Effect of Optimized Total Aggregate Gradation on Portland Cement Concrete for Wisconsin Pavements

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Most state paving specifications for portland cement concrete pavement allow a broad range of total aggregate gradation for concrete mixes. It has long been debated whether special efforts to control total aggregate gradation provide concrete improvements that justify potential increased costs. The results of an investigation examining the effect of optimizing total aggregate gradation on the properties of concrete used for paving in Wisconsin are reported. The investigation used concepts presented by Shilstone to optimize gradations consisting of carefully selected proportions of locally available aggregate. Unit weight, shrinkage, change in the water-to-cement ratio (w-c) at constant slump, change in slump at a constant w-c ratio, compressive strength, and possible segregation under vibration were measured in field test sections and laboratory mixes. This investigation showed that use of optimized total aggregate gradations instead of near-gap-graded gradations in pavement resulted in an increase in compressive strength of 10 to 20 percent, reduced water demand by up to 15 percent to achieve comparable slump, air contents achieved with 20 to 30 percent reductions in air entraining agent, potentially higher spacing factors in the air void system of hardened concrete, and reduced segregation following extended vibration (1 to 3 min). Not all efforts at gradation optimization in this study yielded measurable improvements in performance and the availability of local aggregates may still limit, to varying degrees, the ability to optimize. However a reasonable effort to optimize gradation can lead to significant mix benefits.

Most state paving specifications for portland cement concrete pavement allow a broad range of total aggregate gradation for concrete mixes. This is consistent with traditional mix design philosophy allowing wide variation in aggregate gradation such that economy can be maintained by allowing naturally occurring aggregates to be used from one locality to the next. The topic of total aggregate gradation has been debated repeatedly, and while acceptable concrete can be made with a range of total aggregate gradations, recent work by Shilstone (*1*) has suggested that concrete performance can be improved by optimizing total aggregate gradation. The use of aggregate classified into two categories as coarse and fine can lead to gradations where intermediate-sized particles are scarce or absent, and this in turn can lead to harsh, unworkable concrete. The research reported here explored the possible benefits of controlling total aggregate gradation for different Wisconsin pavement mixes by monitoring unit weight, shrinkage, change in the water-to-cement ratio (w-c) at constant slump, change in slump at a constant w-c ratio, compressive strength, and possible segregation under vibration. Research was conducted in the laboratory and in field pavement test sections.

It has long been debated whether gap gradings produce better concrete than continuous gradings (*2*). It appears clear that there is no one answer to this question and that application as well as local conditions play roles in providing an answer for each situation (*3*). Other literature concerning the effect of aggregate gradation consists of case studies and anecdotal evidence by experienced concrete practitioners. Such reports include the work by Sehgal (*4*) that described the important linkage between aggregate gradation and concrete performance. Equations for theoretically ideal grading curves are found in a work by Popovics (*3*). Popovics points out that it is unrealistic to expect a single grading curve to be ideal for all concrete properties simultaneously and the expense of complying with a grading specification can increase rapidly as the number of specified details increase.

In this study, an *ideal gradation* is defined as a precise mix of particle sizes that leads to the most workable, durable, and strongest concrete possible from given aggregate sources. In contrast, an *optimized gradation* is defined as one where practical and economic constraints are combined with attempts to obtain and use a mix of aggregate particles sizes that will lead to improved workability, durability, and strength. The subjective nature of the later definition recognizes the give-and-take as well as common sense that must be applied in optimizing aggregate gradations.

The primary motivation for this investigation originated from concepts presented in a work by Shilstone (*1*). Logic and case histories have been presented suggesting that optimizing total aggregate gradation improves mix workability and mix durability and provides a more reliable basis for mix design. The methodology is based on (a) aggregate particle size distribution, (b) a coarseness factor, (c) a workability factor, and (d) a mortar factor. A definite formula for particle-size distribution has not been presented, but it appears that the examples of optimized particle distribution presented hold some similarities to the 0.45 power curve (*5*). The *coarseness factor* (*1*) is defined as the percentage of material larger than the No. 8 sieve retained on or above the 9.5 mm (3/8 in.) sieve. The *workability factor* is the percentage of material passing the No. 8 sieve. The *mortar factor* is the percentage of mortar as defined by the fine aggregate passing the No. 8 sieve plus the paste portion. The coarseness and workability factors are assessed together in a coarseness factor chart presented elsewhere (*1*). This chart reflects the need to balance the fine aggregate portion with larger particles. Too much aggregate passing the No. 8 sieve will lead to a sticky mix with a high water demand. Too little sand will create a harsh mix with other finishing problems. By using Shilstone's method and a third aggregate to achieve a more optimal particle size distribution,

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the Colorado Department of Transportation reported a 5 percent reduction in water demand and a 10 percent increase in strength on a bridge deck project (*6*).

FIELD AND LABORATORY INVESTIGATION

The investigation involved both field testing of concrete using two 0.8 km (½ mi) highway test sections and laboratory mixing and testing. Concrete using a gradation that approached a gap-graded condition (near gap-graded) was contrasted with concrete containing an optimized gradation (optimized). All gradations and mix proportions met the requirements of Wisconsin Standard Specifications for Road and Bridge Construction (*7*). The mix proportions used in the field are shown in Table 1. The laboratory mixes contained similar proportions except for the aggregate where a specified gradation was remanufactured from local aggregate.

The near-gap-graded and optimized gradations are shown in Figures 1 and 2. The aggregate sources were the same for each gradation and consisted of a local sand, an AASHTO No. 67 stone and an AASHTO No. 4 stone derived from crushed limestone. For the optimized mix, the sand was reprocessed through a classifier to remove fine material to better achieve the target gradation. This resulted in some waste material and additional handling cost beyond that associated with a more typical gradation. The optimized UW Laboratory gradation was selected to follow the centerline of the project specification. Later these gradations were evaluated according to Shilstone's coarseness factor chart. According to Shilstone (*1*), the most desirable gradations will lie close or within the bands on the chart. As shown in the chart (Figure 3), the optimized laboratory gradation is further from the preferred gradation bands than the near-gap-graded gradations.

Primary measurements of the fresh mixes were slump, air content, unit weight, and aggregate gradations established from fresh concrete mixes. A procedure was developed such that collected samples of fresh concrete were subjected to a washing process where all material larger than the No. 200 sieve was retained. The washed samples were taken to the laboratory where they were oven-

TABLE 1 Mix Proportions

Constituent	Proportions in kg/m^3			
	Near-Gap-Graded Field Mix		Optimized Field Mix	
Cement	281		284	
Fly Ash	110		110	
Sand	759	41% of total aggregate	757	40% of total aggregate
AASHTO #67 Stone	471	26%	675	36%
AASHTO #4 Stone	619	33%	457	24%
Free Water	143		122	
AE Agent (ml)	434		302	

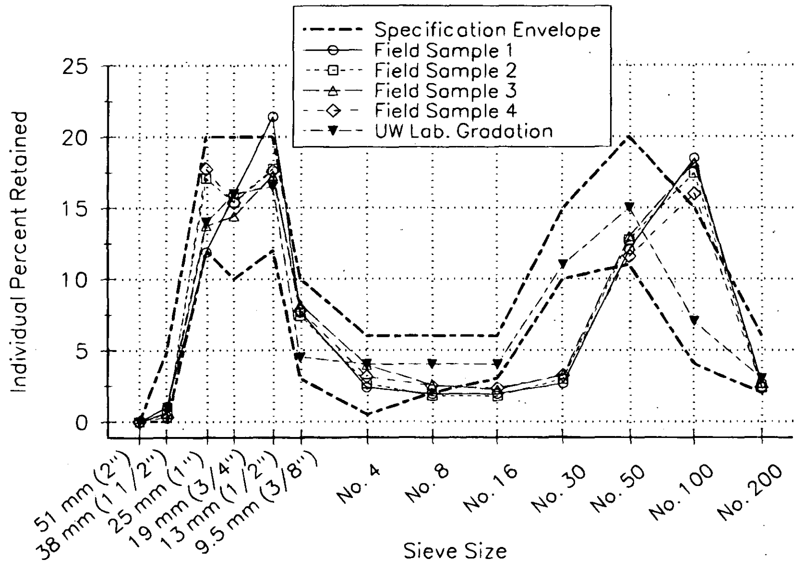

FIGURE 1 Near-gap-graded field and laboratory gradations for pavement mixes.

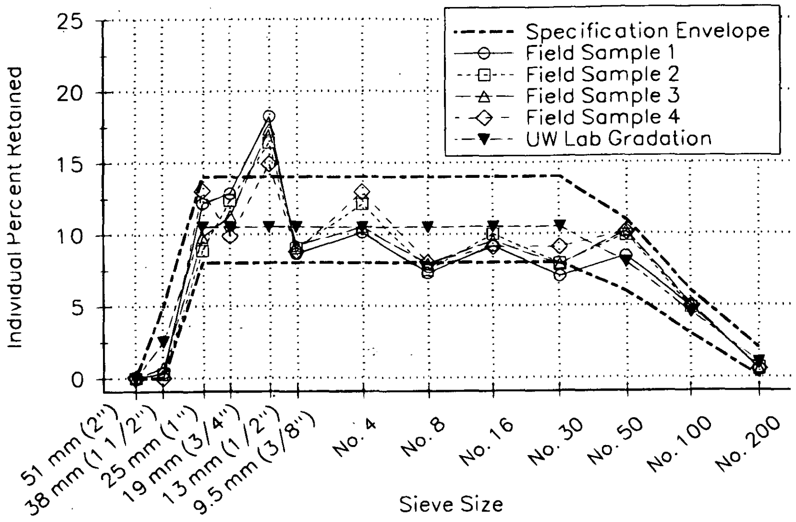

FIGURE 2 Optimized field and laboratory gradations for pavement mixes.

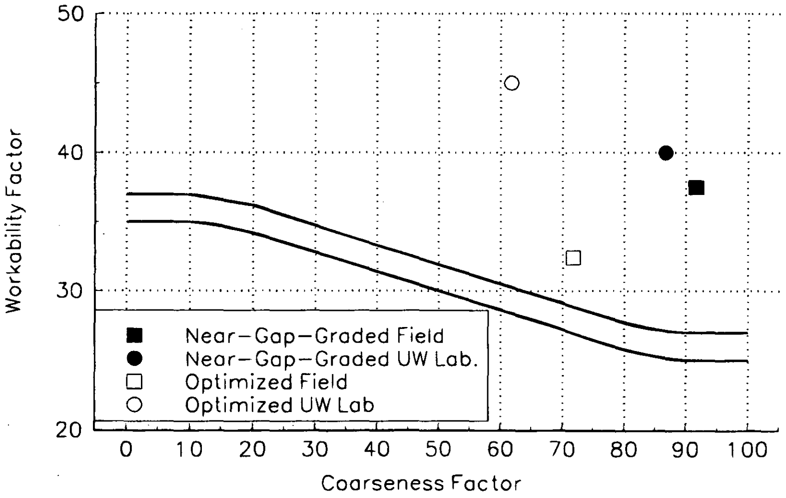

FIGURE 3 Coarseness factor chart for field and laboratory pavement mix gradations.

dried and then subjected to the standard dry sieve analysis. Primary measurements of the hardened mix were compressive strengths at 7 and 28 days, shrinkage, and air-void analysis of cores obtained from the pavement test sections. Test specimens are summarized in Table 2.

Compressive strength results taken at age 28 days are summarized in Table 3. All results were adjusted to a common air content of 6 percent by decreasing strength 1,378 kPa (200 psi) for every percent increase in air content. This adjustment is based on experience with similar paving mixes and is consistent with recommendations (*8*). Strength gains achieved with the optimized mixes ranged from 11 to 22 percent with 95 percent confidence intervals suggesting that the strength gains are statistically meaningful.

Average data resulting from pavement cores are presented in Table 4. These values show that near-gap-graded mixes contained an air-void spacing factor less than the optimized mix, although the near-gap-graded mixes also averaged a slightly lower air content. Generally, a spacing factor of 0.20 mm (0.008 in.) or less indicates sufficient freeze-thaw resistance. The durability characteristics of these mixes must be further analyzed before this finding can be considered significant.

Other collected data suggested that unit weights were no more than 1 percent greater with the optimized mixes. Differences in shrinkage measurements between the two mixes were inconclusive.

Figure 4 shows the average slump and free water content for the mixes. The optimized mixes in the field required an average of 15 percent less water compared with the near-gap-graded mixes in achieving comparable slumps. The same water reduction was not realized in the laboratory mixes, but it can be reasoned that the higher-than-optimal fine particle content (see Figure 3) is the rea-

TABLE 2 Test Specimens Made at Each Test Site for the Pavement Investigation

Mix Site	US Hwy 51 Field Site		Univ. of Wisc. Materials Laboratory		
Mix Type	Near Gap-Graded	Optimized Constant Slump	Near-Gap-Graded	Optimized Constant Slump	Optimized Constant Water
No. of Batches Sampled	4	4	2	2	2
No. of Strength Cylinders	24	24	12	12	12
No. of Shrinkage Prisms	4	4	3	3	3
No. of Core Samples	4	12	NA	NA	NA

TABLE 3 28-Day Cylinder Compression Summary

Mix Type	Location	Air Content, Percent	28 Day Compr. Strength, kPa	95 Percent Confidence Interval, kPa	Optimized/Near-Gap-Graded, Percent
Near-Gap-Graded	Field	6.0	26,300	2,140	NA
Optimized	Field	6.0	29,900	965	114
Near-Gap-Graded	UW Lab	6.0	23,000	1,100	NA
Optimized/ Constant Slump	UW Lab	6.0	28,200	895	122
Optimized / Constant Water	UW Lab	6.0	25,600	1,860	111

TABLE 4 Core Air Void Analysis

Core Identification	Air Content %	Spacing Factor mm	Apparent Specific Gravity	Volume of Permeable Voids %
Near-Gap-Graded Section				
Core 1	6.5	0.15	2.54	12.3
Core 2	5.1	0.18	2.53	13.1
Core 3	6.1	0.15	2.53	12.5
Core 4	6.7	0.18	2.55	12.6
Average of 4 Cores	6.1	0.17	2.54	12.6
Optimized Section				
Core 1	5.8	0.25	2.49	12.6
Core 2	7.1	0.13	2.57	12.5
Core 3	4.9	0.28	2.60	12.3
Core 4	4.7	0.28	2.62	12.8
Average of 4 Cores	5.6	0.23	2.57	12.6

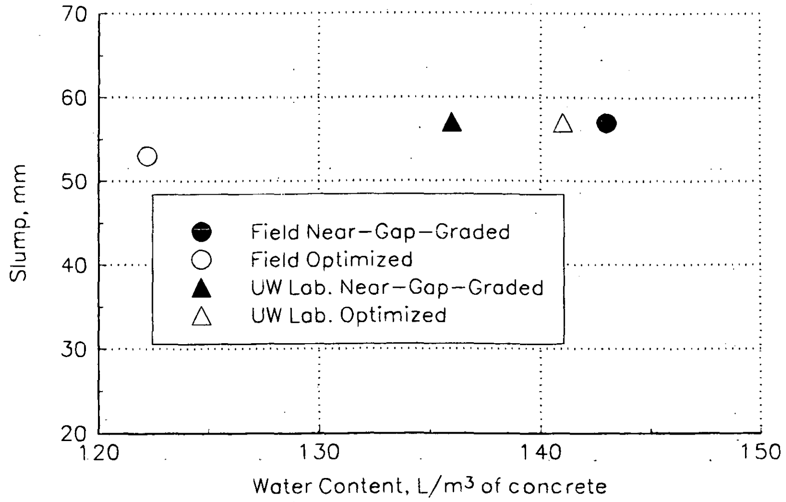

FIGURE 4 Average slump and free water content/m^3 of concrete for all mixes.

son for the higher water demand. In addition, 30 percent less air entraining agent was needed to entrain the same amount of air in the field optimized mix (Figure 5), but as indicated in Table 4 an increase in the spacing factor was subsequently observed in the air-void analysis. For the laboratory optimized mix, 20 percent less air entraining agent was needed.

PARTICLE SIZE REDISTRIBUTION UNDER VIBRATION

The redistribution of particle sizes following vibration was studied by establishing the gradation of individual layers of a larger volume of concrete. A test cylinder consisting of a 560-mm (22-in.) section of a PVC pipe 390 mm (15¼ in.) in diameter was fabricated. The test pipe could separate into four layers. A total volume of approximately 0.05 m^3 (1.7 ft^3) was placed in the test device, with each of the four layers rodded 50 times. A field vibrator was placed in a fixed position in the middle of the test pipe and allowed to vibrate at 10,000 vibrations per minute for a specified time. Both the UW laboratory near-gap-graded mix and the laboratory optimized mix were subject to 20 sec, 1 min, and 3 min of vibration. The washing method described earlier was used for each layer leading to a dry sieve analysis. For 20 sec and 1 min of vibration, each mix retained approximately the same particle distribution in all four layers of the test pipe. At 3 min of vibration, the near-gap-graded mix underwent large redistribution (segregation) of particle sizes while the optimized gradation tended to retain its original distribution in all four layers. The resulting particle distributions from the 3 min tests are shown in Figures 6 and 7.

OTHER EXPERIENCE WITH OPTIMIZING TOTAL AGGREGATE GRADATION

A bridge deck project was also used to explore the effect of total aggregate gradation before the investigation with the paving mixes. As in the pavement study, field test sections and laboratory test

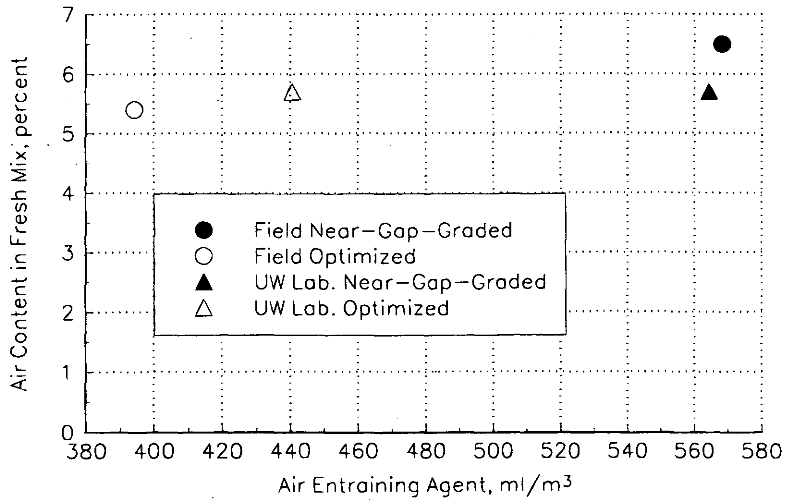

FIGURE 5 Average air content and amount of air entrainment for all mixes.

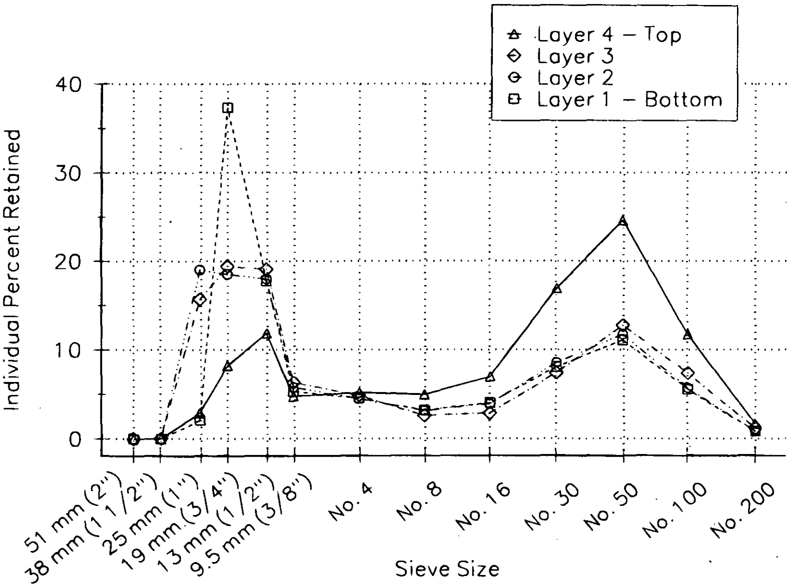

FIGURE 6 Particle redistribution in laboratory near-gap-graded mix subject to 3 min vibration.

mixes were investigated using locally available aggregates. The near-gap-graded and slightly optimized gradations that could be achieved with local aggregates were not as distinctive as in the pavement investigation. Figure 8 shows the near-gap-graded and slightly optimized gradations used in the field portion of the bridge deck project. Laboratory gradations were only slightly more distinctive than those used in the field. In designing these gradations, the coarseness factor chart was ignored and subsequent computation suggested that the slightly optimized mix did not represent an improvement over the near-gap-graded mix.

The results obtained from the bridge deck investigation were not as conclusive as in the pavement study described earlier. In the field and the laboratory, the slightly optimized mixes again required less water than the near-gap-graded mixes to achieve similar slump, but these water reductions were not as large as in the pavement study and ranged from 1 to 7 percent. Strength comparisons ranged from a 13 percent increase in strength in laboratory work to a 6 percent decrease in strength in the field work when the slightly optimized mix was compared with a near-gap-graded mix. Shrinkage and unit weight measurements again showed no difference between the two gradations.

The bridge deck investigation provided several cautionary footnotes to the favorable findings observed in the pavement study. First, available aggregates and economics may limit the optimization that can reasonably be obtained in many projects. Second, minor attempts to mitigate a near-gap-graded gradation by simply

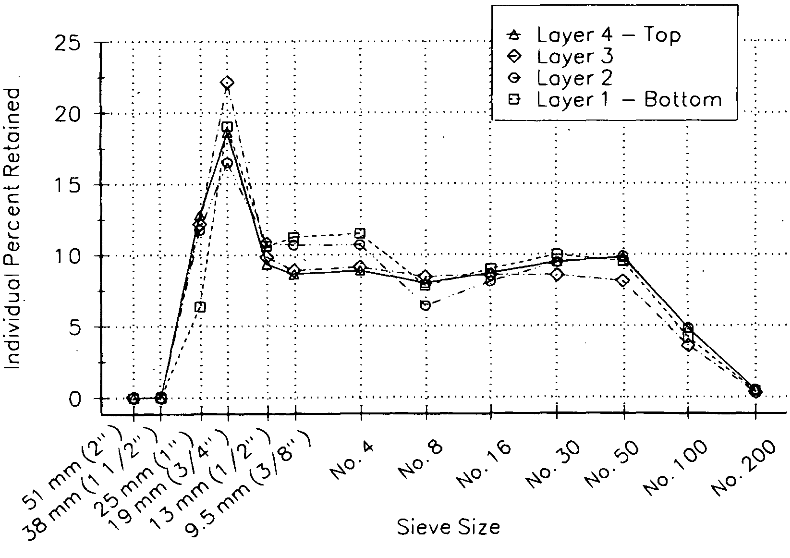

FIGURE 7 Particle redistribution in laboratory optimized mix subject to 3 min vibration.

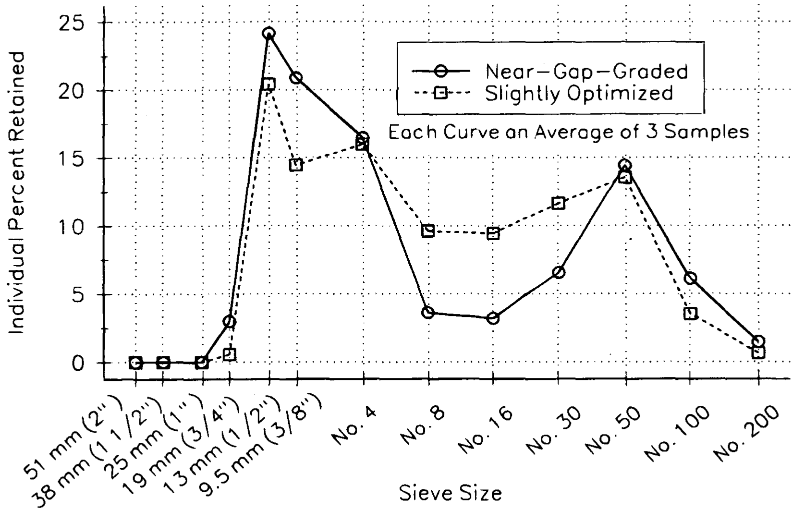

FIGURE 8 Near-gap-graded and slightly optimized bridge deck mix field gradations.

adding some intermediate-sized particles that are scarce do not guarantee an identifiable improvement in concrete strength or workability. Attention to the concept of the coarseness factor chart appears to hold some importance besides simply filling in scarce intermediate-sized particles.

SUMMARY AND CONCLUSIONS

This pilot study examined the differences in portland cement concrete performance for pavement mixes containing near-gap-graded total aggregate gradations and those using an optimized total aggregate gradation. Optimized gradations were established on the basis of a methodology (*1*) by which a continuous particle-size distribution was achieved. Field and laboratory investigations were directed toward evaluating unit weight, shrinkage, change in the w-c ratio at constant slump, change in slump at a constant w-c ratio, compressive strength, and possible segregation under vibration.

This investigation showed that use of optimized total aggregate gradations in place of near-gap-graded gradations in pavement resulted in

- An increase in compressive strength of 10 to 20 percent,
- Reduced water demand by up to 15 percent to achieve comparable slump,
- Air contents achieved with 20 to 30 percent reductions in air entraining agent,
- Potentially higher spacing factors in the air-void system of hardened concrete, and
- Reduced segregation following extended vibration (1 to 3 min).

Not all efforts at gradation optimization guarantee measurable improvements in performance, and the availability of local aggregates may still limit to varying degrees the ability to optimize. Further investigation into the effect of total aggregate gradation on durability is planned and is needed before widespread use of total gradation optimization will be considered in Wisconsin. This study suggests, however, that reasonable effort to optimize gradation can lead to significant mix benefits.

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