approach consists of three decisions, which are part of an iterative process:

- Choose the aggregate system as discussed at the beginning of this section



Ley et al. 2014 with data from Maria Masten

Figure 5. MnDOT 1996 – 1998 combined gradation with data showing poor correlation to Tarantula curve



Ley et al. 2014 with data from Maria Masten

Figure 6. MnDOT 2010 combined gradation with 98% of mixtures meeting Tarantula curve

- Choose the quality of the paste (binder combination, w/cm and air content, other admixtures)
- Choose the volume of paste required to fill all the voids within the aggregate system and provide adequate workability

Using a spreadsheet developed by the National CP Tech Center for this process (see www.cptechcenter.org/research/projects/detail.cfm?projectID=531824887), the Microsoft Excel solver tool is helpful in finding the combination of the available materials that best meets the requirements, including combined gradation (Tarantula, Power 45), w/cm, and air content.

In some cases, it may not be possible to find a blend of the chosen aggregates that will meet all of the objectives (Tarantula curve and/or economic). If this occurs, you may need to select alternative materials, or modify some of the requirements. This decision is typically based on balancing the costs of importing aggregates with the additional effort required, or extra paste required to maintain the needed engineering properties of fresh and hardened concrete.

Finally, trial batches must be prepared to confirm that the mixture does indeed perform as desired both in terms of workability and mechanical performance (e.g., resistivity and strength).

2. Construction

The laboratory mixture needs to be field-verified before production paving begins. You will need to compare sieve analyses of the materials as delivered to those used in the original design, and make modifications in relative proportions to maintain the accepted gradation.

Aggregate stockpiles must be constructed properly to prevent material segregation. You should establish and use a plus/minus tolerance for each sieve size for quality control purposes.

You will need to adjust the mixture proportions for the moisture content of the aggregates being batched because the w/cm and workability properties are sensitive to the water content of the aggregate.

Fresh concrete properties and early age strength development characteristics should be similar to the laboratory mixture test results and all efforts should be made to batch uniform concrete.

Mixing time needs to be adequate to provide a homogeneous mixture throughout the entire batch. Batching and mixing procedures should assure uniformity between batches (w/cm, unit weight, and workability).

Other practices to assure uniform high quality concrete from batch to batch are discussed in detail in the following publications:

- *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor, ed. 2006)
- *Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012)

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