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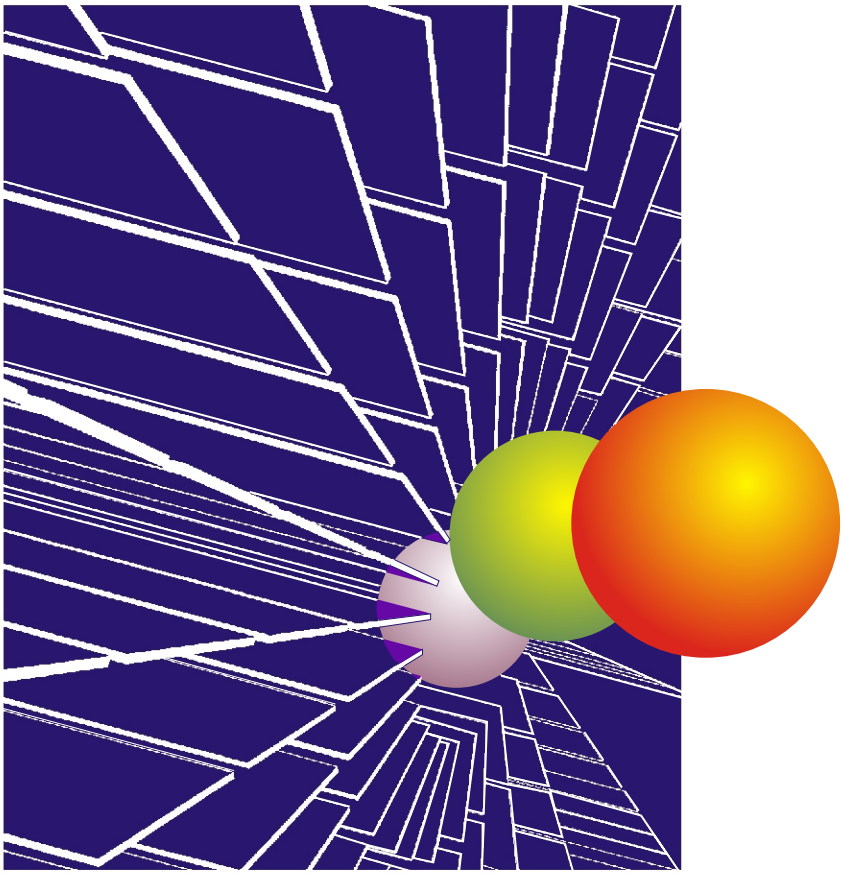

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16. Abstract: A brief analysis of current MoDOT specified limits on gradations was undertaken. Depending on which side (fine or course) the gradations were running in relation to the limits, various combinations of sand and course aggregates A, B, or D were all over the Coarseness Factor chart, with behavior ranging from rocky to good to sandy.		
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AGGREGATE GRADATION OPTIMIZATION-
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EXECUTIVE SUMMARY

For almost 100 years, efforts have been made to achieve desired concrete properties through adjustments in aggregate gradation. Initial efforts dealt with the concept of maximum density with the idea that a denser gradation would contain fewer voids to be filled with cement paste. Unfortunately, mixtures formulated with few voids tended to be harsh.

At some point, the intermediate size of the overall aggregate gradation started to be removed for use in other products, and typical practice evolved into the use of two distinct aggregate fractions, coarse and fine, for routine production of concrete. Many times this left the gradations in a gap-graded state. In the early 1970's, Shilstone began to propose that the industry revert to a more well-graded set of materials. He developed and promoted the evaluation of total gradations on a volume basis, not a weight basis, by use of the following analysis charts: 1) the individual percent retained plot, 2) the Coarseness Factor Chart, and 3) the 0.45 power gradation plot. The use of aggregate fractions that would supply the missing intermediate (3/8 in. to #30) material was highly recommended. The use of aggregates that would not necessarily meet ASTM C 33 specifications was put forth as a possibility. Certain state DOT's (Iowa, Minnesota, Kansas, Washington) as well as other specifying agencies (ACPA, MCIB, USAF), have formally adopted some form of the concept of optimization of aggregate gradations. A number of other states are in the stages of considering optimization

and allowing it on an experimental, case-by-case basis. Based on discussions on the internet, private industry seems to have moved forward more quickly than the public sector. Several commonly used specifications contain language permitting/ encouraging/recommending the use of aggregate gradation optimization, including ASTM C 33, ACI 301, ACI 302, and ACI 304.

A side issue related to the general concept of optimization is the so-called “8-18” band. The consensus, even among specifiers, seems to be that the 8-18 (or 8-22) should be used as a guide and an ideal to strive for, not a rule, knowing that absolute adherence may be too costly to be of practical use.

Concurrent with the Shilstone movement is the growing body of specifiers that want a return to coarser, higher fineness modulus sands to get away from water demand related shrinkage issues.

Most reports of the use of aggregate optimization point out the benefits of using a more well-graded material, including less paste and hence less concrete shrinkage, greater strengths, better pumpability, and enhanced finishability. Well-graded mixtures tend not to have as many problems as gap-graded mixes in terms of pavement edge slump, segregation during vibration, finishing, raveling at joints, and wear resistance. One of the main benefits of characterizing the mix as a single point on a Coarseness Factor-type chart is the ability to adapt to changing gradations in a timely manner.

Concern about the practicality of producing optimized aggregates centers on the difficulty in producing the gradations, especially coarser sands, in quantities large enough for typical jobs. Extra equipment may have to be purchased, extra handling may be involved, extra shipping costs may be present, and some natural sources of materials may not be conducive to providing the missing sizes.

One caution about trying to overcome a gap-graded mix by adding an intermediate size aggregate is that the particle shape must at least be compact, and preferably rounded. If the intermediate aggregate is flat and elongated, the result may be quite far from what was intended.

A brief analysis of current MoDOT specified limits on gradations was undertaken. Depending on which side (fine or coarse) the gradations were running in relation to the limits, various combinations of sand and coarse aggregates A, B, or D were all over the Coarseness Factor chart, with behavior ranging from rocky to good to sandy.

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INTRODUCTION

Aggregate gradation in concrete mixtures has been shown to affect constructability, strength, durability, pavement smoothness, and economy, as well as segregation, water requirements, and admixture dosage requirements. Various models have been put forth as to the best way to predict the effects of gradation. Several more recent agency specifications have been implemented to take advantage of optimized gradations. Optimized gradations are those that have been enhanced in some manner, such as making the material more well-graded, in order to enhance some property of the concrete. Additionally, particle shape has been mentioned as a possible factor in the successful use of optimized gradations.

The potential benefits resulting from using optimized gradations can be significant. Initial costs may be reduced if cement paste content can be lowered, as well as required air entraining agent dosage. If required water content can be lowered, shrinkage can be reduced along with potential cracking. If constructability is enhanced, then durability and smoothness can be improved, resulting in both lower initial and life-cycle costs.

RESEARCH OBJECTIVES

The objective of this research is to perform a literature search which summarizes the findings in various publications that involve aggregate optimization issues

such as the effect of optimization on constructability, strength, smoothness, segregation, and required water and air entraining agent dosage.

LITERATURE SEARCH

PAST METHODS OF GRADATION CHARACTERIZATION AND COMBINATION OF AGGREGATE FRACTIONS

Maximum Density Methods

Fuller and Thompson did the groundbreaking work on adjusting gradation to render the greatest strength and workability. They concluded that aggregate should be graded in sizes and combined with water and cement to give the greatest density. They developed an ideal shape of the gradation curve. They noted that the gradation that gave the greatest density of the aggregates alone may not necessarily give the greatest density when combined with the water and cement because of the way the cement particles fit into the smaller pores (Fuller and Thompson 1907). The idea that aggregate gradation could be controlled and thus affect concrete properties led to other research and ultimately to specifications governing aggregate gradation.

Work by Wig, et al. suggested that Fuller and Thompson's conclusions could not necessarily be extrapolated to aggregates different from the ones used in the original study. It was shown that the Fuller curve may not always give the maximum strength nor maximum density (Wig et al. 1916).

Talbot and Richart developed the well known equation:

$$P = \left(\frac{d}{D}\right)^n \tag{1}$$

Where:

P= amount of material in the system finer than size “d”

d= size of the particular group in question

D= largest particle in the system

n= exponent governing the distribution of sizes.

Their work indicated that for a given maximum particle size, D, The equation produces the maximum density when n= 0.5. They concluded that aggregate so graded would produce concrete mixtures that were harsh and difficult to place and were not really usable (Talbot and Richart 1923). Other authors are in agreement with this conclusion, and eventually maximum density proportioning methods fell out of favor (McMillian 1929; Walsh 1933; Besson 1935; Blanks et al. 1940; Frost 1967).

Surface Area

Edwards theorized that the surface area of aggregate particles would control the amount of water required for a workable concrete mixture. The controlling factors

were the characteristics of the cement and the fine aggregate surface area (Edwards 1918).

Young further discussed the concept that the quantity of water required is dependent upon the quantity and consistency of cement and the total surface area of the aggregate, which in turn is dependent upon the grading. He concluded that the concrete aggregate having the least surface area will require the least water in excess of that required for the cement and thus will be the highest in strength (Young 1919).

Fineness Modulus

In 1918 Abrams published his now-famous work regarding concrete mix design. He found fault with previous methods of proportioning for maximum strength because they neglected the importance of water. His primary concern was strength, while workability was of interest only insofar as the concrete was workable enough to be used. However, he did state that there was a relationship between aggregate grading and the quantity of water required to produce workable concrete. To aid in the selection of aggregate gradations that would prevent the use of excessive water, he developed a method of representing aggregate gradation known as the Fineness Modulus (FM):

$$\mathrm{FM} = \frac{\text{Cumulative percents retained}}{100} \qquad (2)$$

The sieves used by Abrams were; 1 ½, ¾, 3/8 in., #4, #8, #14, #28, #48, and #100. Note that the #14, #28, and #48 sieves have since been replaced with #16, #30, and #50 sieves. The openings were about half the size of the previous sieve. No justification was given for their selection. In the ideal situation, a greater FM would represent a coarser gradation. He developed charts that gave maximum fineness moduli that could be used with a given quantity of water and cement-aggregate ratio. He asserted that any sieve analysis giving the same FM will require the same amount of water to produce a mix with the same plasticity and strength. He noted that the surface area of the aggregate varied widely within a given FM but did not seem to affect strength. He did not comment on workability. Examination of the experimental work by Abrams reveals that as FM decreased, the amount of water per sack of cement increased (Abrams 1918).

Young produced data that showed a relationship between FM and surface area. As FM decreased, surface area increased (Young 1919). However, other authors stated that fineness modulus and surface area are not related (Abrams 1918; Williams 1922; Hewes 1924; Besson 1935). Young later denounced the relationship (Young 1921). Hewes derived equations to mathematically prove that FM was not connected to surface area (Hewes 1924). Besson pointed out that for one FM there could be numerous gradations of various aggregate contents; the same could be said of surface area (Besson 1935). Joel concluded that ”if a gradation follows a somewhat smooth curve, the surface area will vary similarly to the FM in all cases. If the gradation is gap graded or very irregular, the FM and surface area will differ from the expected trend” (Joel 1990).

Although Abrams continued to adhere to his gradation concept (Abrams 1918; Abrams 1919; Abrams 1919; Abrams 1919; Abrams 1919; Abrams 1922; Russell et al. 1940), other researchers did not support the FM as a useful tool (Edwards 1918; Young 1919; Young 1921; Besson 1935; Kennedy 1940; Mercer 1948). FM of sand has continued to be used in the ACI 214 mix design method. Although under attack for a number of years, there has recently been interest in using the total fineness modulus in mix design (Taylor 1986).

ACI Mix Design Method

In the development of the ACI method (ACI 1985) of mix design, Goldbeck and Grey based their work (Goldbeck 1928; Goldbeck 1928; Goldbeck 1929; Goldbeck 1931; Goldbeck and Grey 1942; Goldbeck 1946; Goldbeck 1950; Goldbeck and Grey 1965; Goldbeck 1968; Goldbeck 1968) on the theories of Talbot and Richart and Weymouth (Talbot and Richart 1923; Weymouth 1933; Weymouth 1938). A controlling principle is that particle interference among coarse aggregate particles affects workability. Weymouth had postulated that workability is achieved by spacing the particles far enough apart that they would not interfere with each other. The ACI method considers the FM of the sand and the dry rodded unit weight (ASTM 1991a) of the coarse aggregate in selecting the proportion of coarse aggregate. This is Goldbeck and Gray's "b/bo" method of arriving at the total gradation of the combined coarse and fine aggregate, as shown in Table 1. As shown, for a given nominal maximum size (NMS), as the

FM of the sand increases, less coarse aggregate is allowed in order to maintain workability.

Table 1 Bulk Volume of Coarse Aggregate Per Unit Volume of Concrete

Nominal Max. Size In.	Bulk Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate			
	2.40	2.60	2.80	3.00
3/8	0.50	0.48	0.46	0.44
½	0.59	0.57	0.55	0.53
¾	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1-1/2	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

Shilstone's discussion (Shilstone and Shilstone Jr. 1987) contends that the b/bo table, conceived in 1938, was for concrete placed without the aid of vibration, thus tending to produce mixes somewhat low in coarse aggregate. "Weymouth based his theory on the size of the space between particles and the next smaller size which would fit into the space. For maximum workability and the greatest economy, the relationship between particle sizes should be one in which particles of one size group are just under the opening provided by the next larger particle group" (Joel 1990). Weymouth presented the equation:

$$t = \left[\left(\frac{do}{da} \right)^{\frac{1}{3}} - 1 \right] \times D \qquad (3)$$

where:

t= average distance between particles of diameter D

do= density of the size group (the solids present in a unit volume alone, secured by a unit weight and specific gravity test)

da= ratio of the absolute volume of a size group to the space available to that size in the concrete

D= average diameter of the particles in the size group

The assumption was that particle interference would occur when “t” was less than 0.5D; unfortunately, sometimes when this relationship occurred, the result was not necessarily harmful. Dunagan furthered this concept and noted that interference occurs only if t is less than 0.5D over a considerable portion of the gradation curve (Dunagan 1940).

MODERN CONCEPTS

Current Practice

It has been suggested that there are problems associated with current gradation specifications such as ASTM C 33 and with the current method of specifying aggregates (Shilstone and Shilstone Jr. 1987; ASTM 1994). Early design

techniques recognized and promoted the use of a continuous total gradation. The 1923 ASTM C 33 version advocated the use of predominantly coarse particles and required that 85 percent pass the #4 sieve. Today's sands are much finer with 95 to 100 percent passing the #4 sieve. Currently, ASTM C 33 lists only two aggregate fractions, coarse and fine. There are 15 alternate gradations of coarse aggregate. Each has fairly wide limits to allow for differences in local conditions and for production variation. At a typical concrete batch plant, only one coarse and one fine aggregate are usually stocked for the purposes of routine production of concrete. This creates the potential for gap-graded mixes with associated concrete behavioral problems. Additionally, this lack of fractions makes for little flexibility at the batch plant for adjusting proportions to meet changes in gradation. Aggregate gradation specifications are relatively wide, and production does vary. Effects of changes in gradation upon concrete properties are difficult to assess and translate into timely corrective action with traditional controls. Although methods of characterizing gradations such as the surface area method and the FM method have been used to tie gradation to the proportioning of concrete, their downfall is that changes in gradations can render little change in calculated surface area or FM, but the workability of the concrete could be significantly different (Shilstone and Shilstone Jr. 1987).

Typical practices involving the use of ASTM C 33 sand gradations and FM's have been criticized. It has been said that the sands currently used are too fine, leading to problems of high bulking volume and will increase water demand for mobilizing the sand (Fig. 1).

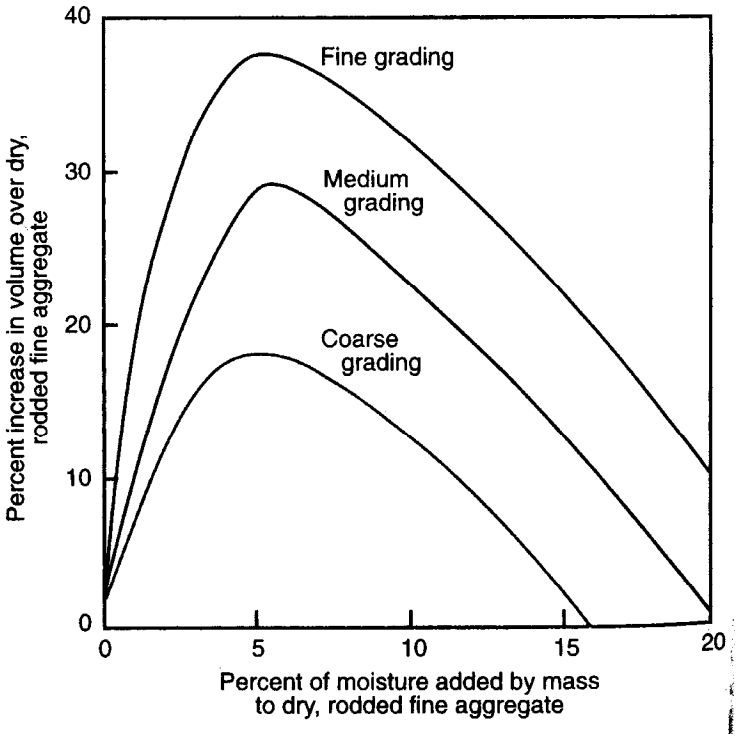

Fig. 1-Sand bulking (Kosmatka et al. 2002) .

Increased water demand may result in increased shrinkage and then cracking. For mixes with cement contents greater than 400 lbs, or with mixes that have supplementary mineral admixtures, the fine sand portion should be deleted to allow the cementitious materials to complete the deficiency in the missing sizes (Lafrenz 2001). The Air Force handbook and guide (Muszynski 1996; USAF 1997) recommend that the C 33 upper FM limit of 3.1 should not be in force, but the lower limit of 2.3 should be retained. Lafrenz states that it would be best if the FM was greater than 3.1 for paving concrete. However, this coarse sand may not be available from local suppliers, and manufactured sands may be necessary. For concrete placed by mechanical means, the sand minimum passing the #50

and #100 sieves should be set toward the lower C 33 optional allowables of 5 and 0%, respectively (Lafrenz 2001) (Muszynski 1996; USAF 1997).

Concrete mixtures designed in accordance with ACI 211 also have been criticized for being poorly graded; they tend to have lower coarse aggregate and greater sand contents. The footnote (Table 1) recommendations regarding additional coarse aggregate are generally ignored. Thus the mixes tend to be gap-graded, highly sanded, and prone to segregation when subject to vibration. These characteristics can lead to problems with edge slump, consolidation, and finishing, although this does not necessarily mean that gap-graded mixes cannot be successfully placed and finished (Muszynski 1996).

Combined Gradation

Shilstone. Shilstone (Shilstone 1990) began work on concrete optimization in the 1970's on a project located in Saudi Arabia. Through experimentation, he found or verified several factors that impact concrete properties as they relate to aggregate gradation. His emphasis was on workability and the ability to easily make adjustments to the gradation. He suggested that slump may be controlled by gradation changes without adjusting the water-cementitious material ratio (*w/cm*) or affecting strength. He concluded that:

“For every combination of aggregate mixed with a given amount of cementitious materials and cast at a constant consistency, there is an optimum combination which can be cast at the lowest *w/c* and produce the highest strength. The optimum mixture has the least particle interference and responds best to a high frequency, high amplitude vibrator. The optimum mixture cannot be used for all construction due to variations in placing and finishing needs.”

Whenever the term “optimized mix” is mentioned, it must be referenced to a specific construction application. Referral to Shilstone’s conclusions as quoted above is recommended.

Shilstone divides the total gradation (on a volumetric basis) into three fractions, coarse, intermediate, and fine. The coarse fraction (Q) is the material retained on the 3/8 in. sieve, the intermediate (I) is the material passing the 3/8 in. sieve and retained on the #8, and the fine (W) is the aggregate material finer than the #8 sieve and coarser than the #200 sieve. The intermediate size fills the major voids between large particles and reduces the need for the fine material.

The intermediate size material can come from the traditional ASTM C 33 coarse or fine aggregate (ASTM 1994). Unfortunately, the intermediate size is often lacking in the coarse and fine fractions, and the voids will have to be filled with sand, cement, and water. By using mortar to fill voids, less of it is available to provide workability, and the mix becomes harsh and difficult to finish. The use of three aggregate fractions was discussed by Gilbert and Kriege in 1930. They

believed that the intermediate size was quite significant toward controlling the void ratio of the aggregate gradation. Total gradation curves were developed, much like Shilstone's, to identify gradations that lacked sufficient intermediate sizes (Gilbert and Kriege 1930).

Shilstone (Shilstone and Shilstone Jr. 1987) has recommended the calculation of aggregate gradations on the basis of volume rather than the traditional weight basis. This makes more sense because particles interact volumetrically, not by weight.

Shilstone has also promoted the use of a method of gradation portrayal by use of an Individual Percent Retained (IPR) *vs* sieve size chart. With this, it is easy to determine which sizes are excessive or deficient. Fig. 2 shows a gradation which has an ideal "haystack" shape (Shilstone 1990).

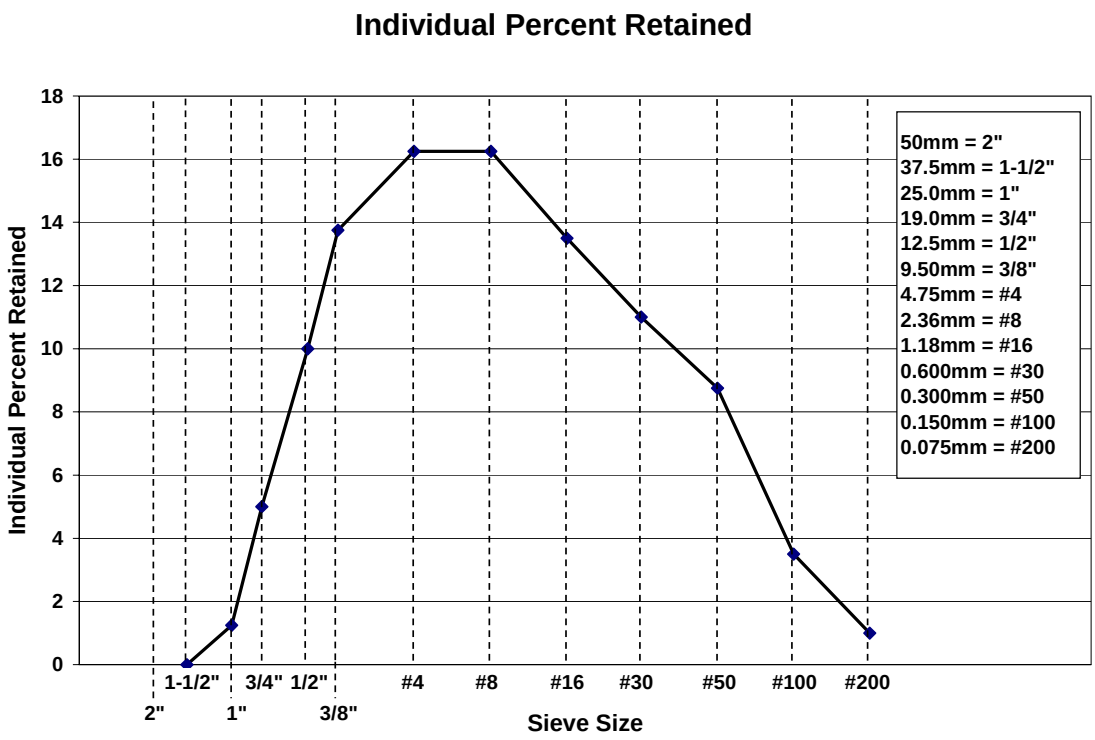

Fig. 2- Ideal "haystack" gradation, Individual Percent Retained.

However, if a mix is proportioned using ASTM C 33 #57 size coarse aggregate and C 33 sand with both gradations running down the middle of the allowable variation for each material, the resulting plot looks like Fig. 3.

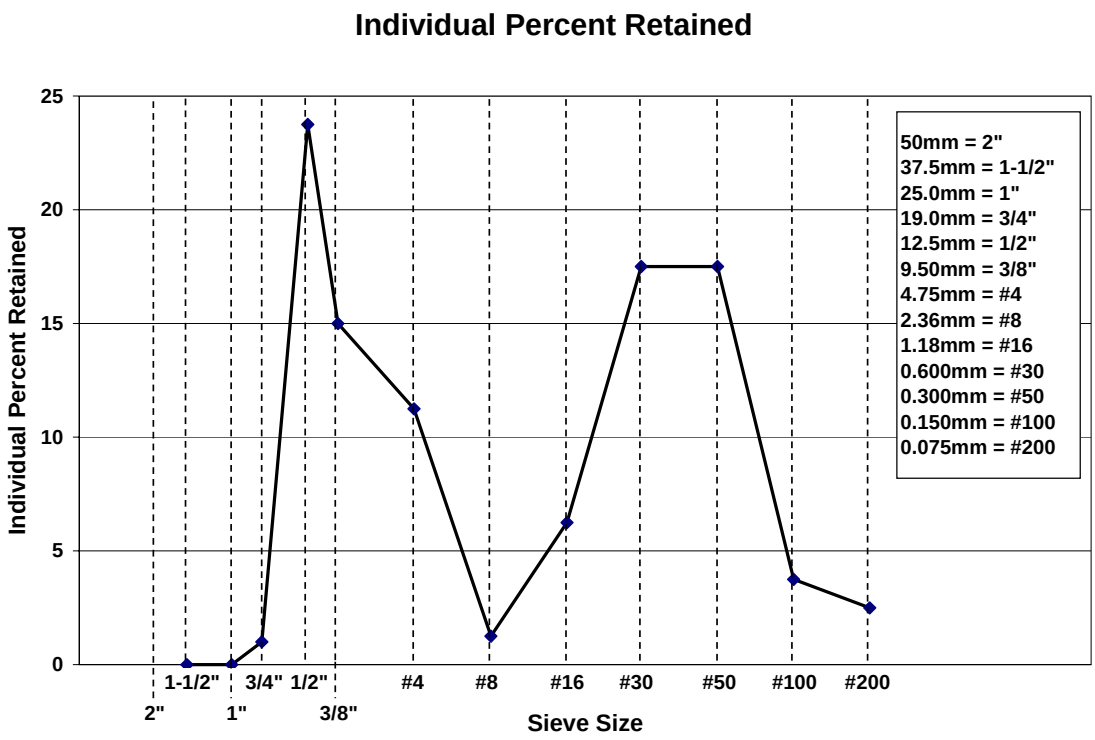

Fig. 3- Double hump, Individual Percent Retained.

As shown, there is a double hump, with a lot of material retained on the ½ in., #30, and #50 sieves. There is a lack of intermediate size material on the #8 sieve. This mix is said to have problems with finishing. If the sand content is increased, the water demand will increase, leading to lower strengths. At this point, the mix would be over-mortared and will cause pumping problems due to increased line friction. An actual mix similar to the mix shown in Fig. 3 was corrected by adding intermediate particles, shown in Fig. 4, which produced a mix that worked well and was easy to finish (Shilstone and Shilstone Jr. 1987).

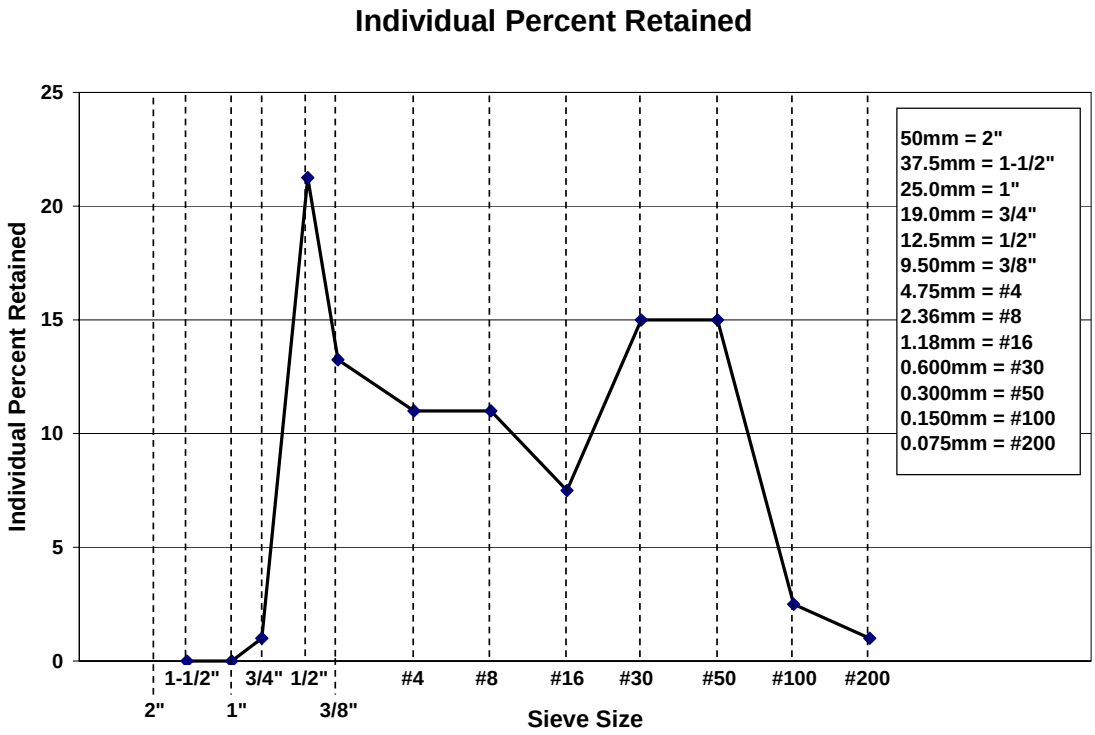

Fig. 4- Adjusted mix, Individual Percent Retained.

Shilstone (Shilstone 1990) compares ASTM C 33-87 with the 1923 C 33 grading standards and with the recommendations of the first issue of the Portland Cement Association's *Design and Control of Concrete Mixtures* (PCA 1925), shown in Table 2. Fig. 5 depicts the combined PCA recommended gradations. This curve shape resembles the desired haystack much more than the modern specified gradations.

Table 2. Comparison of ASTM C 33-87, C 33-23, and PCA Gradations

	Coarse Aggregate			Fine Aggregate		
Sieve In.	C 33-87	C 33-23	PCA	C 33-87	C 33-23	PCA
1-1/2	100	10	100			
1	95-100	95	100			
¾	---	---	85			
½	25-60	40-75	55			
3/8	---	---	30	100	100	100
#4	0-10	<15	0	95-100	85	80
#8	0-5	<5	0	80-100	---	65
#16				50-85	---	45
#30				25-60	---	30
#50				10-30	<30	15
#100				2-10	---	0
#200				0-5	<3	

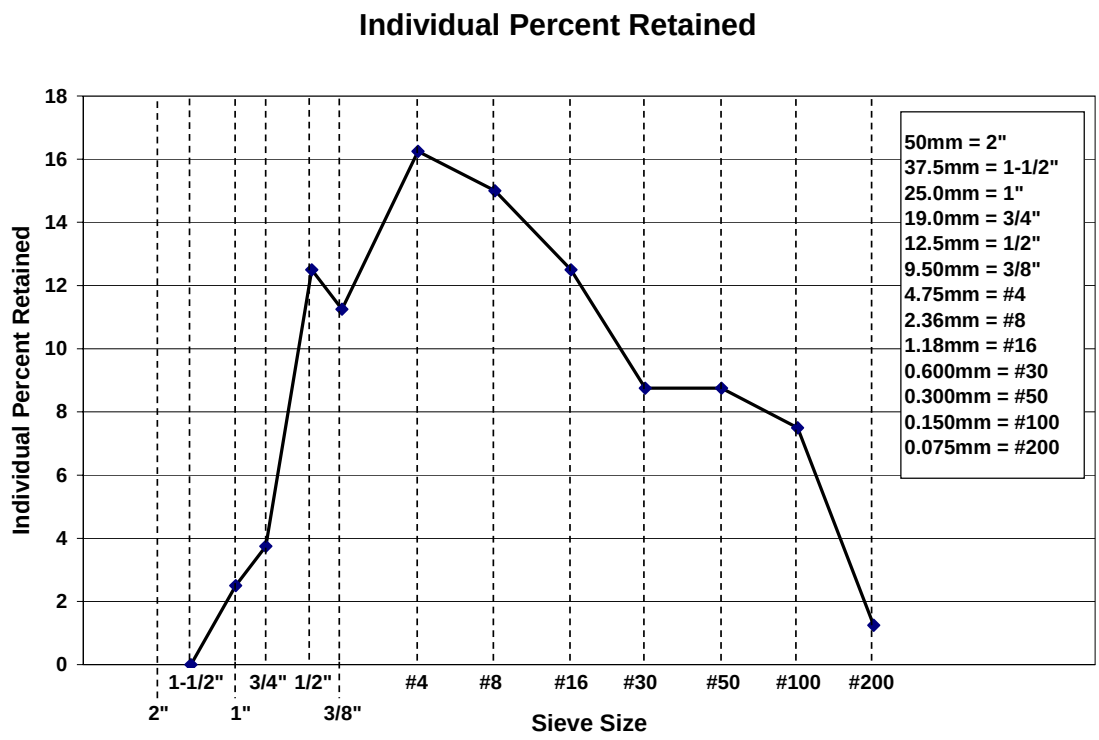

Fig. 5- ASTM C 33 and 1923 sand combined gradation.

Shilstone introduced two factors derived from the aggregate gradation to predict the workability of the concrete mix. The first is the “Coarseness Factor (CF)” which is the proportion of plus 3/8 in. coarse particles (Q) in relation to the total coarse particles (Q+I), expressed as a percent.

$$CF = \left[\frac{Q}{(Q+1)} \right] \times 100 \qquad (4)$$

A CF of 100 would represent a gap-graded aggregate where there was no #8 to 3/8 in. material. A CF of zero would be an aggregate that has no material retained on the 3/8 in. sieve. The second factor is termed the “Workability Factor

(W)”. It is simply the percentage of material passing the #8 sieve. An alternate designation is the “adjusted workability factor (W-adj)”. The W-adj factor reflects the influence of the amount of cementitious material on workability. The workability factor “W” assumes a six sack (564 lbs) mix. The “W-adj” factor is adjusted up or down based on the amount of difference from 6.0 sacks that the mix contains (Shilstone and Shilstone Jr. 1987). The adjustment is 2.5% per sack, or fraction thereof. One sack of cement (0.485 cu ft) represents about 2.5 % of the aggregate absolute volume.

Shilstone developed Fig. 6 to show the relationship between CF, W (or W-adj), and characteristics of the mix, such as harshness, sandiness, excessive shrinkage, pumpability, finishing characteristics, degree of gap-grading, proneness to segregation, and so forth.

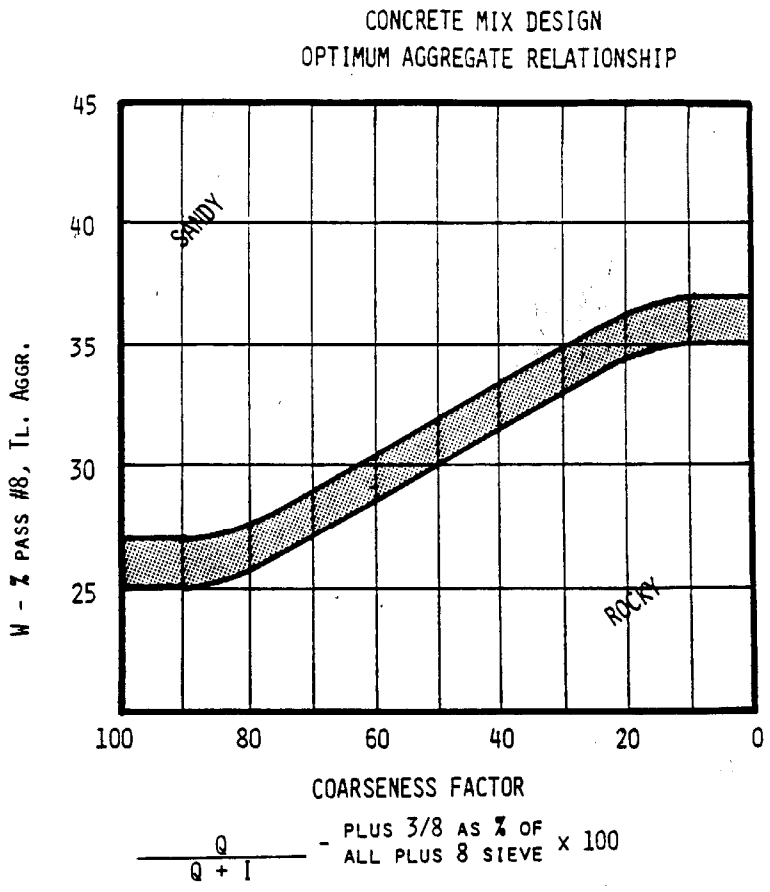

Fig. 6- Original Shilstone Coarseness Factor chart.

Shilstone included a trend bar to act as a reference by which to judge a mixture. A given gradation will plot as a single point on the chart. For compact shaped aggregates, gradations that plot considerably (5 to 7 points) above the trend bar would be overly sanded, with the attendant potential for excessive water demand and thus shrinkage and cracking. Mixtures that plot below the trend bar would be rocky and harsh. Well behaved mixes tend to plot somewhat (3 to 5 points) above the bar. Mixes that plot within the trend bar, if made with gravel or cubical shaped crushed material, and with well-graded natural sand, will require a minimum amount of water (has lowest *w/c* for a given slump) but will exhibit poor

finishability and cannot be pumped. The material should be placed with bottom-drop buckets and consolidated with large vibrators. In addition to prediction of concrete properties, the chart can also be used for maintaining mix characteristics in the face of changing aggregate gradations. Shilstone developed the computer program “seeMIX” which can easily calculate the CF and workability factors and plot the results. Thus, as updated gradation information is obtained, the position of the point can be determined and, if straying too far, the mix proportions can be adjusted to attempt to maintain the original position. As the amount of intermediate particles (“I”) increases (the stone is getting finer), the CF decreases. To maintain workability, the fines content must be increased, staying parallel to the trend bar. Also, as the sand gets coarser, more sand is required (Shilstone and Shilstone Jr. 1987).

A revised version of the CF chart is shown in Fig. 7 (Shilstone and Shilstone Jr. 1997).

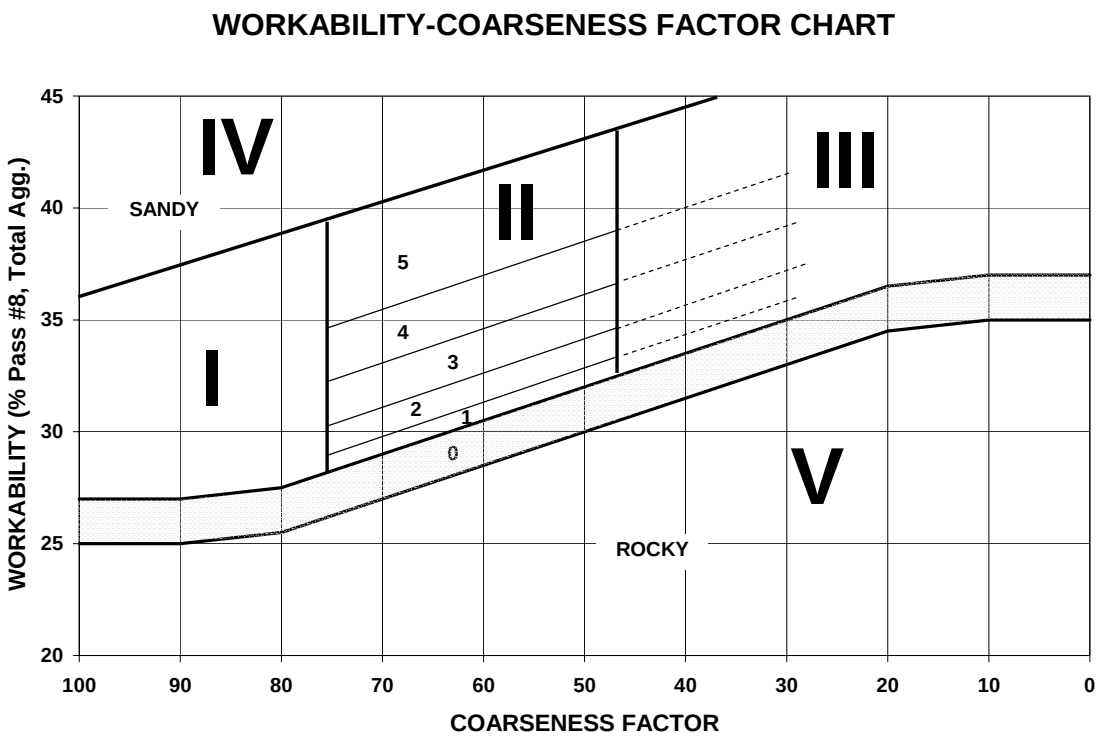

Fig. 7- Revised Shilstone Coarseness Factor chart.

This version of the CF chart has additional delineation zones for prediction of properties: Zone I *coarse, gap-graded, tends to segregate*, Zone II *well-graded 1-1/2 in.*, best spot for everyday mixes, depending on use, Zone III *¾ in. and finer (pea gravel mixes)*, Zone IV oversanded, *sticky,* and Zone V *rocky (may be suitable for mass concrete).* The trend bar is re-labeled “0” *optimum but excellent control required*. Zone II is divided into five areas: II-1 *excellent but caution*, II-2 *excellent paving and slipform*, II-3 *high quality slab*, II-4 *good general*, and II-5 *varies to material and construction needs*. These trends cross into Zone III (Shilstone and Shilstone Jr. 1999).

Shilstone has also explored the use of the 0.45 power plot, commonly used in asphalt work. He suggests plotting the combined gradation with reference to a maximum density line drawn from the origin to the intersection of the 100 percent passing line with either the first sieve to retain aggregate (or the nominal maximum size) or the maximum size. He considers the optimum grading for concrete to be a line following the reference line down to either the #8 sieve (Shilstone and Shilstone Jr.) or the #16 sieve (Shilstone 1993) where it will dip below the reference line, as shown in Fig. 8.

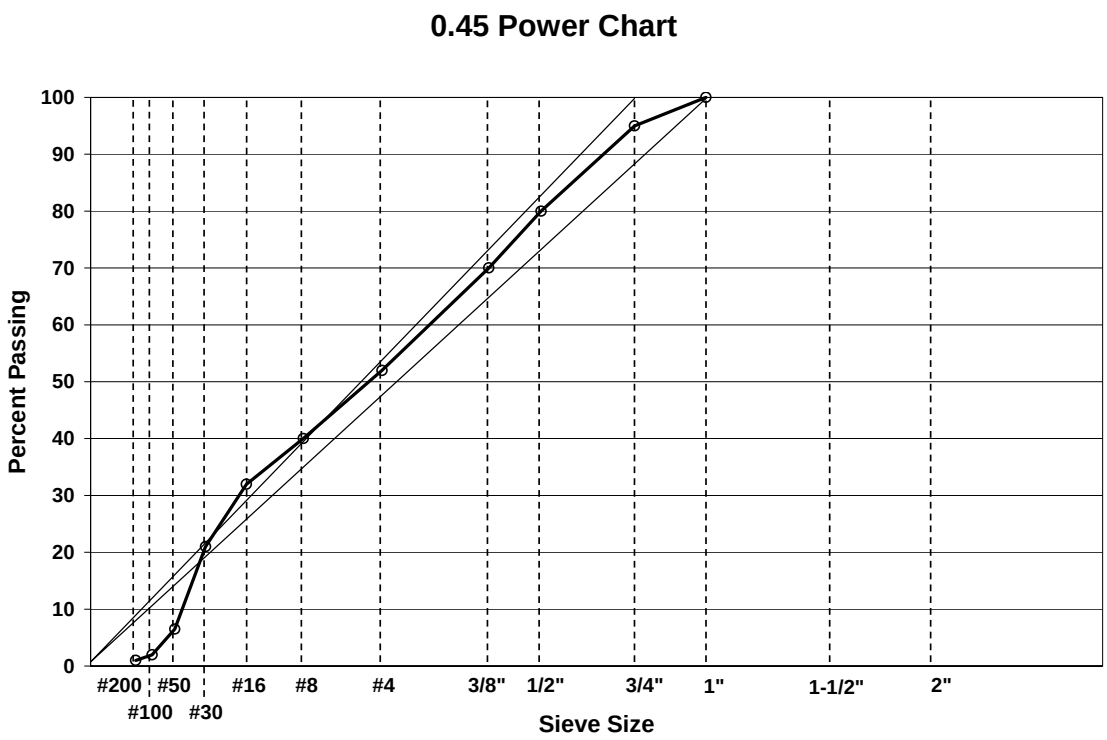

Fig. 8- Shilstone's 0.45 power chart.

Shilstone Case Histories. Shilstone has reported several case histories from his experience in using his method. A low slump mix placed in Canada segregated as it was dropped into the dump truck. This problem is predicted by its position on the CF chart (CF=83, W=31). The segregated coarse areas could not be consolidated as well as other areas, therefore they became high spots on the slab that had to be ground. The mix was adjusted to fill in the IPR plot valleys and the problems disappeared. A second mix, placed in Texas, segregated, again as predicted by the CF chart (CF=78, W=29), as it was placed from a conveyor belt. Edge slough occurred when there was insufficient mortar to provide cohesion (Shilstone and Shilstone Jr. 1997). A third case involving a gap graded two aggregate mix, designed in accordance with the ACI 211 method and produced in the PCA laboratory (CF=79, W=37), was adjusted by adding an intermediate aggregate (CF=58, W=36). The water content for the three aggregate mixture was 23 lbs. less at the same slump, and finishability significantly improved.

Research. Research at several universities has examined the effect of optimized gradation on a variety of properties of concrete, both plastic and hardened.

Studies at the University of Missouri-Rolla by Joel (Joel 1990) and Wilson and Richardson (Wilson and Richardson 2001) have examined the effect of variation of gradation on various plastic properties. Joel varied gradation of ASTM C 33 fine aggregate and #67 coarse aggregate between the allowable limits. Slump

decreased as sand FM increased. The CF chart did a reasonable job of sorting out which mixes would be high in paste and which ones would be rocky. Fig. 9 shows the position of the 12 mixes as plotted on the CF chart.

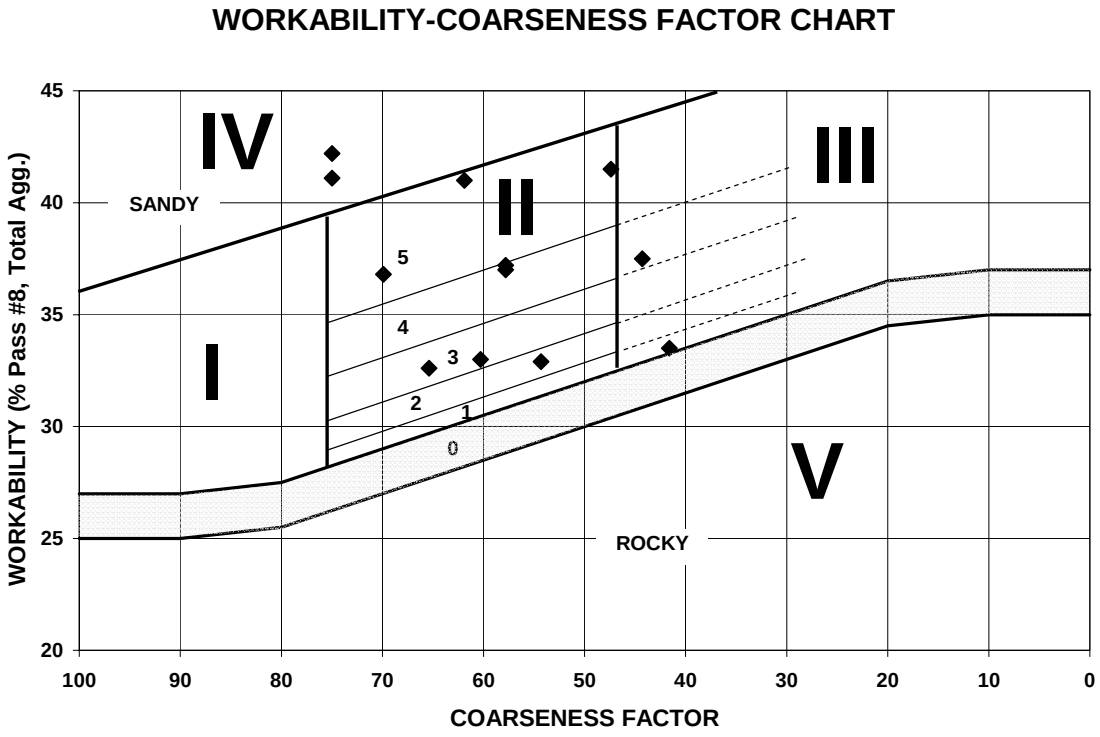

Fig. 9- Effect of varying gradation within ASTM C-33 limits.

As shown, varying within specification without the opportunity to change proportions can result in mixes that plot anywhere from over sanded to somewhat rocky.

Wilson and Richardson examined the effect of adding intermediate size aggregate to a MoDOT-type gap-graded paving mix, and the effect of particle shape of the intermediate size aggregate. The CF chart indicated that the gap-

graded mix was indeed gap-graded and correctly predicted the non-cohesive, segregation–proneness of the mix by its position in Zone II (Fig. 10).

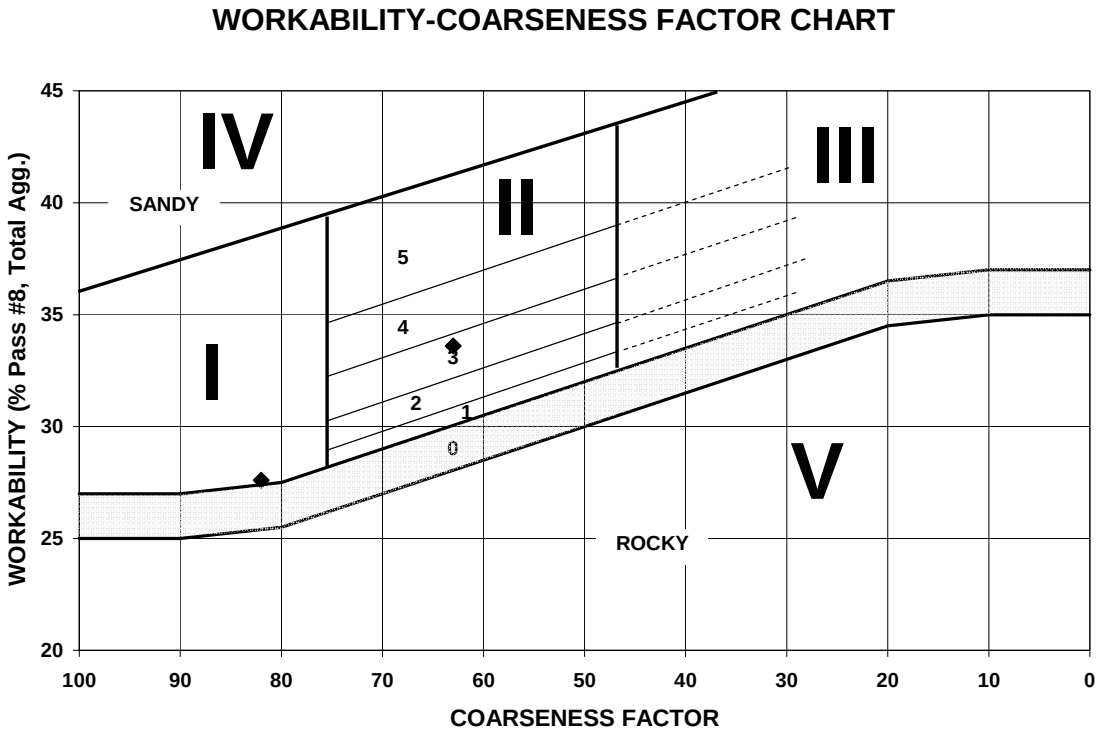

Fig. 10- Wilson and Richardson's 's traditional and optimized mixes.

The addition of intermediate size material moved the point to Zone II-3 and noticeably improved cohesiveness. The rounded pea gravel (intermediate size material) further improved the cohesiveness and required less water to achieve a given slump than the flat and elongated intermediate crushed stone chip, with a resultant greater compressive strength.

In the development of a high performance concrete (HPC) mix at Tennessee Technological University, Crouch et al. found it necessary to optimize the total gradation in order to meet all the goals of the HPC mix. They were able to lower the *w/cm* 8.3 percent with no detrimental effects on plastic properties (Crouch et al. 2000).

In another Tennessee Tech laboratory study, Whitten adjusted the gradation of a standard Tennessee DOT bridge deck mix to a haystack shape and obtained a modest increase in strength (5 percent) at a slightly lower cement content while preserving slump (Whitten 1998).

Practitioners Recommendations. Several prominent practitioners in the area of slabs-on-ground have published their recommendations. Both of the following authors have been the instructors for the ACI Concrete Slabs on Ground seminars given throughout the country.

Commenting on Shilstone's work, Holland disclosed that he had similar findings in regard to the development of combined aggregate gradations as an alternate to specifying by stockpile. For floor slab construction, he required the total percentage of fine and coarse aggregate retained on any one sieve to be between 8 and 18 percent. When that was not possible, he allowed the limits to be widened to 6 and 22 percent. On those occasions, the results were not as good as the 8 to 18 specification but far superior to the typical range which could be as wide as 1 to 30 percent (Holland 1990). Holland is generally credited with

having initiated the interest in the specification or recommendation of the “8-18” band. This is discussed more fully later in this report.

Harrison (Harrison 2004) discussed the desired properties of slabs-on-ground. Harrison emphasized the reduction of shrinkage by minimizing water content through use of optimized gradations. He recommended using the largest coarse aggregate maximum aggregate size possible, coarse sand, sand gradings as recommended by ACI 302.1R-96 (not ASTM C 33), and the use of IPR and CF charts. He pointed out that ACI 302 recommends 8 to 18 percent retained on each sieve for a 1 ½ in. maximum aggregate size gradation, but 8 to 22 percent for 3/4 and 1 in. maximum-size aggregates. The IPR chart should be used as a guide only, and it may be necessary to allow one or two non-adjacent sizes to fall outside the limits. The intent is to follow the contour of the limits while avoiding adjacent sizes below 8 percent. The optimum CF range for 1 ½ in. maximum-size aggregates typically is between 62 and 72, while for a 1 in. gradation, the range would be 60 to 65. For most slab mixtures, the W-adj is generally 32 to 40. The relationship between CF and W-adj should be within the following range:

$$\mathrm{Wadj} = \left[\frac{(75 - \mathrm{CF})}{6.67} + 34 \right] \pm 3 \qquad (5)$$

This describes a parallelogram as shown on the CF chart in Fig. 11:

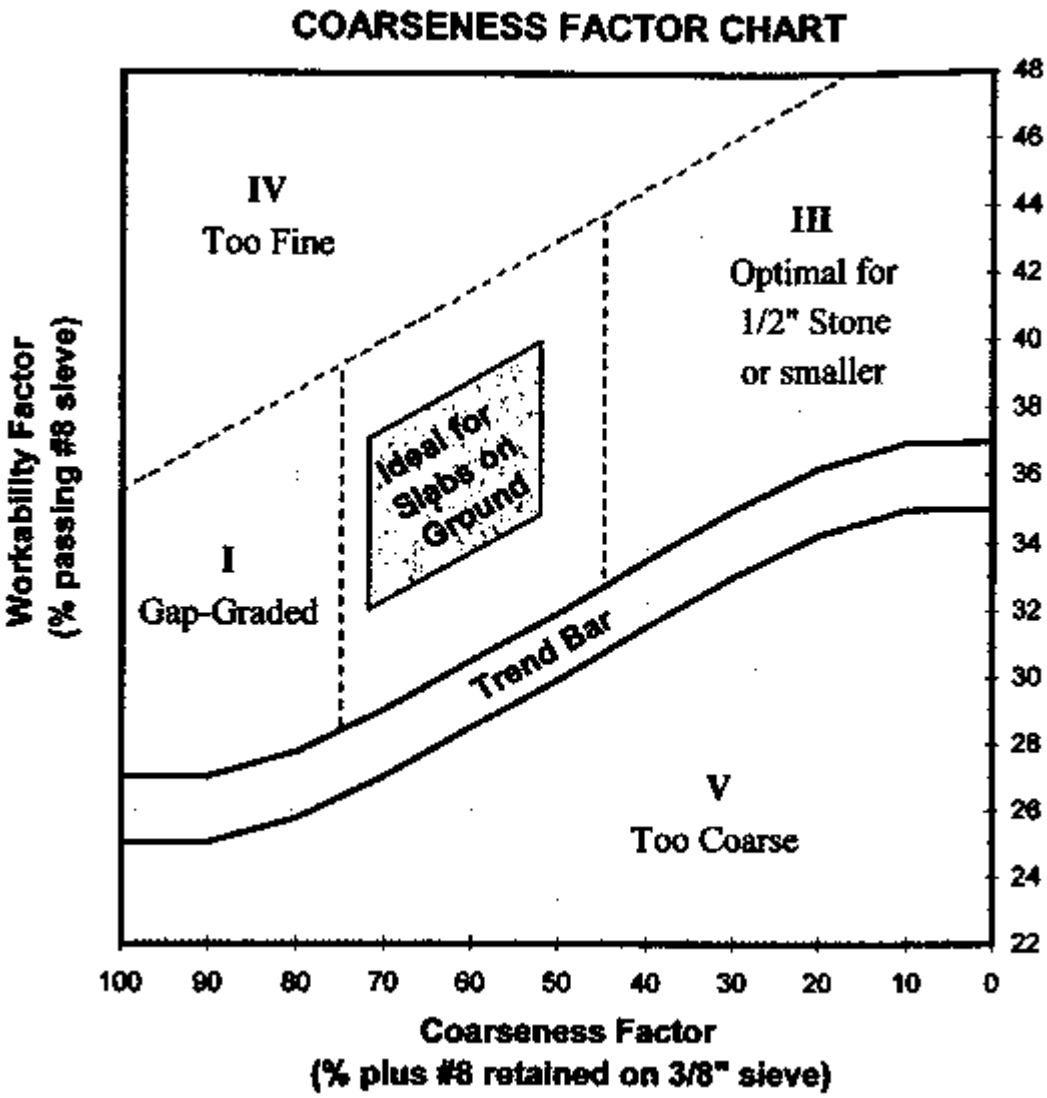

Fig. 11-Optimum location on CF chart for slabs-on-ground.

U.S. Air Force. In response to premature joint spalling and surface delamination or raveling, the USAF adopted the CF concept for their specification guide for military airfield construction paving projects (1996; Muszynski 1996; USAF 1997). The guide requires the use of the following plots: individual percent retained *vs* size with the “8-to18” band applied, modified CF chart, and a 0.45 power chart. The “8-18” band is an attempt to force the gradation into more of a haystack

shape and to get away from a double humped shape. The idea is to keep the individual retained percent between 8 and 18 percent for sieves #30 through the sieve one size below the nominal maximum size, and to keep all sizes below 18 percent retained. This is discussed later in more detail. Also, the plot should not have a significant valley between the 3/8 in. sieve and the lowest specified sieve size. A significant valley is one that has more than two sieve sizes between two peaks. An acceptable plot is shown in Fig. 12. For a straight line drawn between the IPR's of the 3/8 in. and #16 sieves, the valley at the #8 IPR is close to the same percentage deviation from the straight line as the peak height at the #4 sieve.

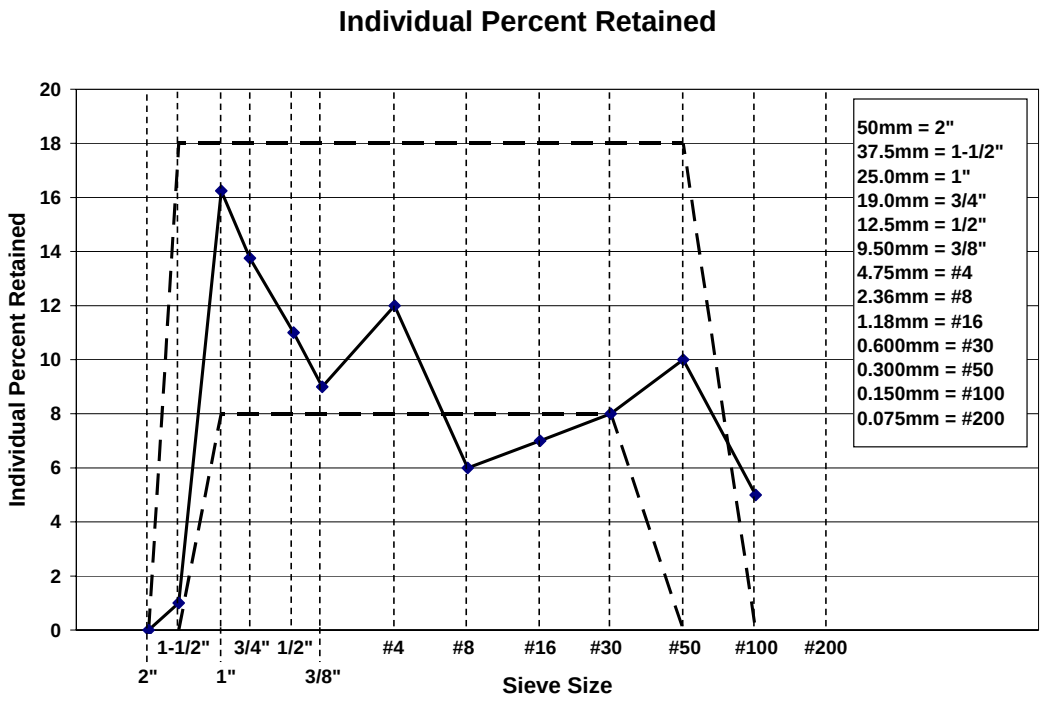

Fig. 12-Example of an acceptable mix.

Fig. 13 shows an unacceptable gradation. There is a significant valley (more than two adjacent sieve sizes) between two peaks.

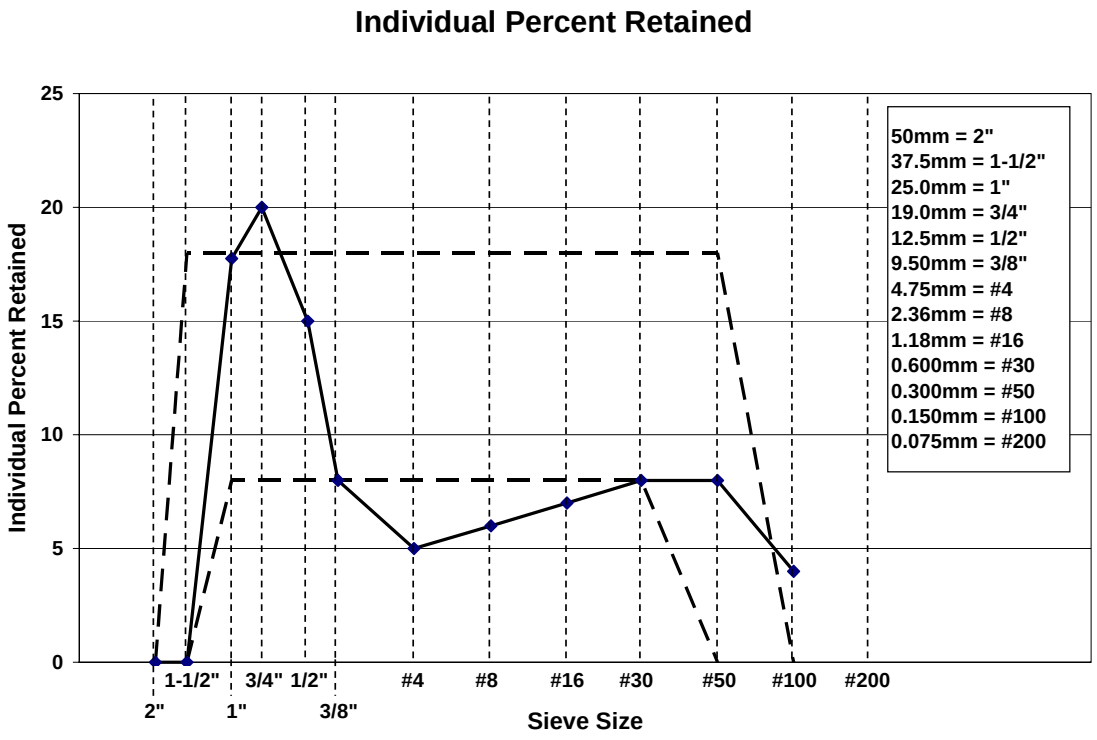

Fig. 13- Example of a problem mix-more than two adjacent sieves between two peaks.

Another unacceptable gradation is shown in Fig. 14. Here, there is an excess of large stone. The mix will have a ”plums in the pudding” effect and may tend to segregate upon vibration and finish poorly because of excessive voids that must be filled with mortar. Another criterion for concern is a peak that has exceeded the 18 percent guideline on two successive sizes.

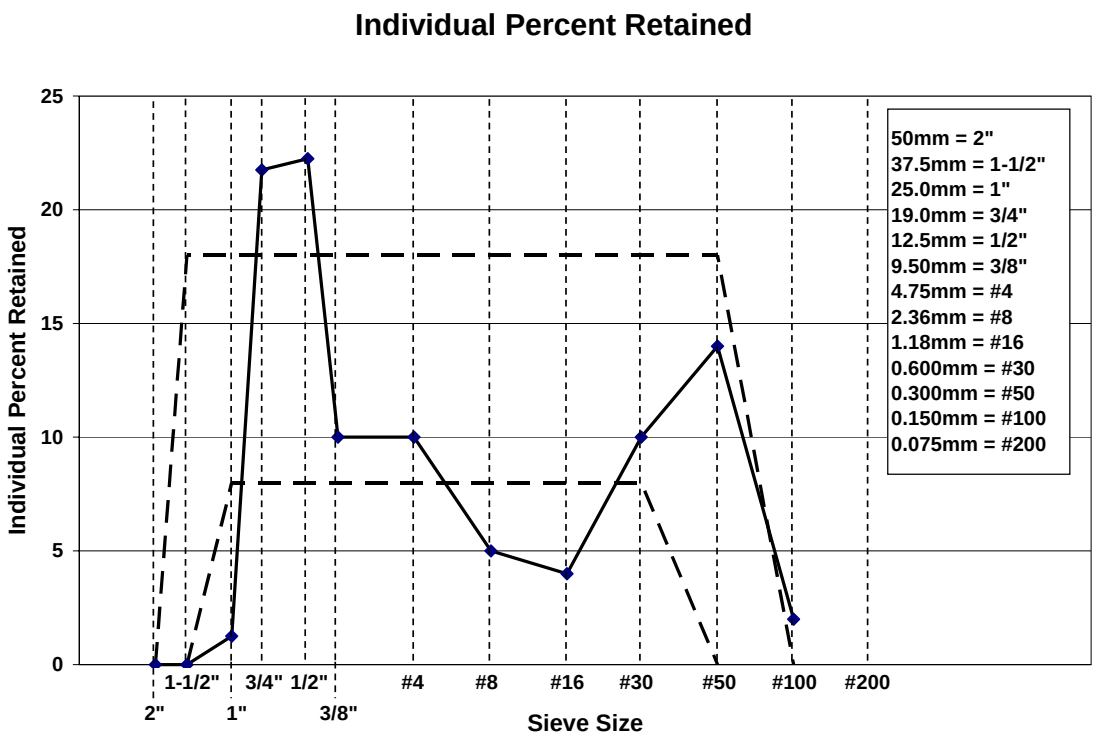

Fig. 14- Example of a problem mix-large percentage of large stone.

The Air Force Aggregate Proportioning Guide (Fig. 15), similar to Shilstone's CF chart, concentrates the Shilstone chart between CF's of 30 and 80. CF's beyond 75 tend to be coarse and gap-graded. The area bounded by the above CF's, the control line, and an upper diagonal line is called the "workability box".

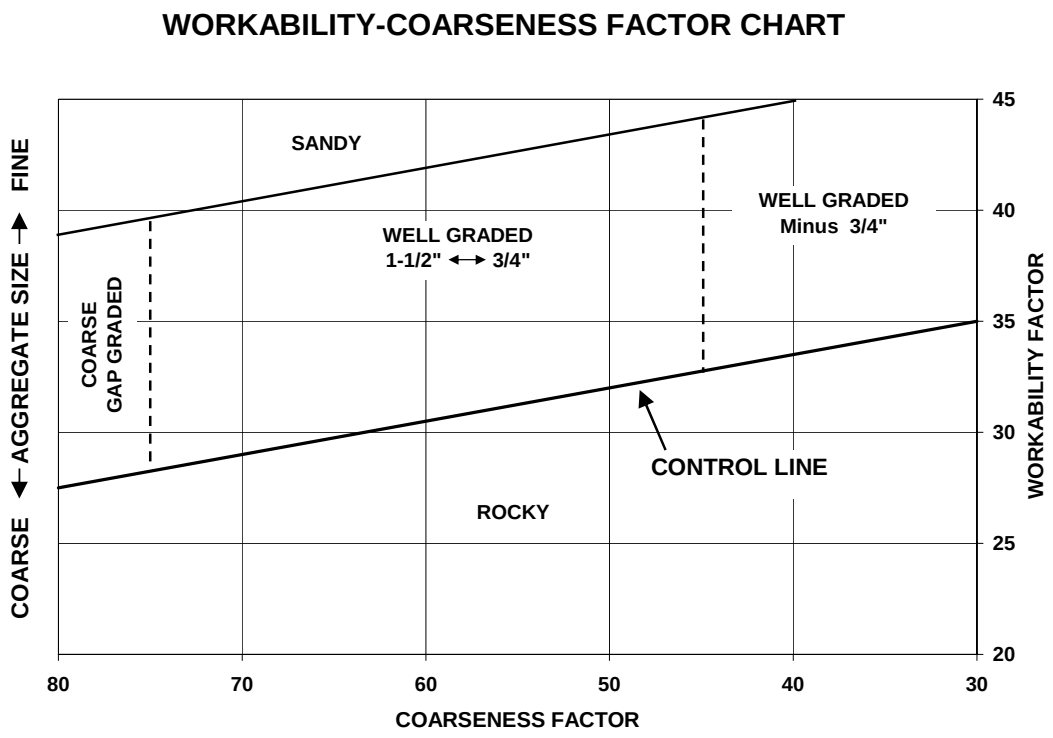

Fig. 15- Air Force Aggregate Proportioning Guide.

The Air Force Aggregate Proportioning Guide adopts Shilstone's areas of rocky, segregation–prone, and sandy, but it deletes the Zone numerical designations. Within Zone II, it replaces the five areas with three areas which are recommended places for slip form paving (A), form-and-place mechanical paving (B), and hand placement (C) as seen in Fig. 16.

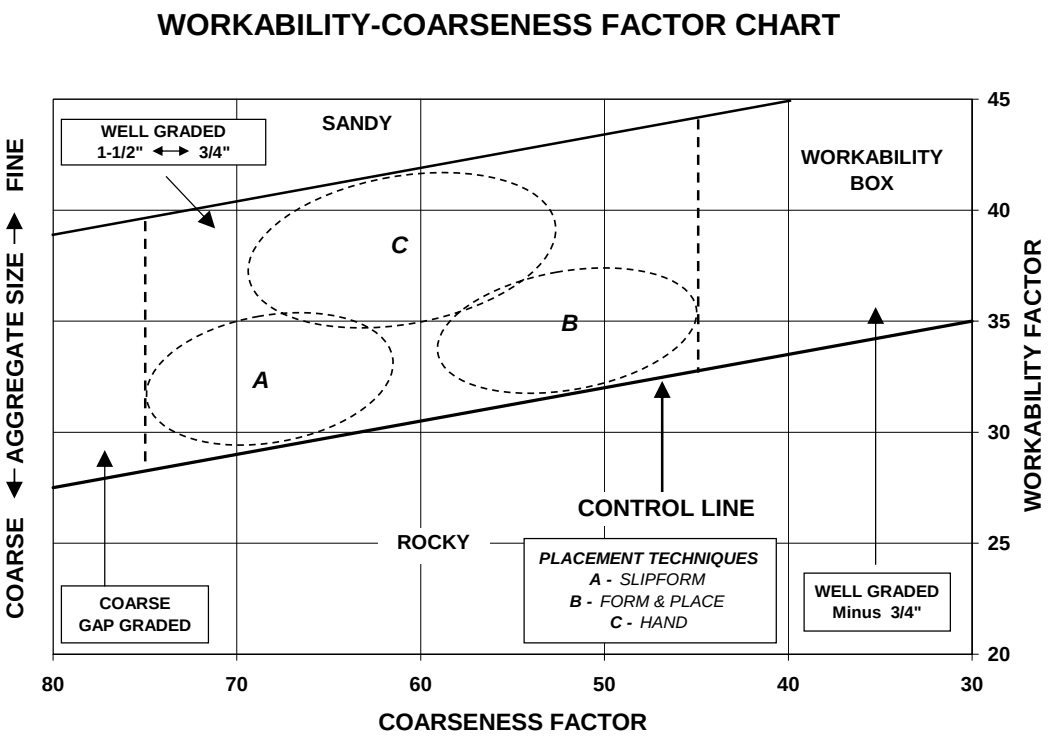

Fig. 16- Air Force Aggregate Proportioning Guide with construction-related areas.

Mixtures placed by hand or for general work should plot about 4 to 6 points above the control (trend) line. During design, the design mix should plot so that the CF is between 30 and 80, and not below the control line, and should allow for variance in the stockpile grading. This means the point should be located a significant distance in from the boundaries. When choosing the final design grading, consideration should be given to expected daily variations of about 3 points vertically and 5 points horizontally, as illustrated in Fig. 17. Note that Design A will have days that the gradation is out of the desired area due to gradation variability.

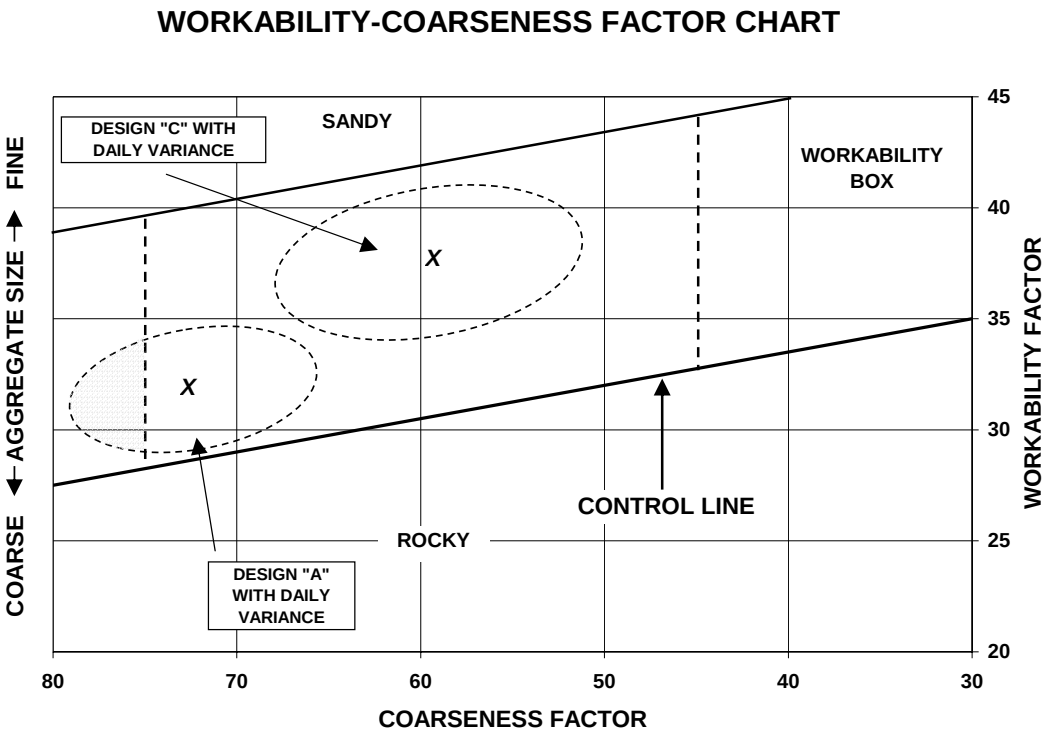

Fig. 17-Air Force Aggregate Gradation Guide showing effect of variation in gradation.

It is required that during production, the batch weights may be adjusted, and the point re-plotted. The updated gradation should plot either on the design point or on a line that runs parallel to the control line and through the design point. If the point plots above the design point, more cementitious material should be added to comply with the specified *w/cm*. It is stressed that the Guide is just providing recommendations, not rules. The data presented must be balanced with the results of previous paving projects. The Handbook cautions that the Guide is not exact because there are other workability factors not accounted for in the Guide, such as particle shape, air content, and presence of admixtures.

The tolerance for grading variation is 3 points vertically and 5 points horizontally. When variation exceeds these amounts, the mix can be re-proportioned. If the point falls on or below the control line, the material shall be rejected (USAF 1997).

The third type of plot is the 0.45 power plot. The handbook states that if any doubt remains about a combined gradation, it should be plotted on the 0.45 plot. There are three reference lines. The actual gradation should meander along the top size line; any meandering (crossing and returning) over this line indicates where the material is gap-graded. If the gradation line wanders across the lines on either side of the top size line, there is excessive gap-grading. An example is shown in Fig. 18.

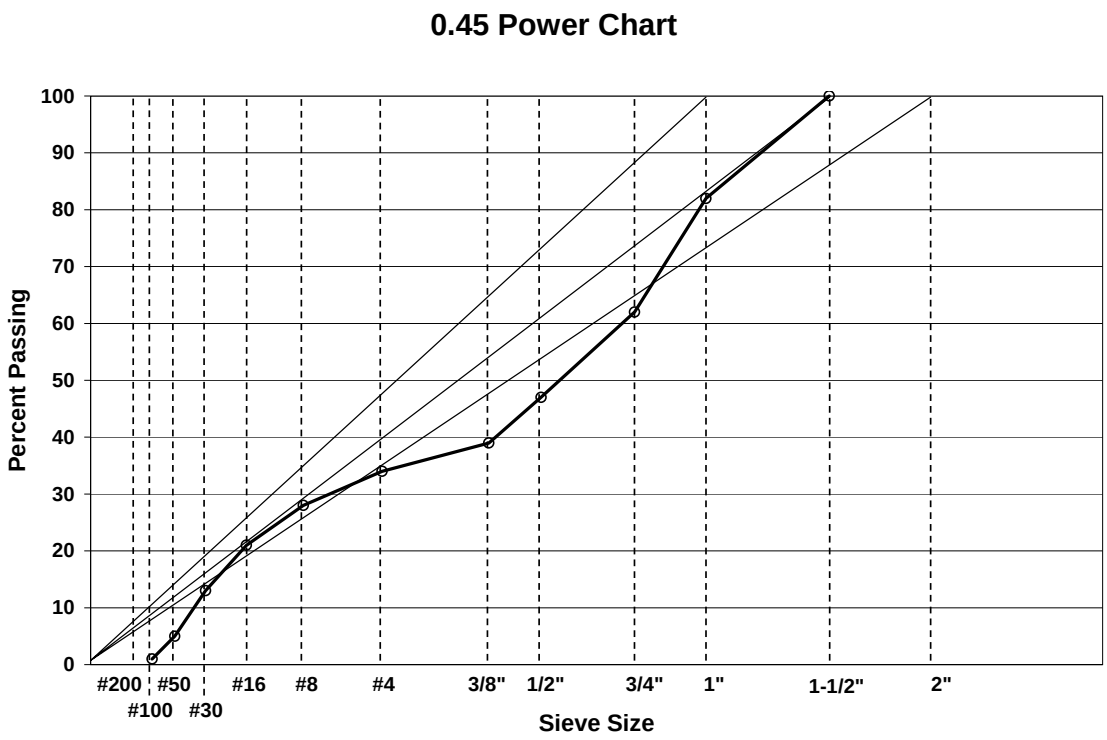

Fig. 18- Air Force 0.45 power chart.

Lafrenz. In a discussion of the research that led to the creation of the above USAF documents, Lafrenz drew the following conclusions : 1) projects that have gradations with CF's above 80 result in mixes that are gap-graded, difficult to place and finish, exhibit rock pockets, honeycombing, and fatty patches, and result in early cracking, 2) mixes with CF's between 75 and 80 experience variable results, and may have problems of segregation, uncontrolled voids, and excessive laitance, 3) gradations that plot below the control line may be rocky and subject to surface voids development., 4) combined gradations in the sandy area of the chart are difficult to finish and usually have excessive surface laitance, and 5) mixes that will be mechanically placed should not have CF's greater than 75 and workability factors greater than 29. He also pointed out that

even though a given sand may be excessively fine, it still may be usable by trying a finer coarse aggregate, such as a #67 instead of a #57, in order to move the material into the CF chart's workability box. The resulting mix may still be too sandy for slip form paving, but it could be utilized with form-and-place paving methods (Lafrenz 2001).

ACPA. Others have adopted Shilstone's concepts. For instance, the ACPA has included a discussion of the importance of the intermediate size aggregate in its Fast Track publication (ACPA 1989).

Mid-continent State DOT's. A search of state DOT specifications including Missouri and its surrounding states revealed a wide variety of optimization scenerios. Arkansas (Casteel 2004), Nebraska (Wilson 2004), Michigan, Mississippi, Texas, Kentucky, Colorado, and South Dakota make no mention in the way of aggregate optimization. Wisconsin allows some form of optimization of its coarse aggregate, but only on a case-by-case basis (Parry 2004). Tennessee has a similar stance (Egan 2004), as does Illinois for pumped bridge deck mixes (Dirks 2004). Indiana allows the contractor to propose the use of "alternate gradations" (InDOT 2004). Kansas, Iowa, Minnesota, and Missouri all have specifications that deal with the subject, as outlined below. Oklahoma is expecting to let a project in May, 2005 with an optimized gradation based on specifications done in Iowa (Hobson 2004).

Missouri DOT. The Missouri DOT allows the contractor the option to use an optimized gradation mixture. The total gradation has allowable ranges associated on each fraction. The contractor may reduce cement content by up to 0.5 sack per cu yd (MoDOT 2004).

Iowa DOT. The Iowa DOT has incorporated the Shilstone concepts into its paving projects specifications (IowaDOT 2002; IowaDOT 2003; IowaDOT 2004). The supplemental specifications that deal with this effort are aimed toward facilitating the use of a combined gradation with three or more aggregate fractions. The contractor is responsible for the mix design and the process control monitoring. Advice is given in the specifications as to typical ranges for Coarseness and Workability Factors for a nominal maximum aggregate size of 1 to 1 ½ in., as follows: 1) for a CF of 52, Workability Factors range from 34 to 38, and 2) for a CF of 68, W ‘s range from 32 to 36. The combined aggregate is to be sampled at a minimum frequency of 1500 cu yds. Individual sieve gradation results are to be plotted on control charts and have working ranges specified for each sieve size. CF and W values are plotted on control charts. They are also plotted on the Iowa version of Shilstone’s CF chart. Aggregate proportions may be adjusted from the job mix proportions by ± 2 percent for both the coarse and fine aggregates without a new job mix being submitted. Standard grading limits are waived with certain exceptions.

Versions of the Shilstone CF chart, the combined individual percent retained chart, and the 0.45 power plot have all been adopted. The CF chart is considered

the primary method to be used to develop the combined gradation. The other two charts are to be used to verify the CF chart results and to help identify areas deviating from a well-graded aggregate. These three charts are depicted in Fig. 19 through 23. Fig. 19, the CF chart, is similar to the latest version of Shilstone's CF chart. It features six Boxes (areas) with Boxes A, B, E, and F subdivided into five zones (areas).

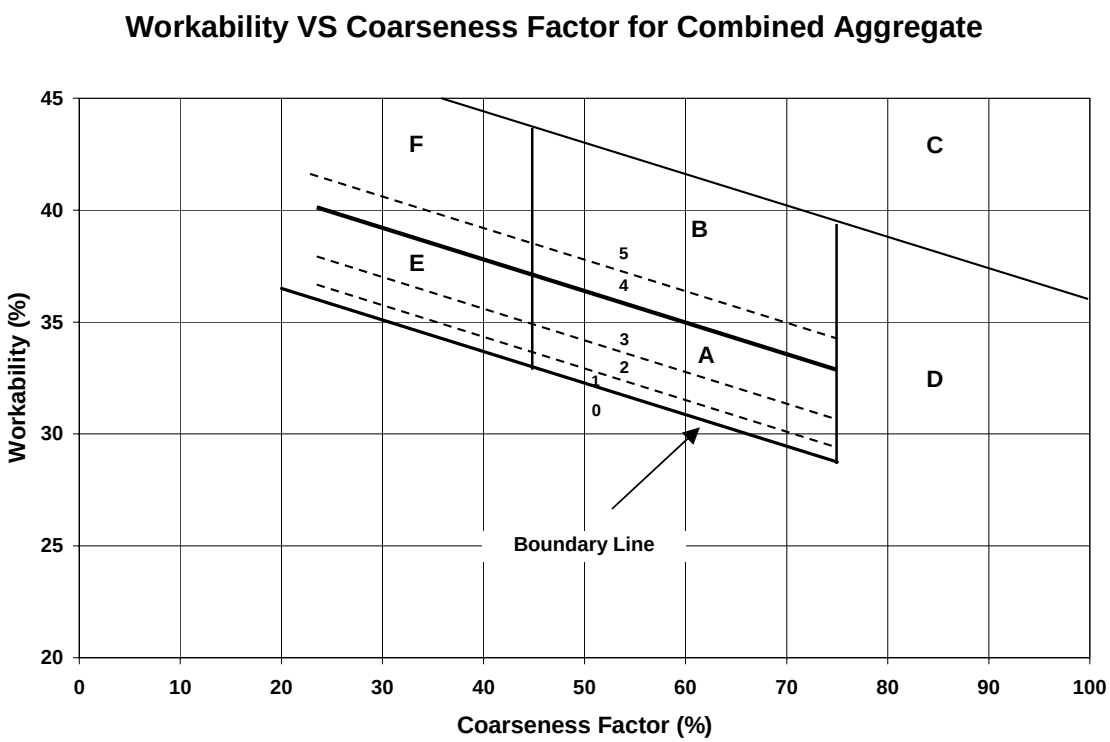

Fig. 19- Iowa DOT Coarseness Factor Chart.

Advice is given in the specifications as to typical positions on the CF chart for slipform paving, as follows: 1) for crushed stone, Zones 3 and 4, and 2) for rounded gravels, Zones 2 and 3.

Adjustments to the contract unit price of concrete are done through Pay Factors, as listed in Table 3.

Table 3. Iowa DOT Pay Factors for Concrete Pavement

Gradation Zone	Pay Factor
Box A, Zone 1,2,&3	1.03
Box B, Zone 4	1.02
Box B, Zone 5	1.00
Box C	0.98

If any two or more consecutive individual gradation test results fall outside Box A or B, the individual test results, representing 1500 cu yds, will have a 0.90 Pay Factor assessed.

Fig. 20 and 21 are examples of 0.45 power plots for a well-graded and a gap-graded mix, respectively, as shown in the Iowa DOT specifications.

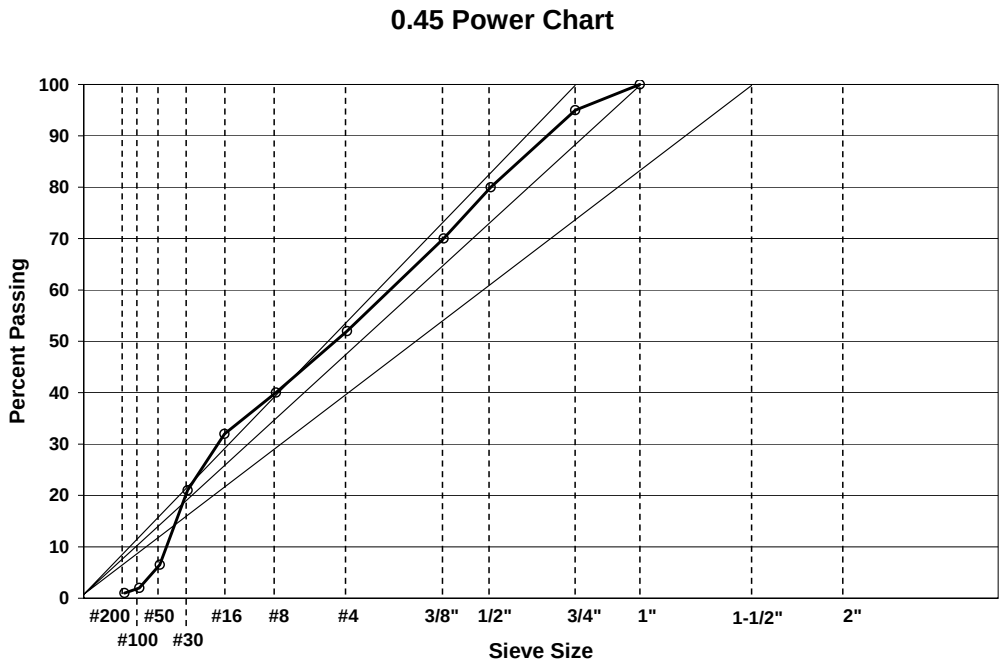

Fig. 20- Example of a well graded mixture, Iowa DOT specifications 0.45 power chart.

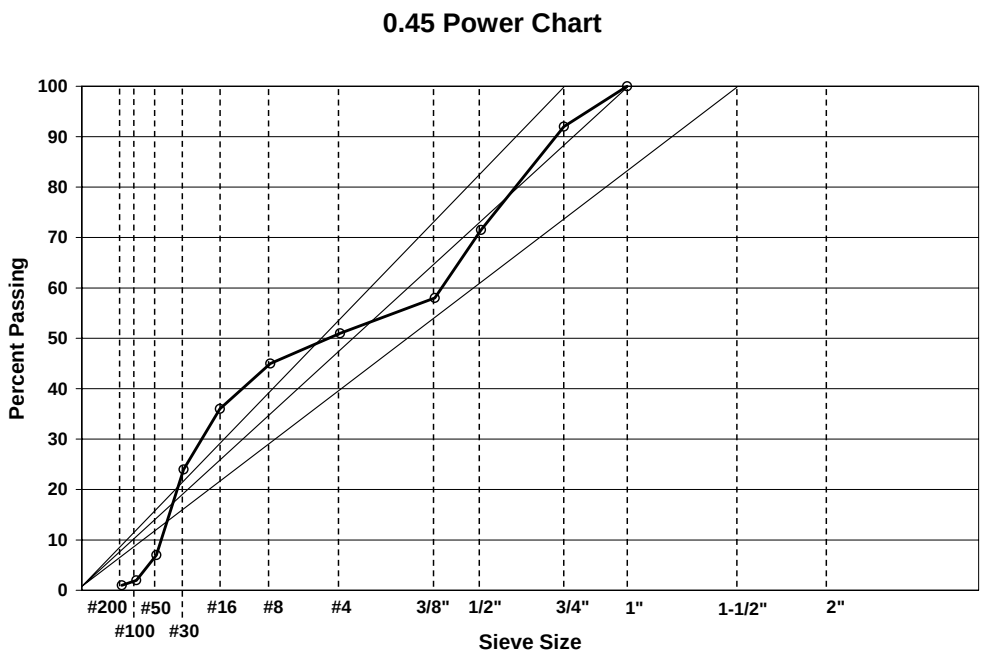

Fig. 21- Example of a gap graded mixture, Iowa DOT specifications, 0.45 power chart.

Fig. 22 and 23 are Individual Percent Retained charts for a well-graded and a gap-graded mix, respectively. Note that the 8-18 band is present, but the specification only mentions that a gap-graded aggregate combination will have peaks above 18 percent or dips below 8 percent and that Shilstone recommends that the sum of the percent retained on two consecutive sieves should be a minimum of 13 percent in order to be an optimum gradation.

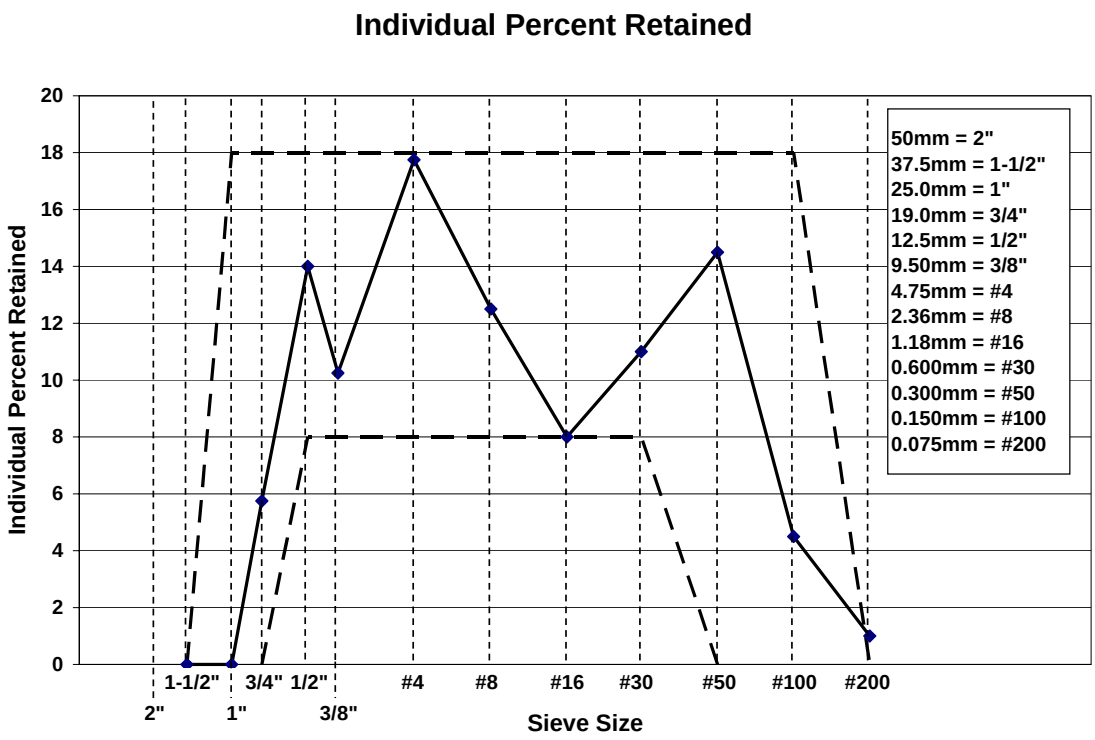

Fig. 22-Example of a well graded mixture, Iowa DOT specifications, Individual Percent Retained.

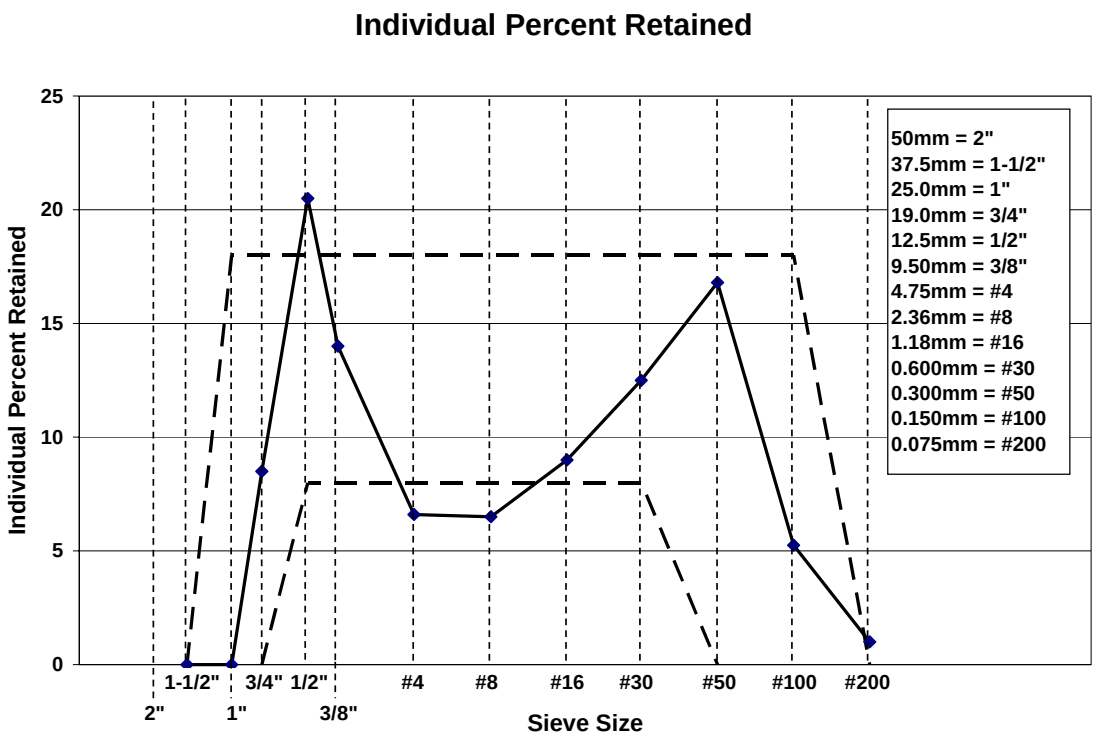

Fig. 23-Example of a gap graded mixture, Iowa DOT specifications, Individual Percent Retained.

On one barrier wall construction project, there were problems with the standard mix, including excessive cracking and difficulty in entraining air. The mix was redesigned with 440 lbs. of 3/8 in. chip intermediate aggregate replacing about 100 lbs. of coarse aggregate and 420 lbs. of sand. Consequently, the new mix did not need as much cement paste for workability, thus the cement content was reduced by about 100 lbs. Cracking was reduced, strength increased, air entrainment increased, and time of placement decreased. The traditional and optimized mixes are shown in Fig. 24 through 26.

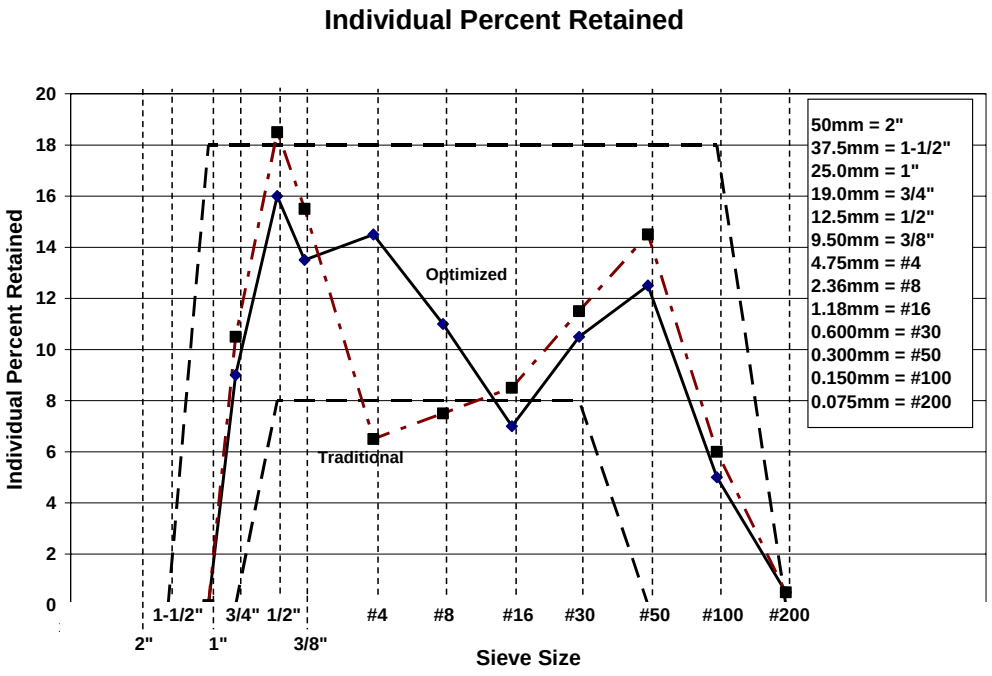

Fig. 24- Iowa DOT barrier wall mixtures-Individual Retained chart.

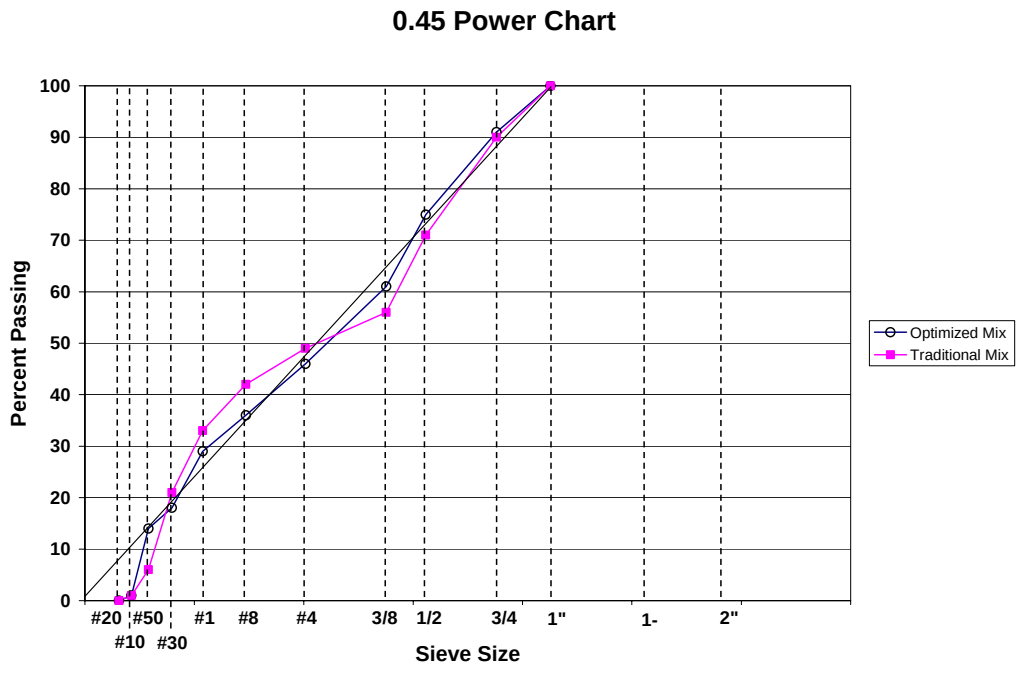

Fig. 25- Iowa DOT barrier wall mixtures-0.45 power chart.

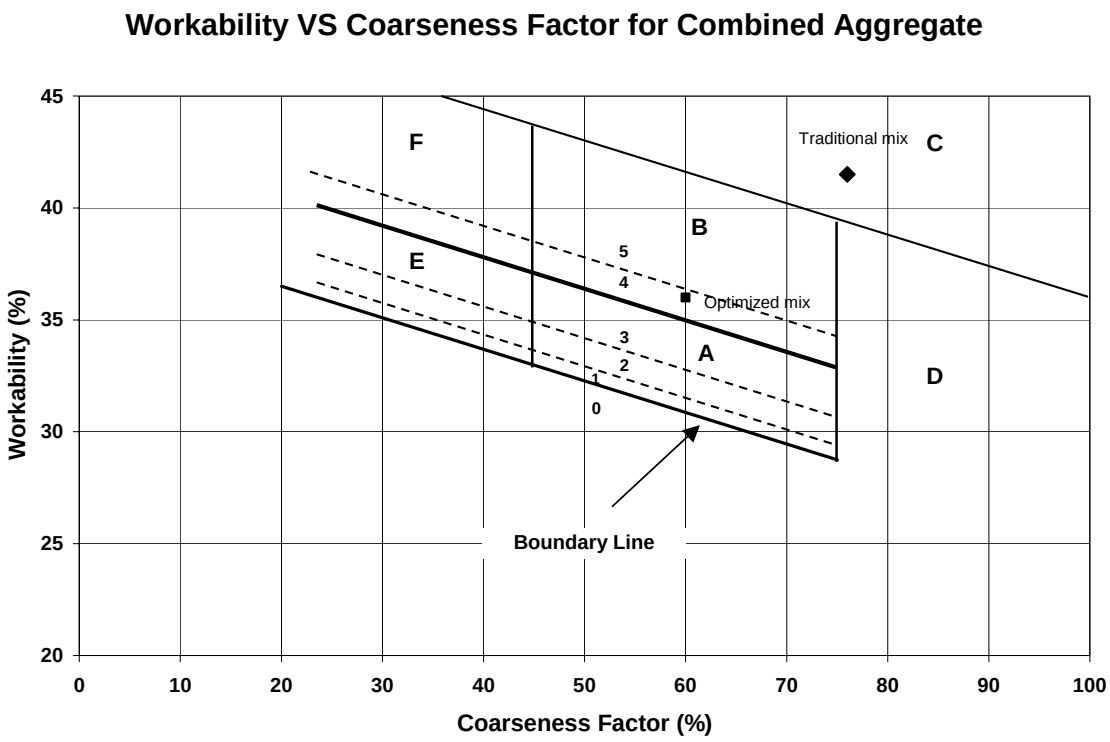

Fig. 26-Iowa DOT barrier wall mixtures-Coarseness Factor chart.

On a paving project, two optimized mixtures (Mix 1 and Mix 2) were compared to a standard paving mix. In both optimized mixtures, 35 percent of the coarse aggregate was replaced with a 3/8 in. chip. Additionally, Mix 2 had a 10 percent cement reduction. Mix 1 seemed to be a little less workable, possibly because of the angular particle shape of the intermediate chip. However, even at the same *w/cm*, Mix 1 exhibited a 34 and 30 percent increase in flexural and compressive strength, respectively, over the standard mix, while Mix 2 with a somewhat higher *w/cm*, had roughly equivalent strengths to the standard mix (Hanson 1996).

Wisconsin DOT. The Wisconsin DOT conducted a study involving a paving project. Both lab and fields mixes were examined. Gap-graded mixes were compared to optimized mixes. The mixes contained similar materials, with three aggregates used in both: AASHTO #67, #4, and sand. The proportions of the two stones were reversed with each other to obtain the optimized mix. The sand was reprocessed through a classifier to achieve the target gradation. The aggregate reprocessing resulted in more waste and some additional handling cost. The gap-graded and optimized gradations are shown in Fig. 27 and 28, respectively. The combined gradations are plotted on the CF chart in Fig. 29.

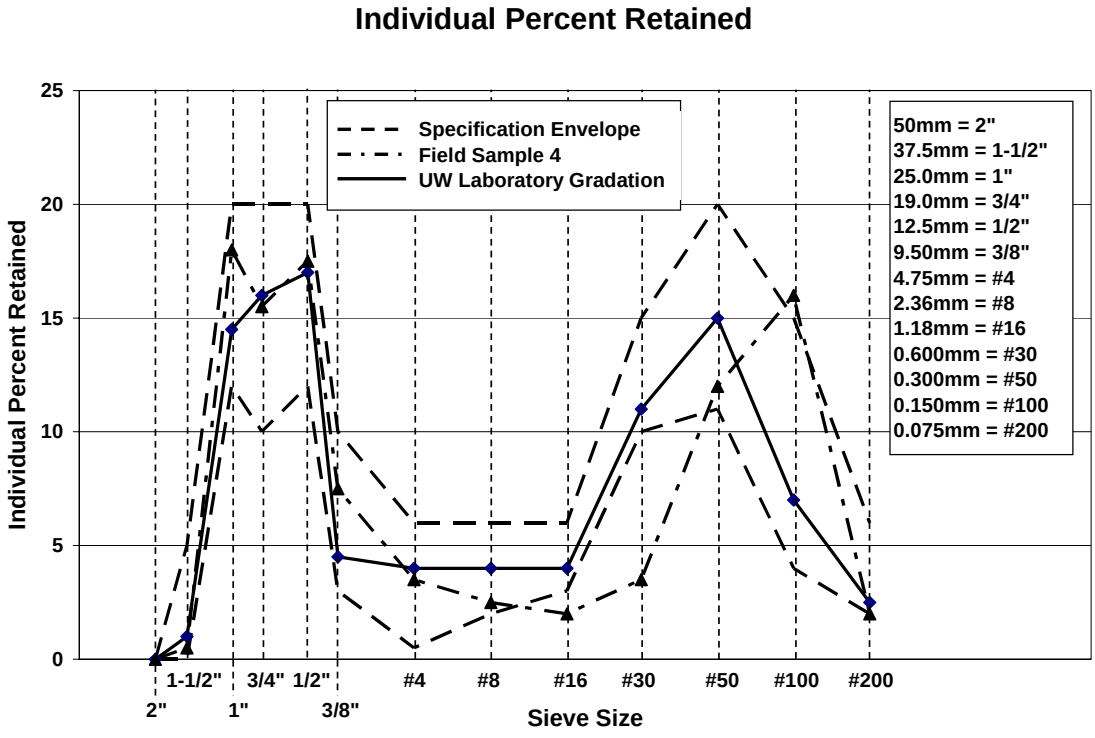

Fig. 27- Wisconsin DOT gap graded pavement mixtures.

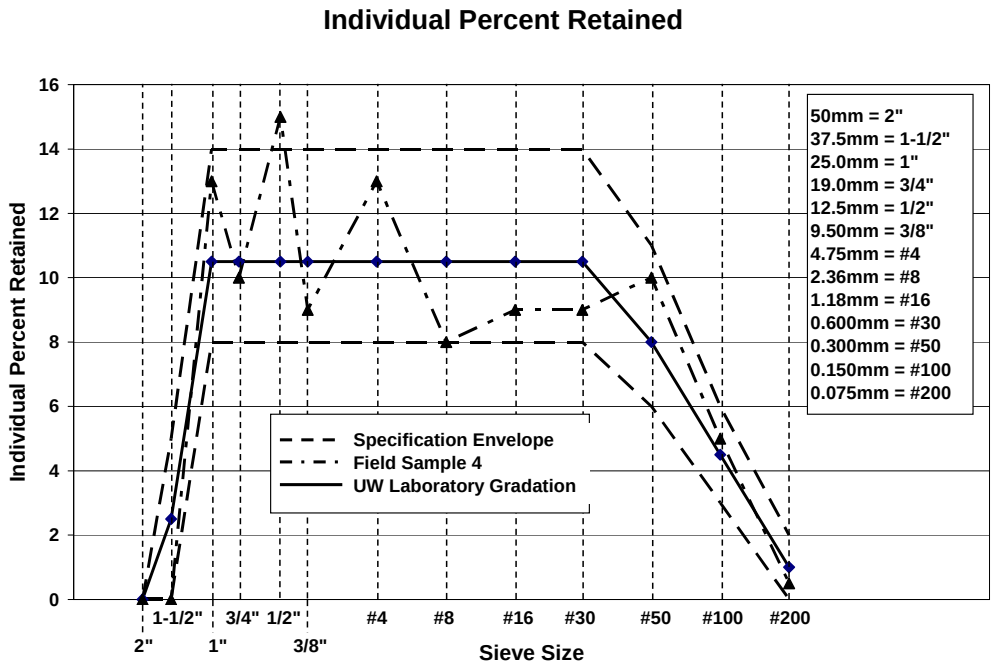

Fig. 28- Wisconsin DOT optimized pavement mixtures.

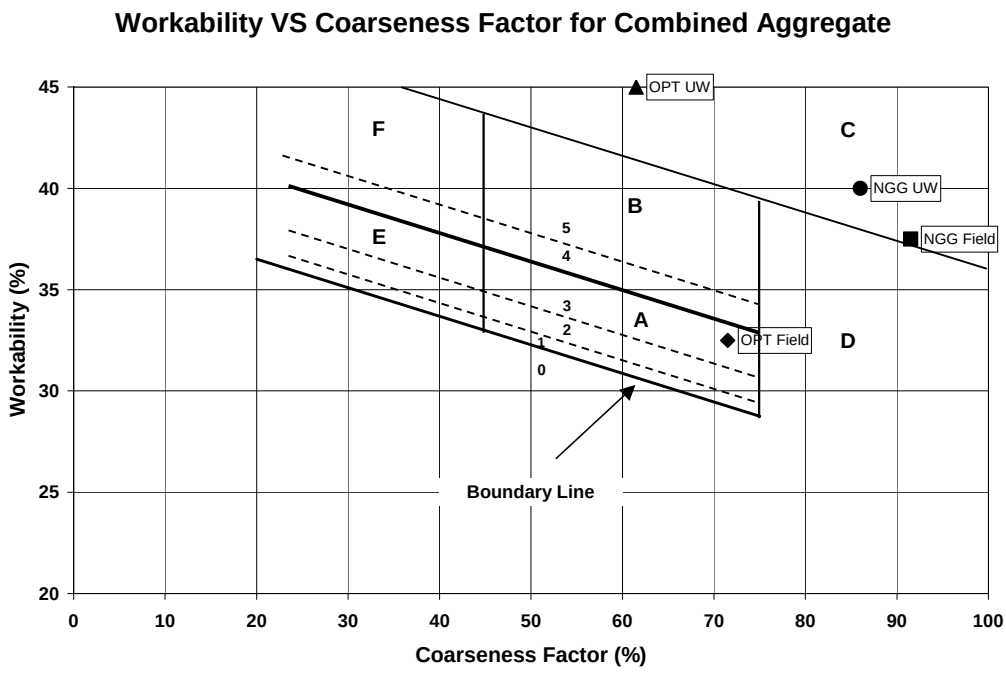

Fig. 29- Wisconsin DOT gap graded and optimized mixtures on Coarseness Factor Chart.

Both the #67 and #4 coarse aggregates were limestone The results showed that in comparing the optimized mixes to the field mixes, the optimized mixes contained up to 15 percent less water to achieve similar slumps, 20 to 30 percent less air entraining agent was required to entrain the same amount of air, and there was less segregation after extended vibration (1-3 min.). Strength increased 10-20 percent in the laboratory and 14 percent in the field. However, the air void spacing factor was greater in the optimized mixture.

A second part of the report was about a project involving a bridge deck. A near gap-graded mix was slightly optimized by increasing the percent retained on the #8 and #16 sieves about 6 percent each. Only modest improvements in water reduction were achieved (Cramer et al. 1995).

Another Wisconsin study was conducted to access the impact of gradation optimization on durability. Six gradations were studied using a variety of aggregate sources which included crushed stones and gravels, and sedimentary and igneous materials. Of the six gradations, one was near gap-graded, one was labeled “optimized”, and four were called “control”; these four were similar in gradation to each other but were from different geologic sources. The near gap-graded, the optimized, and one of the control gradations are shown in Fig. 30. The optimized and the control gradations had their peaks reduced and the intermediate valley filled in compared to the near gap-graded gradation.

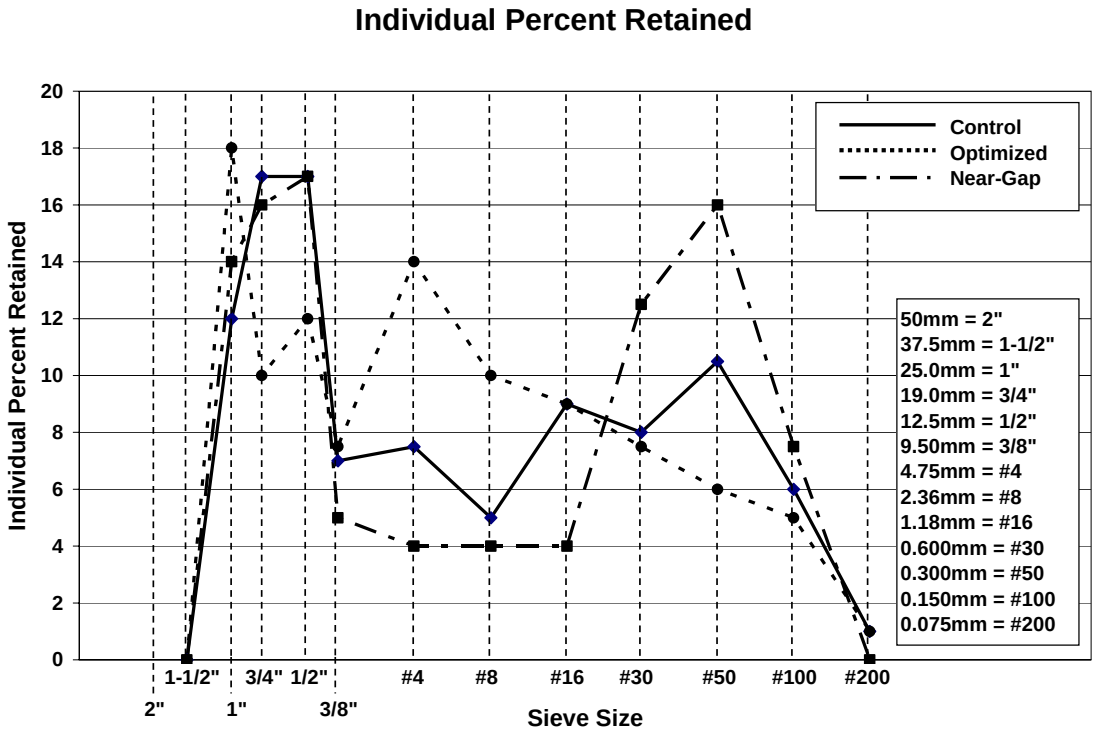

Fig. 30- Wisconsin DOT durability study-optimized and gap graded mixtures.

The near-gap and “optimized “gradations were fabricated. The four “control” gradations were similar, and were 60-40 blends of fine and coarse aggregates as they occur in various locations. As seen in Fig. 31, the near gap-graded mix plotted in Shilstone’s sandy area (IV). The four control gradations plotted in Shilstone’s areas I and II-4, while the optimized gradation plotted in the trend bar.

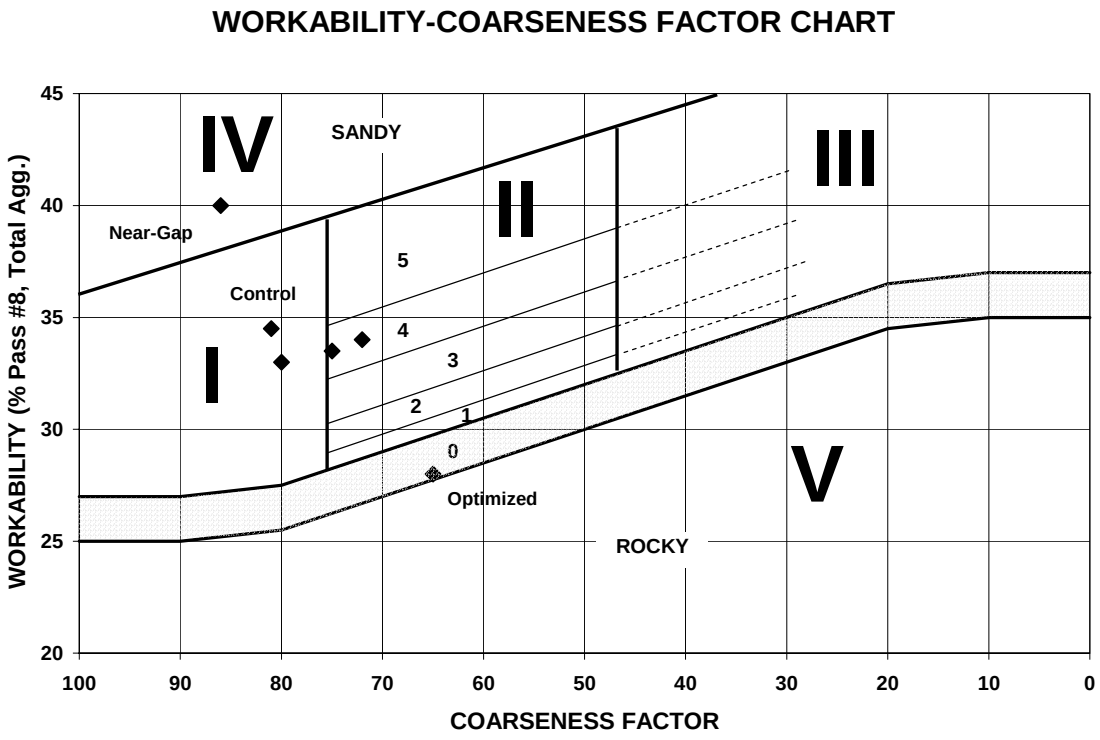

Fig. 31- Wisconsin DOT durability study-Shilstone Coarseness Factor chart.

On the Air Force plot, the near-gap mix was off the allowable chart, the control gradations were much improved, with one right in the area A for slip form paving, while the optimized mix was below the control line (Fig. 32).

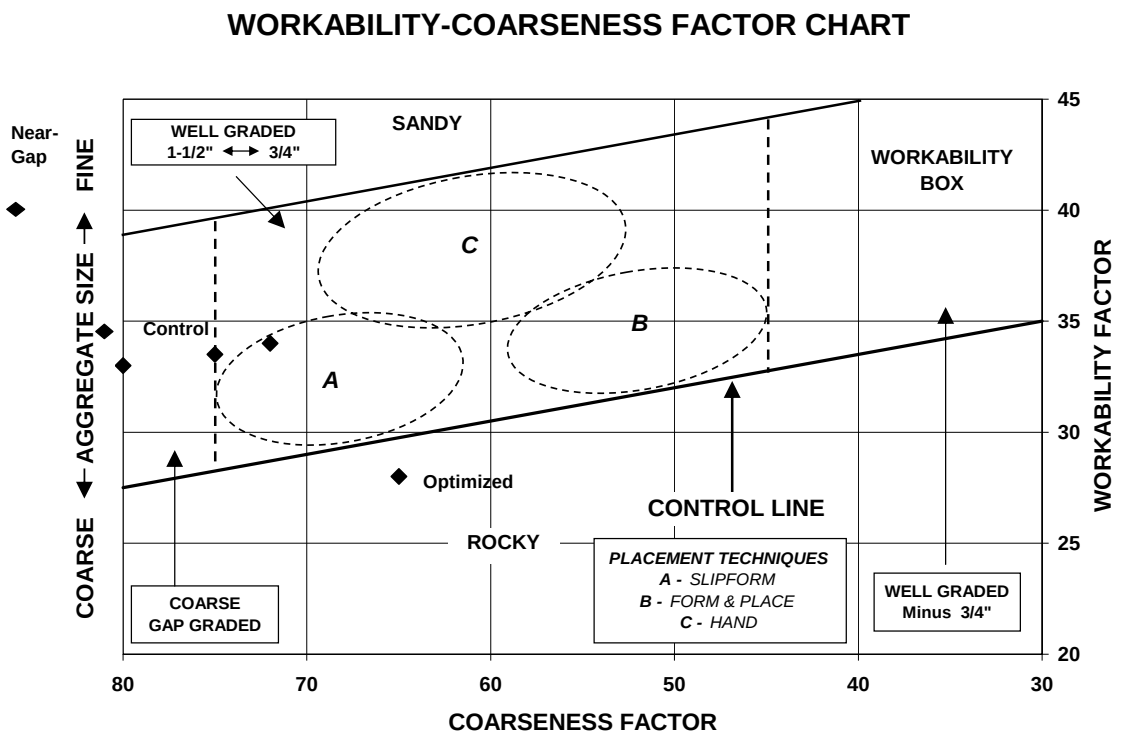

Fig. 32- Wisconsin DOT durability study-USAF Aggregate Gradation Guide.

On the Iowa DOT chart, some of the control gradations would be in bonus, some would be in deduct. The near gap-gradation would be in deduct, and the optimized gradation would be too low on the chart and would, therefore, be in deduct (Fig. 33).

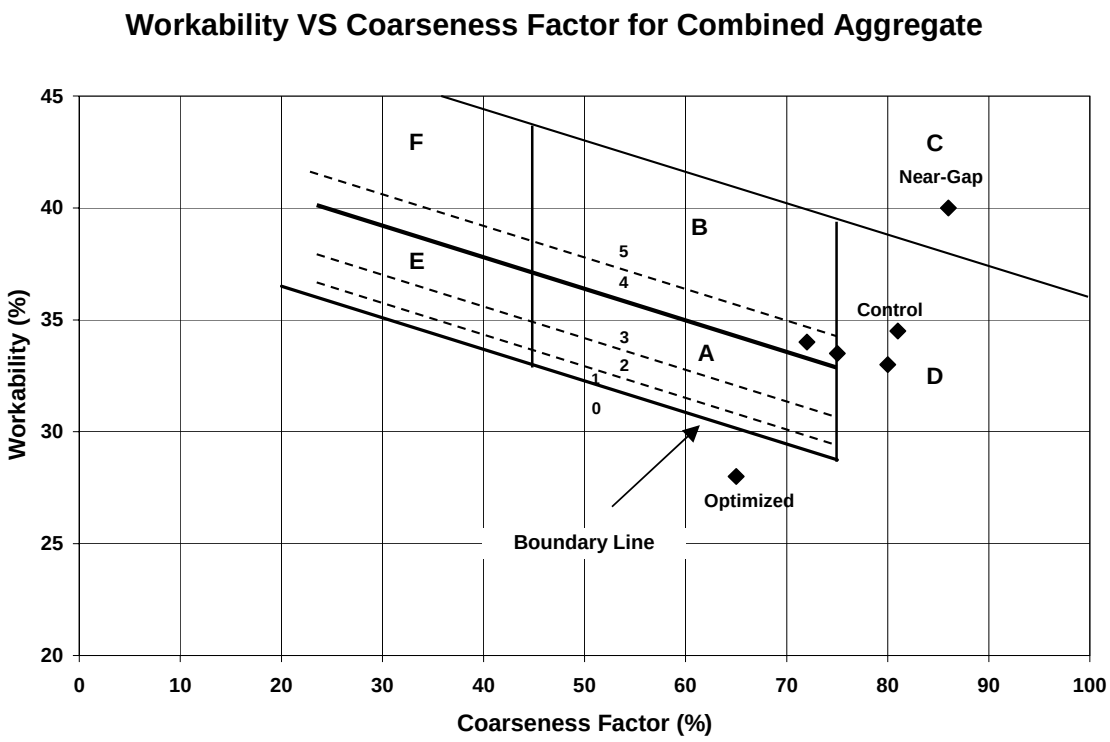

Fig. 33- Wisconsin DOT durability study-Iowa DOT Coarseness Factor chart.

The concrete mixtures were mixed to achieve a given slump. The near-gap mixtures required more water, thus their *w/cm's* were somewhat higher. The results indicated that the near-gap mix had compressive strengths 2 to 14 percent lower than the control/optimized mixes, the mean shrinkage of the near-gap mixes was 8 percent greater than the control, permeability of the near-gap mixtures was 25 percent greater than the control/optimized mixes, and the near-gap mixtures showed lower freeze-thaw durabilities. The control and optimized mixture results were comparable. Overall, the differences between all three mixtures were not great. The conclusions are that moving the CF plotted point out of the sandy region down into a better area as defined by both Shilstone and

the Air Force resulted in improvements to strength and durability. And, there was no real advantage to placing the point in the trend bar. So, as predicted, a mix somewhat above the trend bar, which should be more workable in certain applications, was just as good in terms of durability and strength as a mix that plots in the trend bar (Cramer and Carpenter 1999).

Kansas DOT. The Kansas DOT allows the contractor to propose an optimized mix, and mentions the Shilstone method as a possible way to design the mix. Non-standard aggregate proportions are allowable under this option. For design purposes, one of the possible gradations (MA-3, Optimized for PCCP concrete) has individual percent retained limits of 8-24 for sieves ½ in. through #16 and 8-15 for sieves #30 and #50. Gradation control is by sieve analysis control charts (KansasDOT 2004; KansasDOT 2004; KansasDOT 2004).

Other DOT's. Beyond the mid-continent area, several other state DOT's have had some experience with optimization of gradation.

In Colorado, optimization of an unworkable bridge deck mix via Shilstone's method involved the replacement of 500 lbs of coarse aggregate and 300 lbs of sand with 800 lbs of a material similar to pea gravel. Reports indicate a significant improvement in finishability, a 5 percent reduction in water, and a 10 percent increase in strength. There was an actual overall cost savings because of lower material and labor costs (Anonymous 1990).

Washington state DOT specifications have a section dealing with combined gradation for paving concrete in which the gradation is to be plotted on a 0.45 power chart. The gradation should fall between two lines. One line runs between the zero percent passing and a point where 100 percent passes at the maximum aggregate size. The second line passes through the origin and a point where 100 percent passes two sieve sizes down from the maximum aggregate size (WashingtonDOT 2004).

Comparison of Coarseness Factor-Type Charts. It is interesting to compare the position on the CF-type charts of good quality slabs (that will probably not be slip-formed) as per the recommendations of Harrison, the USAF, and Shilstone. Fig. 34 shows Harrison's parallelogram superimposed on the USAF chart. The parallelogram is well within the USAF workability box and covers portions of all three recommended areas for hand placement, formed and placed mechanical paving, and slip-formed paving. Fig. 35 shows Harrison's box in relation to Shilstone's. Again, the Harrison box is well within Area II, and falls on Zone II-4 (good general), the upper portion of II-3 (high quality slab), and the lower portion of II-5 (varies to material and construction needs). In general, the three methods tend to agree.

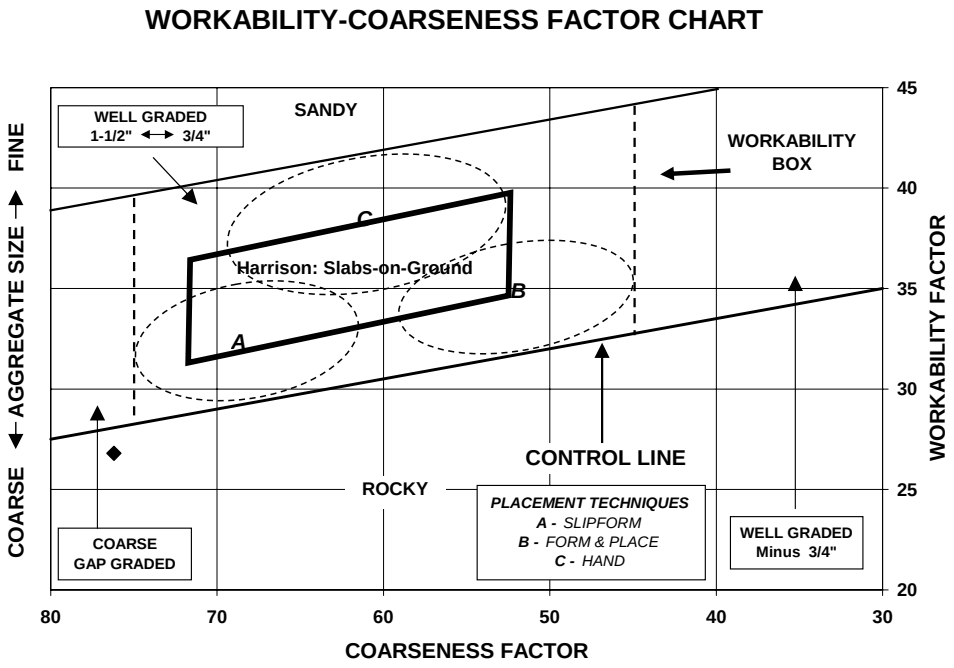

Fig. 34-Harrison vs. USAF recommendation.

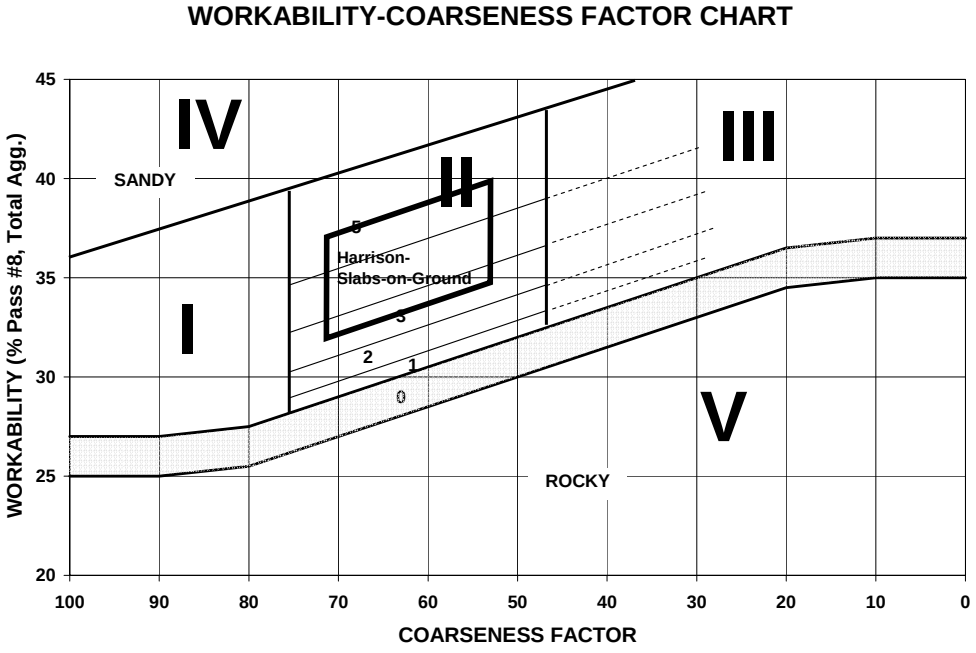

Fig. 35-Harrison vs. Shilstone recommendations.

“8 to 18” Band

Holland, Harrison, and Iowa DOT. As previously discussed, both Holland and Harrison (in private practice), and the Iowa DOT, recommend some form of an 8-18 specification. The 8-18 band is an attempt to prevent severe gap-grading or excessively coarse or fine gradations as characterized by excessive peaks and valleys in a gradation’s IPR plot.

Minnesota DOT. The Minnesota DOT Special Provisions provide for incentives/disincentives for meeting the 8-18 band. For mainline concrete paving, the contractor’s Job Mix Formula combined gradation is controlled with working limits on each sieve. A $2.00 per cu yd incentive is offered for meeting the 8-18 band. A second option available is a $0.50 per cu yd incentive for meeting a 7-18 band (MnDOT 2004). For MnDOT’s High Performance Concrete Paving mix (60 year design, high ADT), the contractor’s combined gradation is subject to a disincentive: $1.00 per cu yd for being one percent out of the 8-18 (meets a 7-18 band), and $5.00 per cu yd for being two percent out (6 or less -18) (MnDOT 2004).

Mid-West Concrete Industry Board. The Mid-West Concrete Industry Board, located in Kansas City, Missouri, has adopted the 8-18 band in its specifications. The #50 sieve may have less than 8 percent retained. Sieves finer than the #50 sieve must retain less than 8 percent. The coarsest sieve retaining any material

may have less than 8 percent retained. Only when necessary can the band be widened to 6-22 (MCIB 2000).

ACI 301- Structural Concrete. ACI 301-99 includes the concept of blending aggregates as a viable proportioning method. The 8-18 specification and the Coarseness Factor chart are included as alternate methods of proportioning blended aggregates (ACI 1999).

ACI 302- Floor Slabs. ACI 302.1R-96 has a strong emphasis on combined gradation. It is recognized that a uniform gradation is important to obtain a desirable matrix and reduce water requirements. It notes that the 8-18 band concept is useful in reducing water demand while producing good workability. It recommends 8-18 for large top size aggregates (such as 1 ½ in.), but for smaller top size material (*eg.* ¾ or 1 in.), 302 recommends 8 to 22 percent. The 8-18 or 8-22 refer to sieves below the top size and above the #100 sieve. Ideally, the #30 and #50 sieves percent retained material should be 8 to 15. A well-graded mix will have zero to 4 percent on the top size and 1.5 to 5 percent on the #100 sieve. However, if the particle shape is not compact (rounded or cubical), then 4 to 8 percent retained on any sieve would be appropriate (ACI 1996).

General trend. The combined gradation concept and a method to achieve it, *i.e.* the 8-18 spec, is gaining widespread use among state DOT's as well as consulting engineers, contractors, and owners. Specifiers have adopted the so-called "8-to-18" (8-18) band in an effort to force producers to supply a well-

graded blend that would not exhibit pronounced peaks and valleys. Of interest is the application of the location of the 8-18 band by different specifiers. As previously shown, Fig. 12 and 22 depict the limits recommended by the Air Force and the Iowa DOT, respectively. Fig. 36 and 37 show the band as specified by the Minnesota DOT and recommended by Shilstone (Shilstone Jr. 2004), respectively. Note that the Air Force limits the percent retained on the #100 sieve to zero, while Iowa DOT allows 18 percent, with Shilstone, MCIB, and MnDOT wanting to see 8 percent maximum. On the #50 sieve, the Air Force, Iowa DOT, and Minnesota DOT all allow 18 percent, while Shilstone would like to see less than about 13 percent and MCIB states that the IPR may be less than 8 percent. On the coarse end of the gradation, the largest sieve that 18 percent is recommended to be retained (Shilstone) is three sizes smaller than the maximum aggregate size (MS); both MnDOT and the Air Force like to see this largest sieve at two sizes smaller than the MS, and Iowa DOT wants it at one size smaller than the MS.

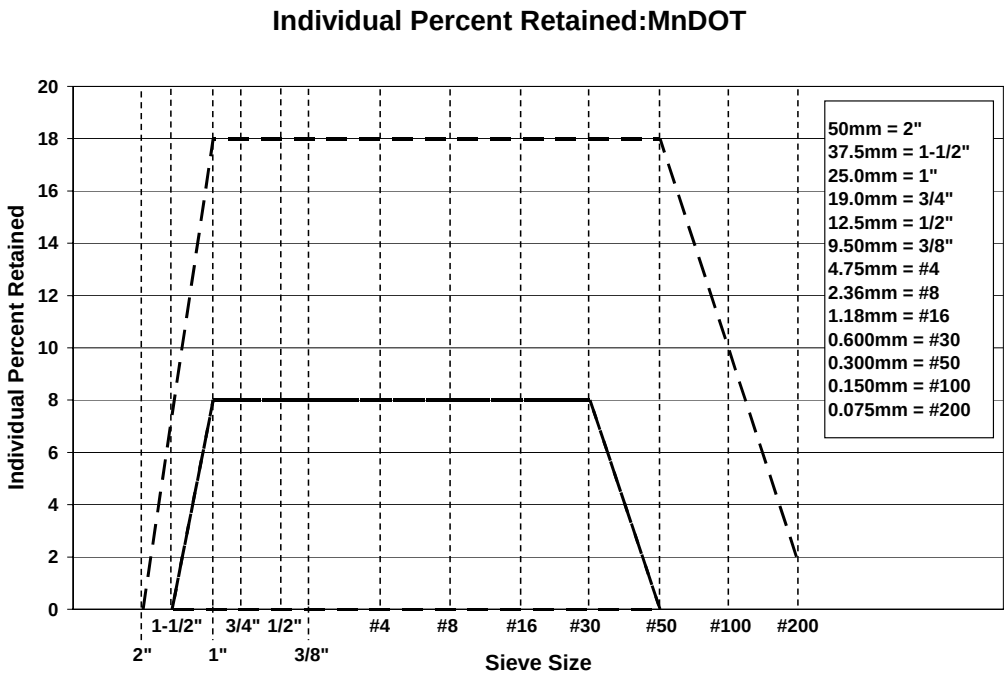

Fig. 36-MnDOT 8-18 band.

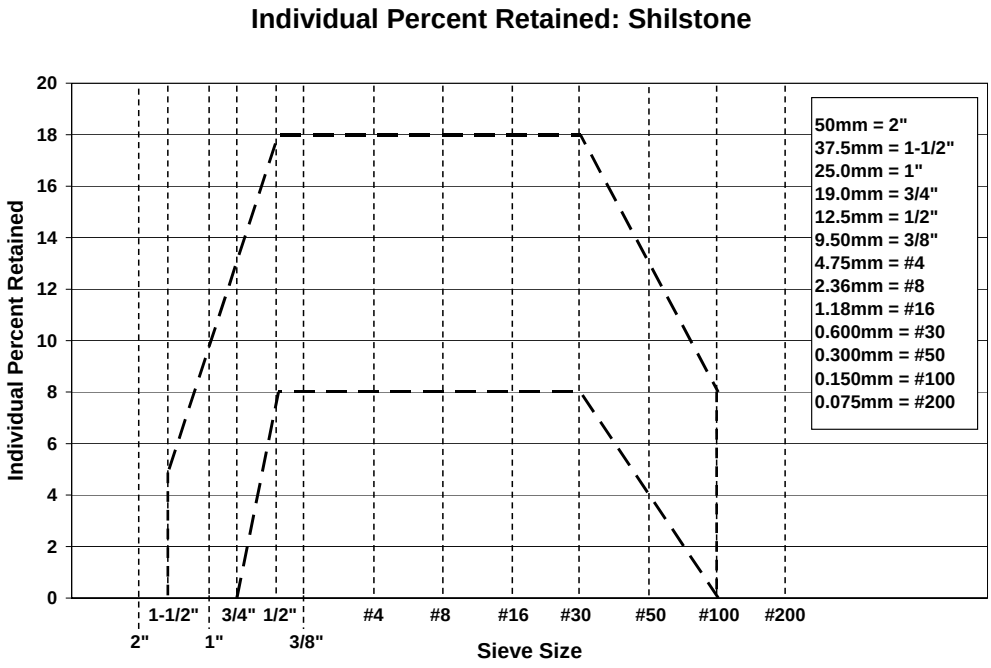

Fig. 37- Shilstone 8-18 band.

This specification/recommendation/guideline has led to much discussion of the pros and cons of the 8-18 band in particular and the combined gradation concept in general. Some of the discussion is supported by experiece, while other viewpoints are founded on conjecture (Various 2002-2003).

Detractors are divided into two camps. One camp says that the combined gradation concept is good, but the 8-18 method of achieving a combined gradation is too restrictive. The other camp is against the combined aggregate concept in general. The following are some negative viewpoints discussed on the Aggregate Research Industries Q and A Forum:

1) Experience has shown that aggregates can be blended to meet the 8-18 and still not result in good concrete.

2) Some aggregate producers are fearful that the 8-18 specification cannot be met because the native materials do not have the fractions available to make the gradation, and that there will be a large amount of waste to produce the specified grading. It is pointed out that some areas of the country may never be able to produce the 8-18 gradation efficiently—areas of fine sand, for instance.

3) Another line of thought is that sources of good aggregate are disappearing. The pace of permitting new deposits is not keeping up with demand, and this will make it even more diffficult to meet what is perceived as more restrictive aggregate specifications.

4) More expensive equipment and plant modifications will be required, both at the aggregate producer's site and the concrete plant.The building industry will not be willing to pay the extra costs of production or longer haul distances.

5) Aggregate producers (who apparently have not had experience with Superpave asphalt mixes) express fears that having more stockpiles will lead to more costs associated with the additional stockpiles. Space is an issue; if the concrete producer does not have space for more aggregate fractions, they will have to pay the aggregate producer to store the additional fractions.

6) It seems that one thing that is impeding the general use of a combined gradation specification is that on most speculative commercial work, mixes cannot readily be re-designed or adjusted to reflect gradation changes because of the contractural and business relationships between the concrete producer, the concrete subcontractor, the general contractor, the engineer, and the architect. Communication opportunities need to be improved.

7) Additionally, rapid response to gradation changes is hampered by the time it takes to dry the aggregate so that sieve analyses can be performed.

Advocates of the combined gradation concept point out the following:

1) The 8-18 spec is just a tool to be used as a guideline, and that upon due examination of the supplier's submittal, being out of specification on a few sieves will not significantly detract from the final quality of the concrete.

2) Further, it is not to be expected that one source of crusher-run stone can meet the 8-18 band, rather, it will take a blend of materials to achieve the desired product. The blended material might very well be an out-of-specification material

that meets quality requirements but not any particular gradation specification. Some sand and gravel producers routinely are able to put blends together using four aggregates. Use of a 3/8 in. by #20 aggregate has been recommended.

3) Producers have said that as long as the desired sizes are in the feed material, a sand system can be designed to create the required gradation.

4) The days of being able to make a gradation just with a sand screw are fading fast. Sophisticated equipment that is in routine use in the silica sand industry can be used in the concrete sand industry to do the job, such as density separators.These are said to be able to make accurate cuts at high production rates.

5) Still others have cautioned about the influence of particle shape on whether the percent retained material should run on the high or low side of the gradation band. For instance, if the intermediate aggregate size is highly angular, 18 percent retained is too high.

6) In areas that there is a plentiful supply of intermediate aggregates, the cost of the concrete can actually decline due to increased cement efficiency and use of non-standard (waste) materials. Savings of up to $5 per cu yd have been reported.

7) Those that specify and use concrete made with aggregate that meets the 8-18 specification report very workable concrete mixtures.

8) Near 8-18 gradations have been achieved with C 33 sand, # 57, and #8 aggregates for a warehouse floor with very good results and very uniform strength results.

9) It is said that highly successful floor contractors have learned that 8-18 mixes actually save money and improve quality.

Specifiers such as the USAF and Iowa DOT have encouraged, rather than required, the use of the band as a guideline, an ideal to strive for, a starting place. Then the mix needs to be proven with testing. Others, such as MnDOT, have required the 8-18 band. Shilstone has gone so far as to say that the rigid use of the 8-18 band has caused problems in regard to the high cost in some areas to fully comply with the limits. His experience is that if there is a gap at only one sieve, a peak at an adjacent sieve will minimize the problem. In the case of a gap at two consecutive sieves, peaks on either side will help in producing a good mixture. However, three low points will result in problems. A well-graded coarse sand can overcome problems of the coarse aggregate (Shilstone and Shilstone Jr. 1999). However, Shilstone has also said that if there is less than 5 percent retained on one or more intermediate sieves, there will be problems. Less than 13.5 percent retained on two adjacent sieves is a problem, especially on the #16 and #30 sieves. And, if 20 to 22 percent of the combined aggregate is retained on a single sieve, there may be finishing probems (Shilstone and Shilstone Jr.). Lastly, Shilstone has stated that the 8-18 band should be applied to moving averages of two consecutive sieves, rather than individual sieves (Shilstone Jr. 2004) .

Meininger performed a survey of 70 commercial mixes. The majority of the mixes were “not close” to meeting an 8-18 specification, yet most had no reported

pumping or finishing problems. Those mixes with problems were not necessarily weighted toward severe double-hump or gap-graded gradations. Meeting an 8-18 specification would be difficult without proportioning at least three aggregates. Use of a smaller maximum aggregate size would facilitate the implementation of an 8-18 gradation because of fewer sieve sizes. An appropriate use of the 8-18 specification might be cases of workability control of pumping, slip form paving, or high slump segregation-prone mixes (Meininger 2003).

Phelan recommends use of the 8-18 band with the understanding that one or more sizes may fall outside the limits. He presents examples from numerous successful projects which use optimized ACI 302-type gradations for floor slabs and elevated roadways (in one case combining a #8 with a #57 coarse aggregates) (Phelan 2004).

In general, successful uses of the 8-18 specification seem to involve superflat floor construction and paving projects.

Packing Models

SHRP Packing Handbook. The SHRP Packing Handbook (C-624) and the companion Guide (C-334) present a method for determining the optimum coarse/fine aggregate ratio for use in proportioning concrete, based on packing models (Anderson and Johansen 1993; Roy et al. 1993) The model assumes dry packing of spherical particles. The contention of the method is that the workability

of the concrete at a fixed cement content and *w/c* is mainly a function of the binary packing of the coarse and fine aggregates. The optimal workability was found to be when the sand-to-coarse aggregate ratio is equal to the densest packing of these two materials.

Input to the method is as follows: 1) gradation of the CA and FA, from which the "characteristic diameter" of the coarse and fine aggregate are found, and 2) the void content of each as determined by ASTM C 29 (which requires the oven-dry bulk specific gravity). Knowing the characteristic diameter and void contents, the "dry weight packing density" (PHI) is calculated for each aggregate. From prepared tables in the Handbook, the coarse aggregate percent volume is found. Then, ACI 211 or some other concrete mix design proportioning method is used to find cement, water, and air contents. From that, aggregate contents are calculated. The Handbook tables are set up to handle one sand and up to three coarse aggregates.

An example of the use of the Packing Handbook for a sand-and-one-coarse aggregate (stone) mixture is as follows (Cox 1993):

1) A sieve analysis is performed on the sand and coarse aggregate materials and plotted on a graph of particle size *vs* percent passing on Rosin-Rammler graph paper. A best-fit straight line is drawn, and the "characteristic diameter, d" is determined as the size corresponding to the 63 percent passing value (Fig. 38 and 39). In this example, d_{sand} = 0.054 in. and d_{stone}= 0.59 in.

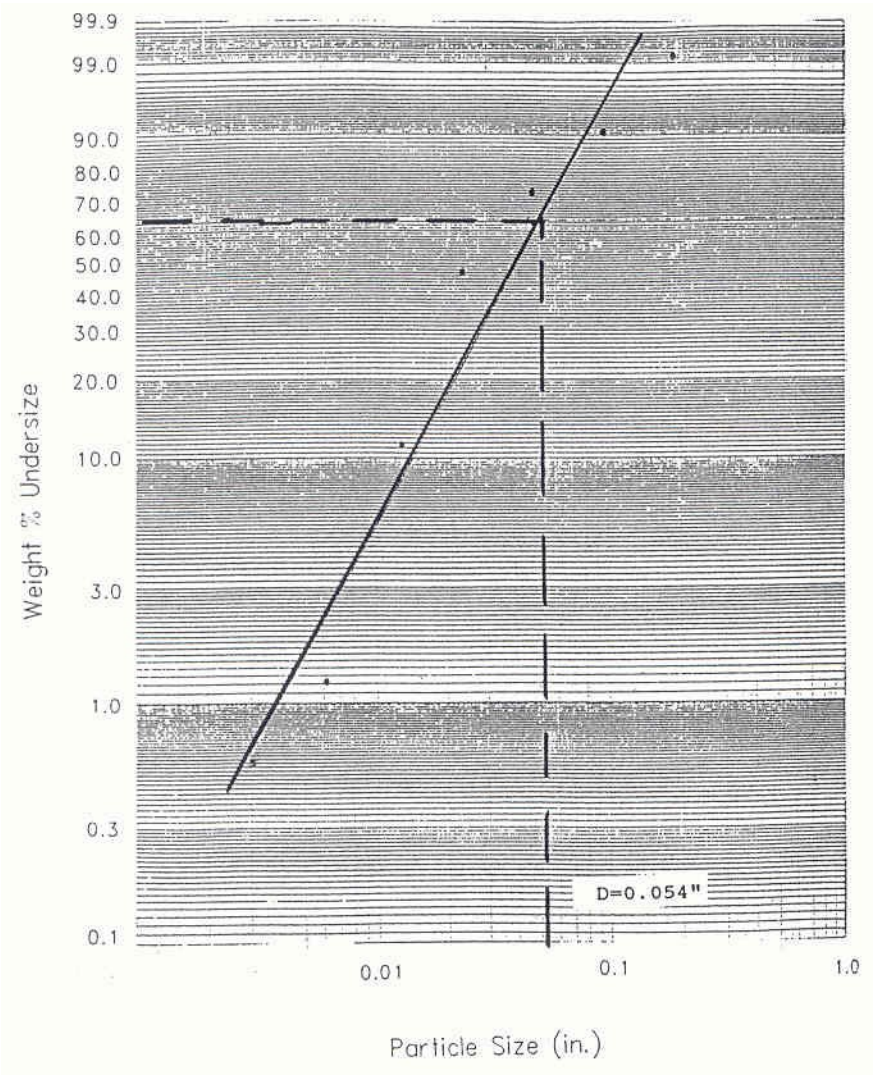

Fig. 38- Rosin-Rammler Plot for sand.

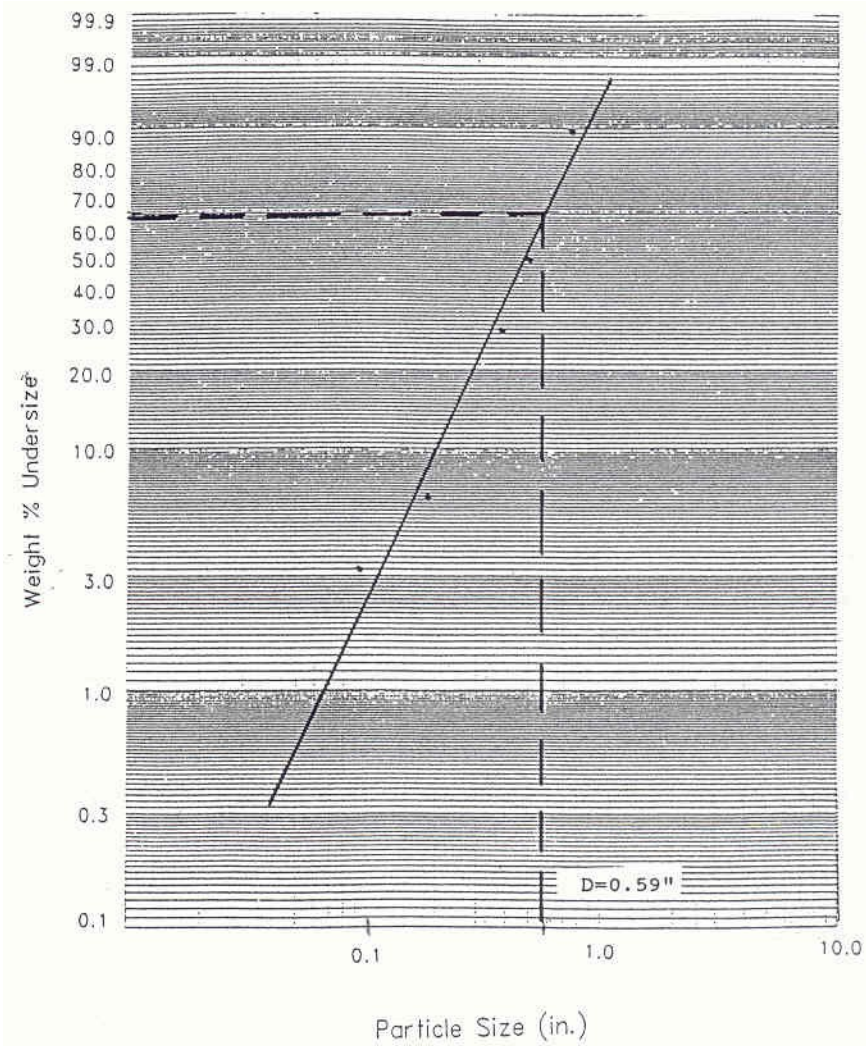

Fig. 39- Rosin-Rammler Plot for coarse aggregate.

2) Each aggregate is subjected to ASTM C 29 to determine the void content. (34 percent for the sand and 42 percent for the stone.)

3) The dry weight packing density (PHI) is determined for both aggregates (0.66 for the sand and 0.58 for the stone):

$$\mathrm{PHI} = 1 - \left(\frac{\%\mathrm{voids}}{100} \right) \qquad (5)$$

4) The four input values (d_{sand}, d_{stone}, PHI_{sand}, and PHI_{stone}) are rounded to match the intervals in the Handbook tables. These values are used as input. A portion of one of the tables is shown in Fig. 40. From this, the resulting percent coarse aggregate is 72%.

SAND		COARSE AGGREGATE		VOLUME%
D1	PHI,1	D2	PHI,2	COARSE AGGREGATE
0.06	0.50	0.51	0.65	82
0.06	0.55	0.51	0.65	80
0.06	0.60	0.51	0.65	78
0.06	0.65	0.51	0.65	78
0.06	0.70	0.51	0.65	76
0.06	0.50	0.51	0.70	86
0.06	0.55	0.51	0.70	84
0.06	0.60	0.51	0.70	84
0.06	0.65	0.51	0.70	82
0.06	0.70	0.51	0.70	80
0.06	0.50	0.51	0.75	90
0.06	0.55	0.51	0.75	88
0.06	0.60	0.51	0.75	88
0.06	0.65	0.51	0.75	86
0.06	0.70	0.51	0.75	86
0.06	0.50	0.59	0.55	74
0.06	0.55	0.59	0.55	72
0.06	0.60	0.59	0.55	70
0.06	0.65	0.59	0.55	68
0.06	0.70	0.59	0.55	66
0.06	0.50	0.59	0.60	78
0.06	0.55	0.59	0.60	76
0.06	0.60	0.59	0.60	74
0.06	0.65	0.59	0.60	72
0.06	0.70	0.59	0.60	70

Fig. 40- Portion of coarse aggregate volume table from Packing Handbook.

5) Standard mix design procedures are followed to select the water, cement, and air volumetric contents. The remaining volume is the total aggregate. It is divided as per the above-determined coarse aggregate content; knowing specific gravities, weights are determined.

6 Trial batches are then made to verify/adjust the mix.

In the case of multiple coarse aggregates, steps 1-3 are followed. In step 4, the appropriate table is used to find the percent proportions of the coarse aggregates. The blend of coarse aggregate gradation is calculated, plotted on a Rosin-Rammler chart, and the characteristic diameter of the blend is determined. Then, treating the mix as a one coarse aggregate-sand mixture, steps 4-6 are followed.

A portion of SHRP-C-339 (Roy et al. 1993) was an evaluation of the 13 ASTM C-33 coarse aggregate gradations then in use by use of the packing model. For each of the 13 size numbers (gradations) in C-33 Table 2, five variations were analyzed with varying emphasis on: 1) amount of coarse material (H), 2) amount of middle size material (M), 3) amount of finer size material (L), 4) amount of coarse and fine but minimizing the middle sizes (HL), and 5) use the mean value of the allowable percentages (ASIS). The fine aggregate gradation was kept constant and represented the mean values of the allowable percentages. The analysis made use of a ternary chart (Fig. 41) which shows contours of packing density. It also depicts sensitivity to changes in fine-to-coarse proportions (closely spaced isodensity lines in the horizontal direction) and magnitude of

range of fine-to-coarse proportions that have a constant maximum packing density (large area of plateau). Both of the last two criteria are tests of the tolerance level of small changes in proportions of fine and coarse aggregate.

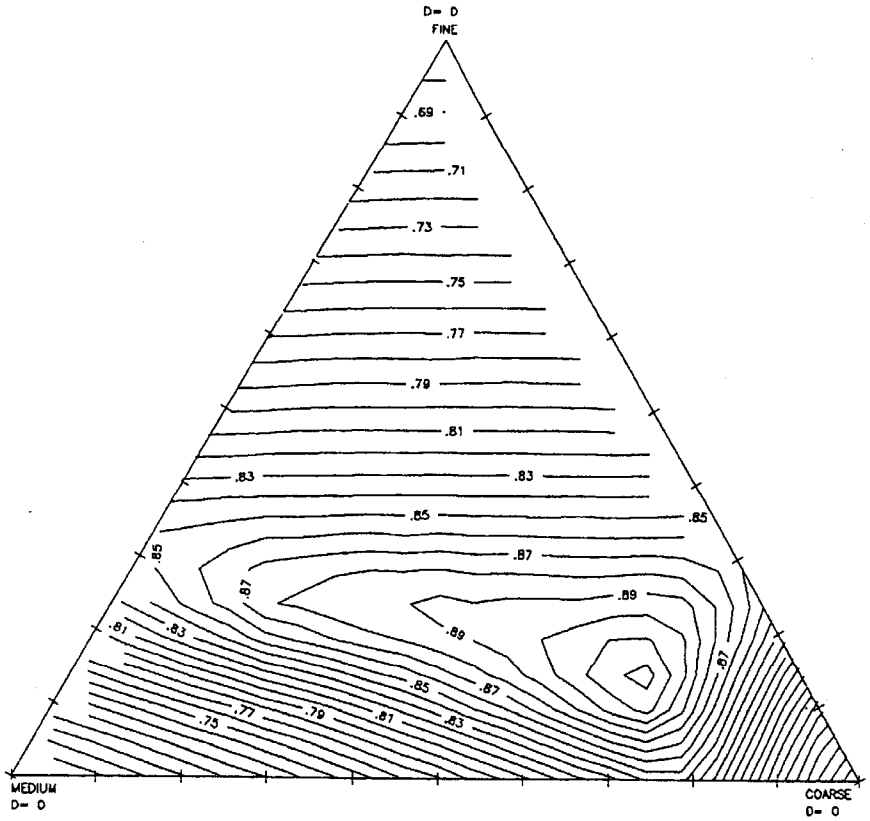

Fig. 41- Packing Handbook example ternary chart.

The resulting analysis showed that by varying between the allowable C-33 gradation limits, the packing densities varied considerably. The size number gradations were evaluated based on magnitude of packing density (higher was

deemed better), relative area of maximum packing density within the size number group, and sensitivity to fine/coarse volume fraction variations. For typical size numbers used for concrete, the #467ASIS and #467L were considered the best of the #467 size group (highest packing density, lowest sensitivity, largest area of density on the ternary chart). Best of the #57 was #57L, #57H, and #57 ASIS. Best of the #67 were #67ASIS and #67LH. All #8 size number variations fared worse than the coarser size number groups.

Cox et al. evaluated the C-624 Packing Handbook by comparing four mix types. Each of the four was mixed as per: 1) lab-reproduced field mixes designed by use of a standard method, and 2) mixes designed with the Packing Handbook. Cement content, *w/c*, and admixture dosage were kept constant between the two methods. The Packing Handbook mixes had more coarse aggregate and less sand, therefore were harsher, harder to work (hand finishing more difficult due to less mortar), had lower slumps by ¾ to 1.5 in., had less air (1 to 3 percent) probably due to less sand, but flexural strengths were about 10% higher. Addition of air entraining agent resulted in higher air contents but more variability. Placement was still possible with a vibrator. It was concluded that the Packing Handbook has promise because concrete cost could be lower as a result of lower cement contents and *w/c*, but workability and air issues needed to be overcome. One of their references indicated that maximum packing density gives the best workability, minimum porosity, minimum permeability, and maximum compressive strength. Another of their references stated that maximum density gives a harsh, somewhat unworkable mix (Cox 1993).

INTERACTION OF GRADATION AND PARTICLE SHAPE

It has been recognized that there is an interaction between the desired gradation and particle shape. In order for workability and other desired concrete properties to be achieved, the aggregate particle shape is usually required to be compact. Although Shilstone advocates the use of an intermediate size to create a well–graded gradation, he comments that for aggregates with an elongated, sharp, or flat shape, gap-grading must be used because the intermediate size particles may cause more problems than they solve (Shilstone and Shilstone Jr. 1989). Of the entities included in this study that have some form of combined/optimized gradation written in their specifications (Missouri DOT, Iowa DOT, Kansas DOT, Minnesota DOT, USAF, MCIB), only the USAF, the Missouri DOT, and the Minnesota DOT regulate particle shape. In all three cases, the specification is limited to flat and elongated of the coarse aggregate. The Air Force publications require that particles be “cubical in shape without the presence of elongated or slivered materials”. Flat and elongated percent is limited to a maximum of 20 percent with a ratio of 3:1 (1996; Muszynski 1996). The Missouri DOT limits thin and elongated (flat and elongated) to a maximum of 5 percent at a 3:1 ratio. The Minnesota DOT limits thin and elongated to a maximum of 15 percent at a 3:1 ratio. The general consensus of the literature seems to be that it is not advisable to insert an intermediate size aggregate if it is of an inappropriate particle shape.

EFFECTS ON CONCRETE PROPERTIES

Optimized mixes are reported to respond better to vibratory consolidation and finishing operations. This is said to result in greater smoothness, which means less corrective grinding and greater smoothness pay factors (Anonymous 1990).

Shilstone has examined cores from 1923 era specification concrete and more modern C 33 specification concrete. The older concrete contained intermediate sized aggregate, while the newer material was more gap-graded. The older concrete showed much less deterioration because it contained less mortar. Additionally, Shilstone asserted that wear resistance will be greater in denser graded mixes because once the concrete surface mortar is worn down, the many hard intermediate stones are at the surface, as opposed to a fewer number of larger stones in a more gap-graded mix. The mortar wears and leaves the larger stones projecting.

It is said that *w/c* can be lowered more by gradation changes than by use of a water reducer (while maintaining slump), with the resultant increase in strength. Durability can increase also because the optimized mix may contain less water, resulting in a less porous mix. Less water also means less shrinkage.

Well-graded mixtures tend to have less segregation problems. With well-graded mixtures, segregation can occur when the concrete is placed by chute. The

coarser material moves forward while the mortar recedes under the end of the chute. The paving machine augers may not be able to put it all back together. The resulting rocky spots end up being high points and may have to be ground. If a saw cut goes through such an area, it will tend to spall and scale prematurely (Shilstone and Shilstone Jr. 1999).

Well-graded aggregate mixtures will also take a thixotropic set as it emerges from the paver, thus preventing edge slump. Well-graded mixtures also will minimize finishing labor, and will tine readily (Shilstone and Shilstone Jr.).

DIFFICULTY IN ECONOMIC PRODUCTION OF AGGREGATE

As previously mentioned, the natural sands in many parts of the country are relatively fine, lacking in the intermediate sizes. Extra equipment at the plant, such as sand classifiers, may be necessary to produce a coarser sand. The extra equipment would contribute to a higher cost. Additionally, the use of classifiers may slow down production, which could be a problem on some projects. Additional stockpiles and bins with the attendant extra handling are also cost items.

GUIDE TO PRODUCE OPTIMIZED GRADATIONS

In order to be successful in producing an optimized gradation, Shilstone recommends the following (Shilstone and Shilstone Jr.):

1) Find a sand producer that will supply a coarse sand. Sands that have only 65% passing the #8 sieve have much fewer problems.

2) If a coarse sand cannot be found, find a “blending size” aggregate. Use of this size is allowed in C33-93 and later. This type of material goes by a variety of names and designations, such as #89, #9, buckshot, birdseye, squeegee, and shot. The material is typically too fine to be pea gravel and too coarse to be sand. Sieve size ranges from passing the #4 sieve to retained on the #50 sieve.

3) A cold feed can be set adjacent to the belt feeding the bins to blend the fine and coarse sands. Shilstone has recommended that a third aggregate bin be used rather than attempting to pre-blend two aggregates at the quarry because of segregation problems. Additionally, with only two bins, the operator has no leeway to re-proportion the two pre-blended aggregates.

4) The CF should not exceed 75 to 80 percent. It should be between 45 and 75 for paving. The “W” should be 31 to 37 percent but never more than 39 percent except when the sand is very sharp.

5) During production, the gradation should be verified as material is loaded into the bins. As the gradations vary, the proportions should be adjusted to keep the original point on the CF as constant as possible.

At least three aggregate sizes should be used (two coarse, one fine). When ASTM size #467 is specified, three coarse aggregates sizes are recommended (Shilstone 1989) .

RECENT CHANGES TO STANDARDS

Shilstone has outlined the salient recent changes to applicable ASTM and ACI standards (Shilstone and Shilstone Jr. 1992) (Shilstone and Shilstone Jr. 1996).

ASTM C 33- Aggregates for Concrete

Starting with the 1994 version of ASTM C 33, the party responsible for the selection of concrete mixture proportions is allowed to also have responsibility for determining proportions of the aggregate and the addition of blending aggregate sizes, if necessary. Coarse aggregate size number gradations may be altered if both purchaser and aggregate supplier agree. The intent is to allow the producer to use whatever materials are available to produce a desired total gradation, provided that the quality of the aggregates is acceptable and the specified nominal maximum size is not exceeded.

Shilstone has made recommendations to allow the sand supplier to include two sand gradings: one coarse and the current fine one. The coarse sand gradation will be a combination of the 1923 C33 version plus the first issue of PCA's *Design and Control*.

ACI 301- Structural Concrete

As previously mentioned, ACI 301-99 includes the concept of blending aggregates as a viable proportioning method. The 8-18 specification and the Coarseness Factor chart are included as alternate methods of proportioning blended aggregates (ACI 1999).

ACI 302- Floor Slabs

As previously discussed, ACI 302.1R-96 has a strong emphasis on combined gradation. It is recognized that a uniform (well-graded) gradation is important to obtain a desirable matrix and reduce water requirements. It notes that the 8-18 band concept is useful in reducing water demand while producing good workability.

ACI 304- Placing Concrete

Reference is made in ACI 304R-00 to combined grading in the section that deals with pumping, and mentions that additional aggregate can be added to improve the overall gradation (ACI 2000). ACI 304.2R-96 agrees that combination of materials from separate sources can produce excellent results (ACI 1996).

MoDOT SPECIFIED GRADATIONS

An preliminary analysis was performed on several paving grade MoDOT gradations (MoDOT 2004) to see where the specifications might be located in terms of the CF and Individual Percent Retained charts. The gradations analyzed were three coarse aggregates (A, B, and D) coupled with the concrete sand. Five possible combined gradations were examined for each of the three lettered coarse aggregate gradations, using the coarse and fine sides of the allowable limits on each sieve as well as a gradation line running through the mean of the allowable ranges. For example, the combinations for Gradation A were as follows: 1) coarse side of A, coarse side of sand, 2) coarse side of A, fine side of sand, 3) fine side of A, coarse side of sand, 4) fine side A, fine side of sand, and 5) middle of A, middle of sand. The mix proportions for the analysis were of several actual mixes used by MoDOT. Certain sieves were missing from the specifications that were necessary for computation of either CF or W, so the gradation was assumed to follow the highest percent passing possible on the high side of the allowable and the lowest percent passing possible on the low side of the allowable. Specifically, for gradation A, the #8 through #100 values were assumed to be 5 percent on the high side and zero on the low side, the ½ in. to be 10 percent on the low side and 70 percent on the high side, and the 1 in. to be 35 percent on the low side and 100 percent on the high side. For gradation B, the #8 through #100 values were assumed to be 8 percent on the high side and zero on the low side, the 3/8 in. to be zero on the low side and 60 percent on the high side, and the ¾ in. to be 25 percent on the low side and 100 percent on

the high side. For gradation D, the #8 through #100 values were assumed as 8 percent on the high side and zero on the low side, and the ½ in. to be 15 percent on the low side and 100 percent on the high side. The gradation limits for coarse aggregate gradations A, B, and D are shown in Fig. 42-44, respectively.

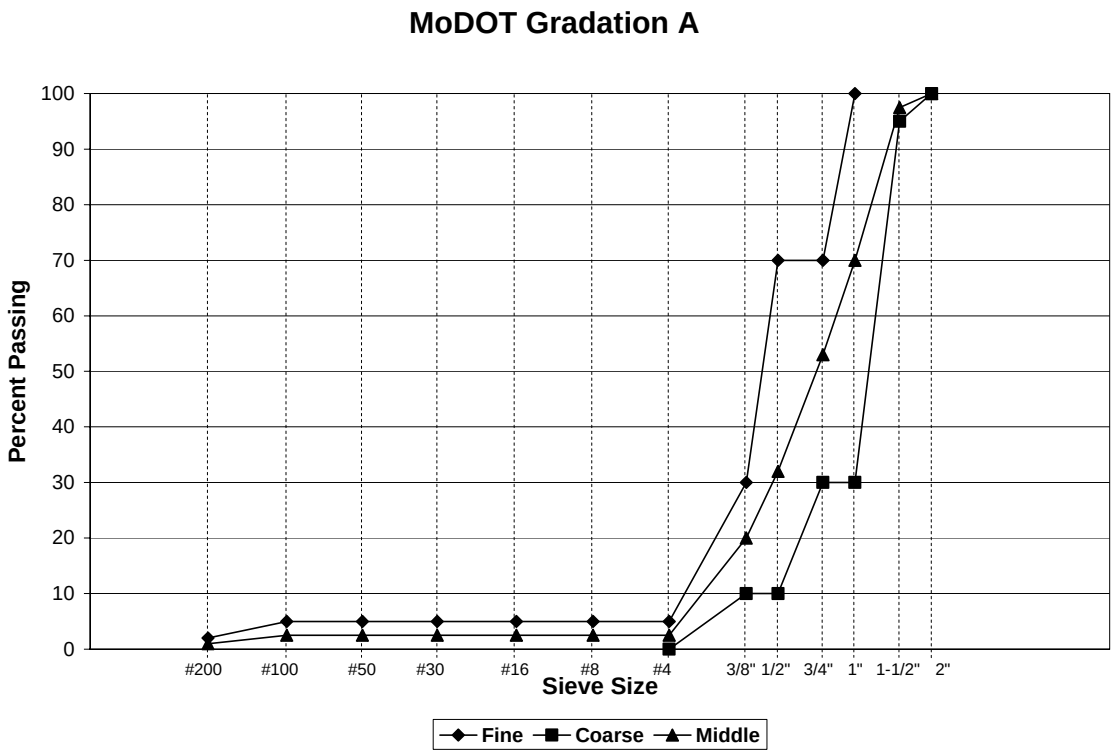

Fig. 42-Gradation A limits.

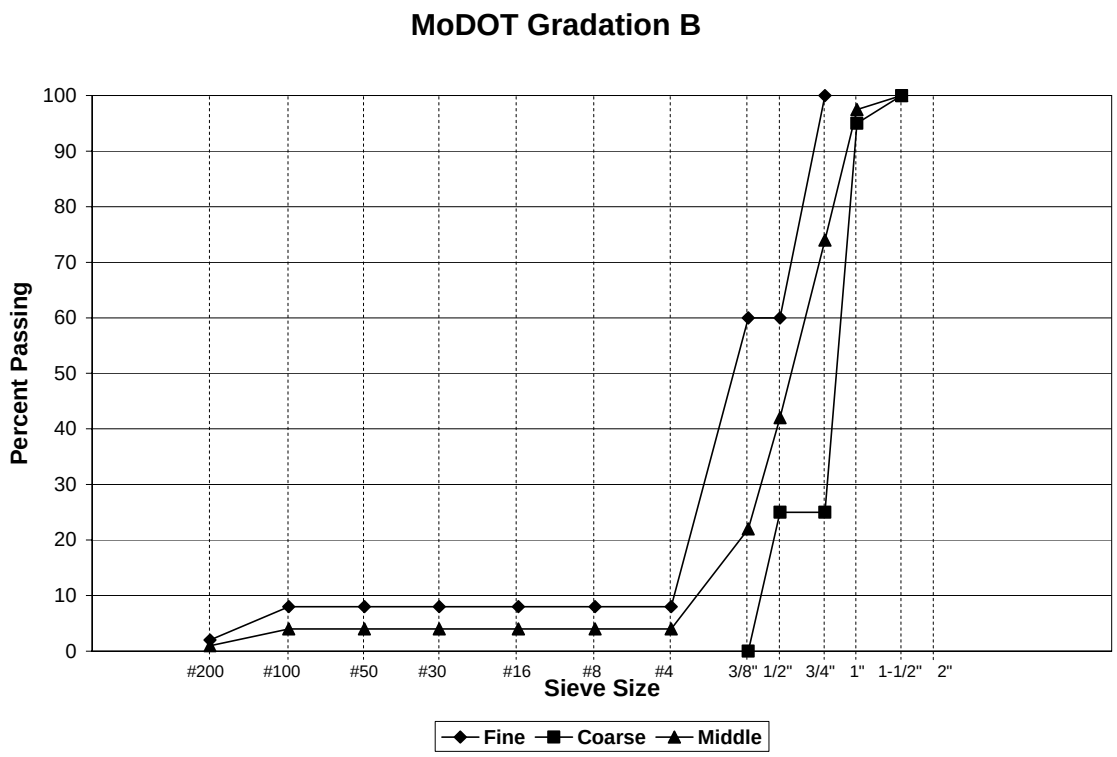

Fig. 43-Gradation B limits.

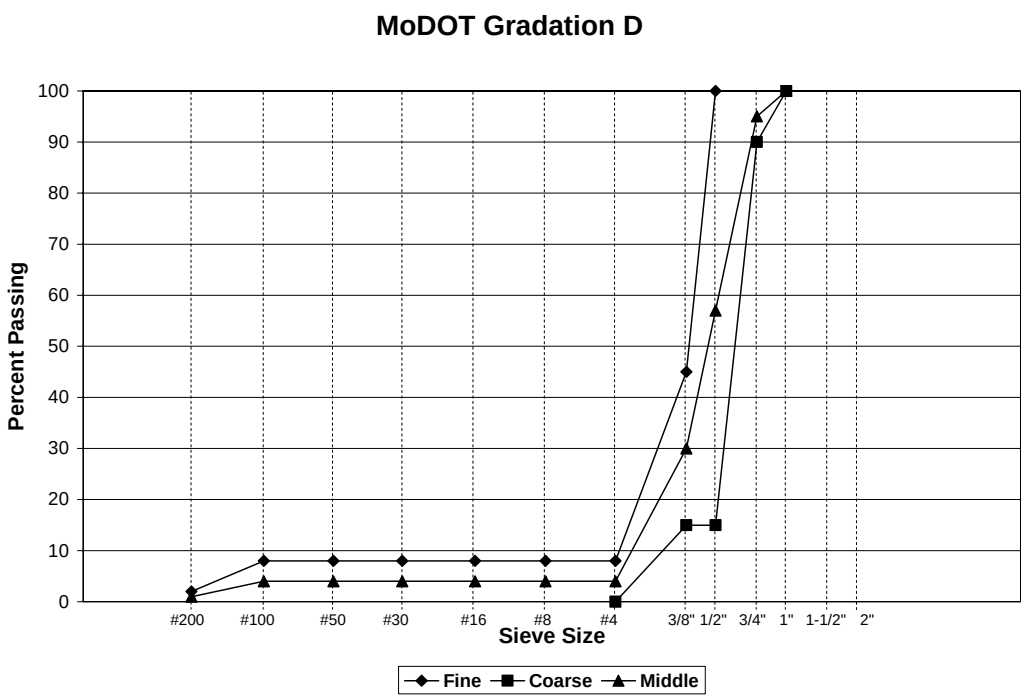

Fig. 44-Gradation D limits.

Table 4 is a summary of the results for all combinations. Designations for each combination are of the following form: first letter is coarse aggregate gradation, the second letter is the coarse aggregate coarse (c) or fine (f) side, and the third letter is the sand coarse (c) or fine (f) side. For instance, Acf indicates gradation A, coarse side of gradation A, fine side of the sand. An “m” designation indicates that both the coarse and sand gradations are in the middle of each allowable range.

Table 4. Results of MoDOT gradation analysis.

Gradation	**W_{adj}**	**CF**	**Shilstone Zone**	**IDOT Zone**	**USAF Zone**	**Description**
Acc	26.8	76.2	trendband	below zero	Rocky	rocky
Acf	38.1	90.0	IV	C	Off chart	sandy/gap-graded
Afc	29.9	61.9	trendband	rocky	Rocky	rocky
Aff	41.2	73.7	IV	C	Near sandy	sandy
Amm	34.0	75.1	I/II-4	B/D	A/gap-graded	borderline gap/well graded
Bcc	26.8	84.7	trendband	below zero/D	Off chart	rocky
Bcf	38.1	100	IV	C	Off chart	gap-graded/sandy
Bfc	31.8	36.3	V	rocky	Rocky	rocky
Bff	43.0	43.5	III-5	F-5	outside box	fine well gradred
Bmm	34.4	74.3	II-4	B-4/5	Near A	well graded
Dcc	27.0	71.9	trendband	rocky	Rocky	rocky
Dcf	38.4	85.0	IV/I	C/D	Off chart	sandy/gap graded
Dfc	32.0	49.9	II-1/0	zero	B/band	borderline rocky
Dff	43.4	59.8	IV	C	sandy	sandy
Dmm	34.9	66.6	II-4	B-4	A-C	well-graded

Fig. 45 through 48 show the IPR, Shilstone CF, Iowa DOT CF, and the USAF Aggregate Proportioning Guide charts, respectively, for a blend that would be expected to have problems. The IPR exhibits a pronounced double hump, the Shilstone CF point is in zone IV, the Iowa DOT point is in area C, and the point is off the USAF chart. All of these charts indicate that the mix may be excessively sandy and gap-graded.

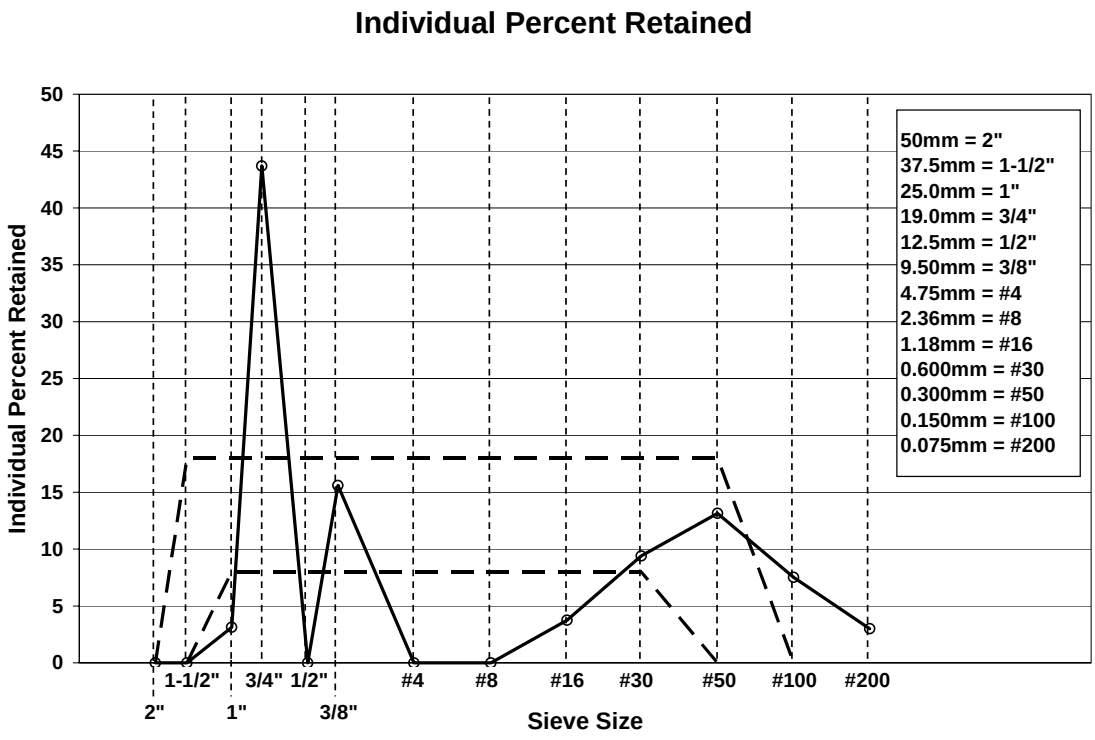

Fig. 45- IPR plot-problem mixture, B_{cf}.

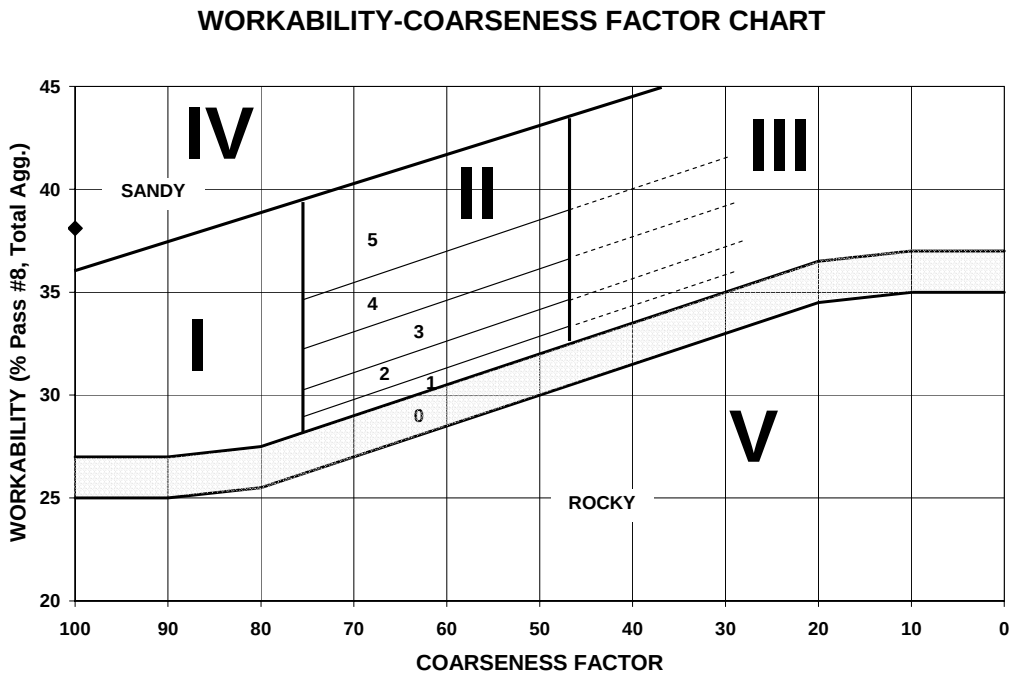

Fig. 46-Shilstone CF chart--problem mixture, B_{cf}.

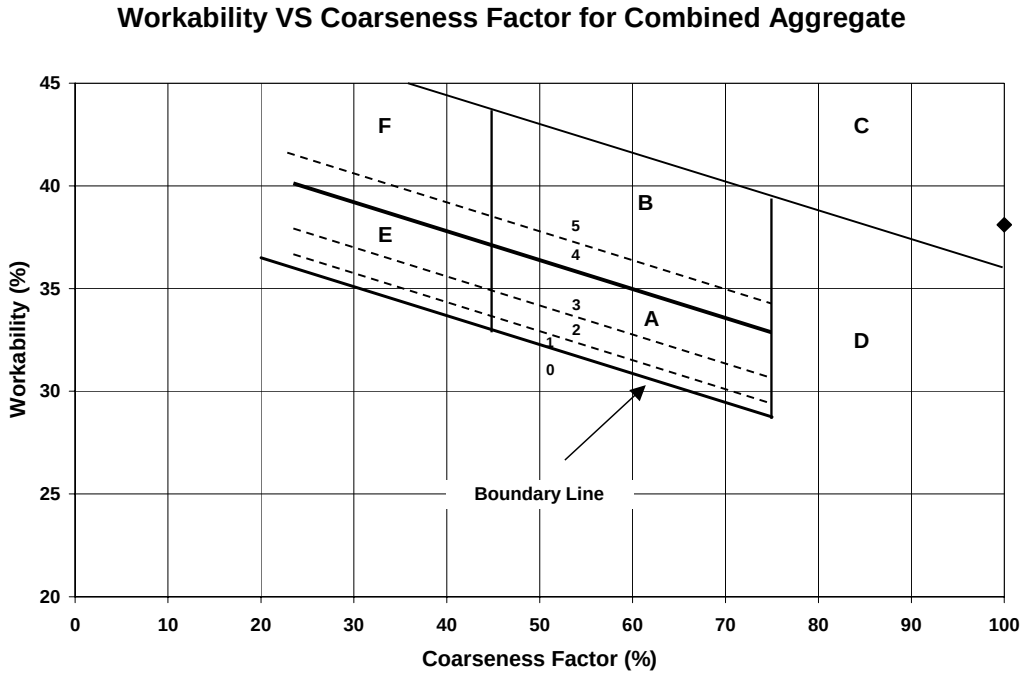

Fig. 47-Iowa DOT CF plot-problem mixture, B_{cf}.

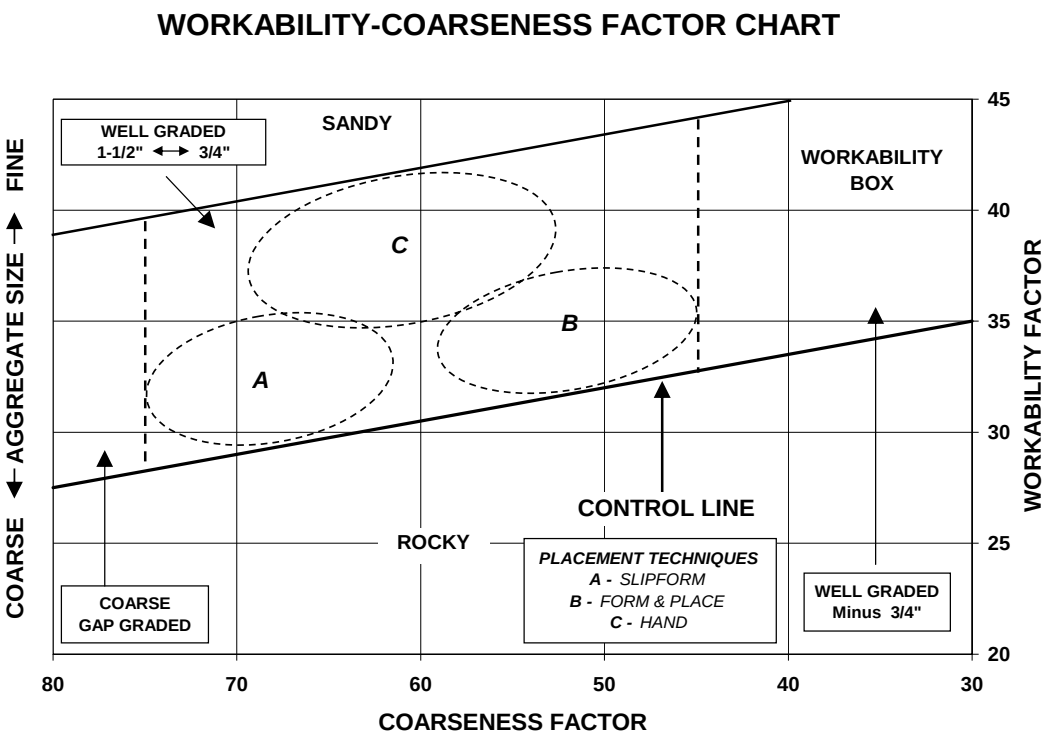

Fig. 48-USAF chart plot-problem mixture, B_{cf}.

Fig. 49 through 52 show the IPR, Shilstone CF, Iowa DOT CF, and the USAF Aggregate Proportioning Guide charts, respectively, for a blend that would be expected to be a relatively good general mixture. Although the IPR does not exhibit a haystack shape, the Shilstone CF point is in zone II-4, the Iowa DOT point is in area B-4 (2 percent bonus), and the USAF CF point is at the A/C juncture. These charts indicate that the mix should perform well.

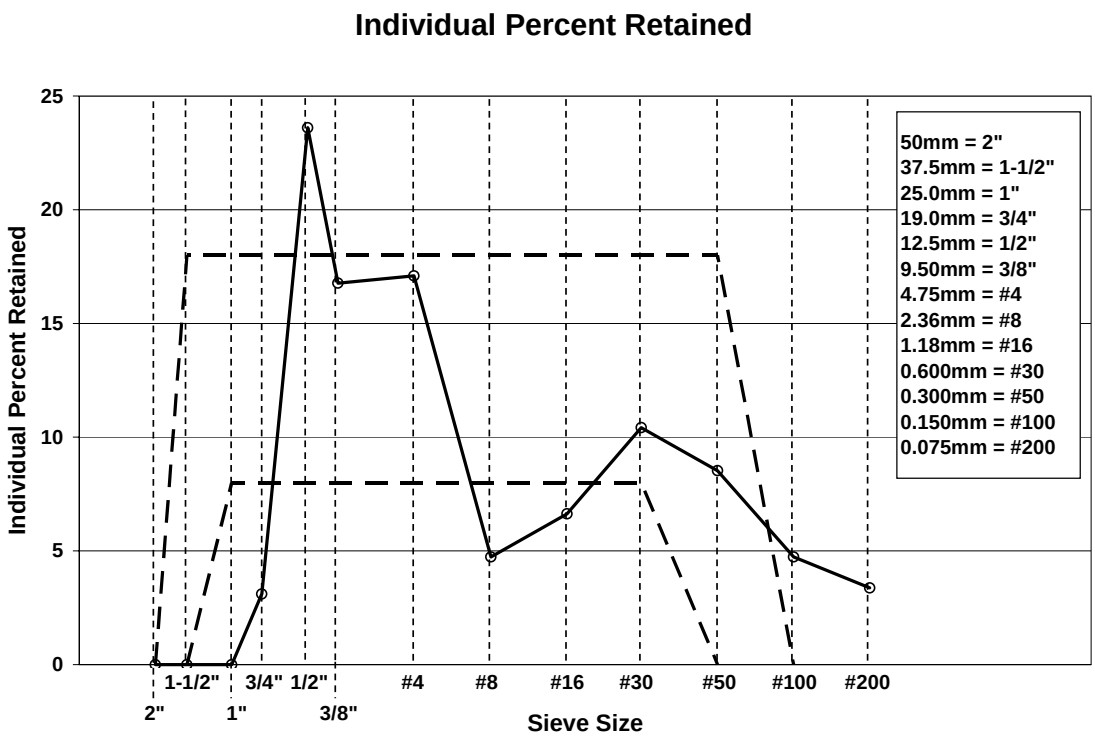

Fig. 49-IPR- better mixture.

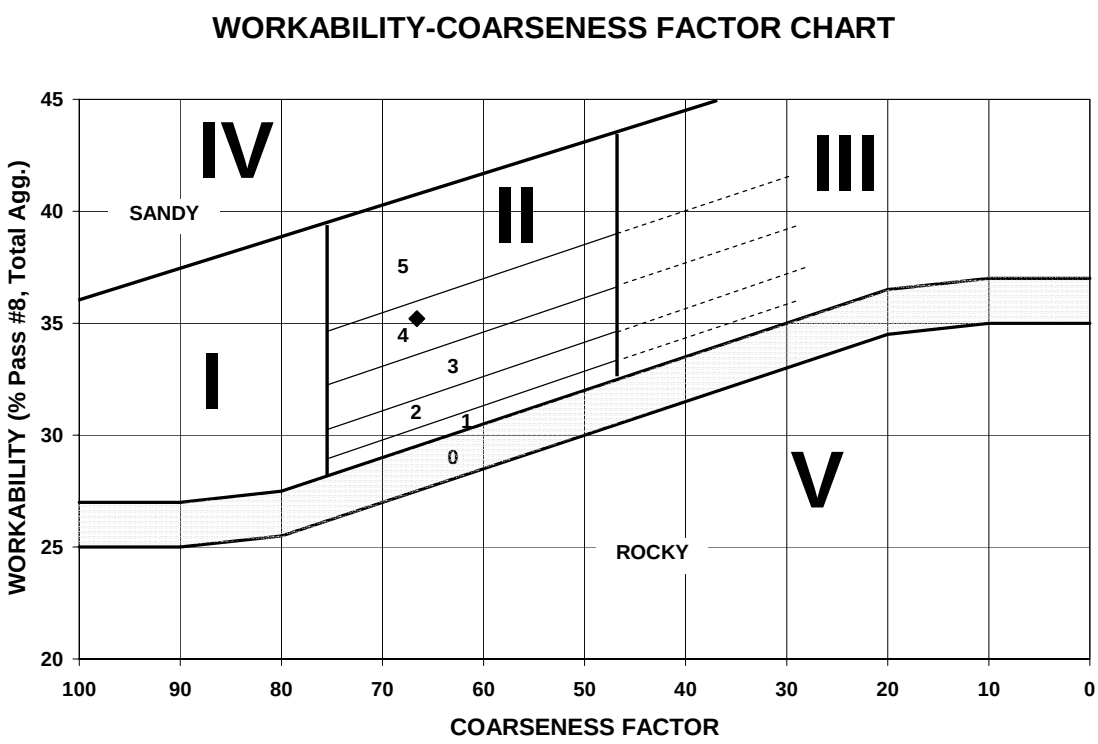

Fig. 50- Shilstone CF chart- better mixture.

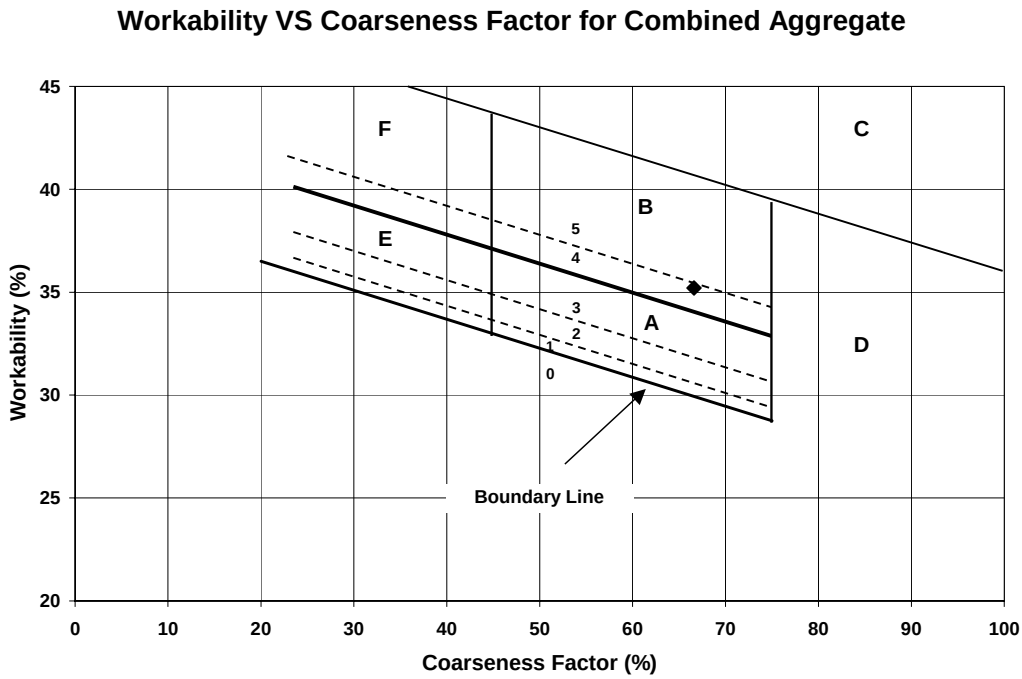

Fig. 51-Iowa DOT CF chart- better mixture.

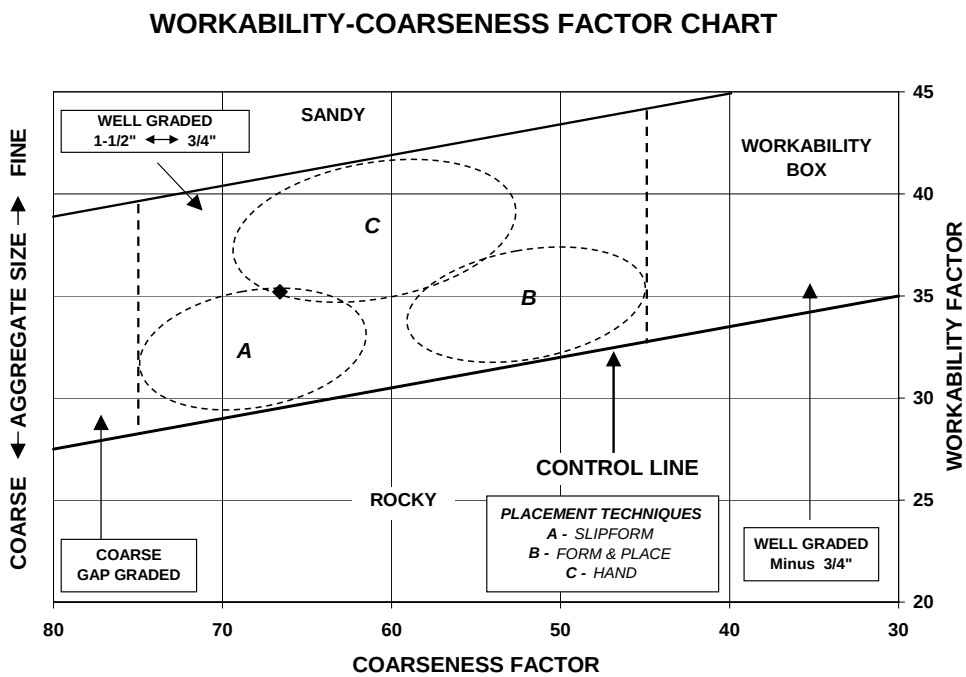

Fig. 52-USAF Aggregate Proportioning Guide-better mixture.

Fig. 53 through 55 show where all mixtures would plot on the various CF-type charts.

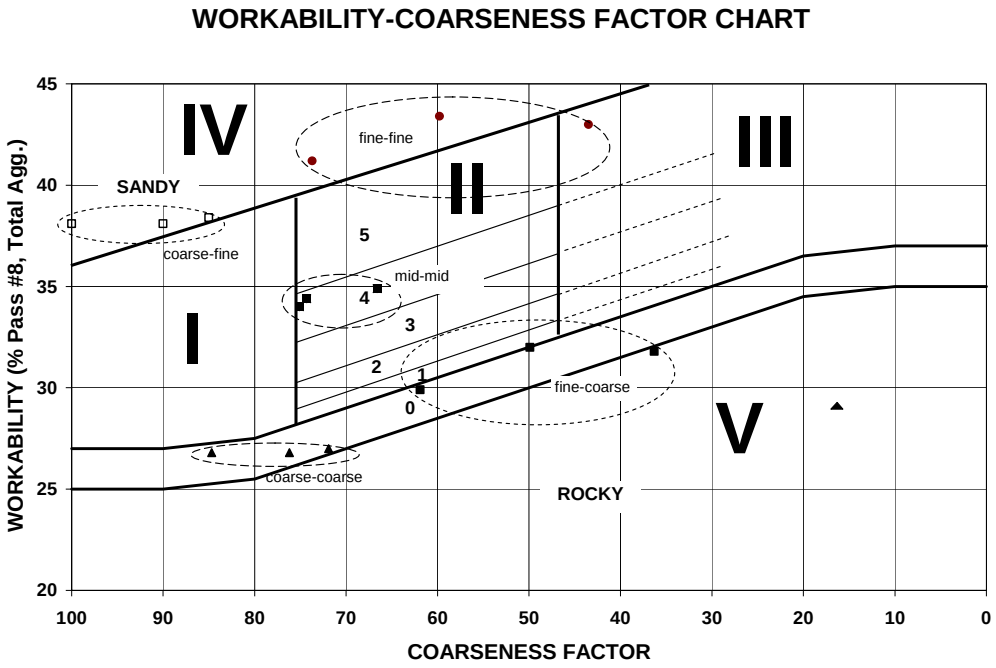

Fig. 53- Summary of MoDOT gradations on Shilstone CF chart.

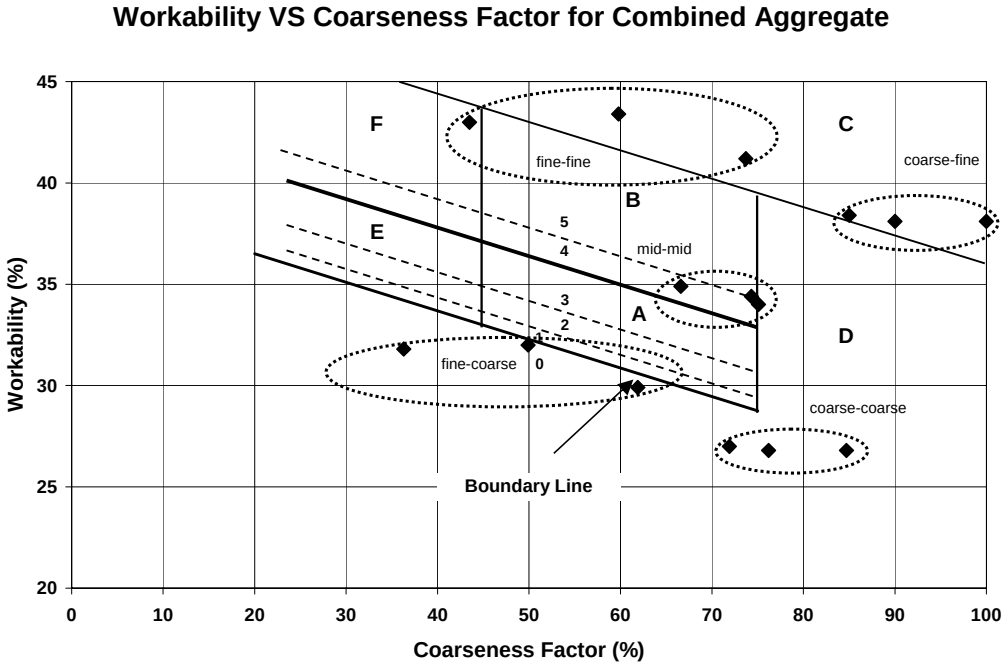

Fig. 54- Summary of MoDOT gradations on Iowa DOT CF chart.

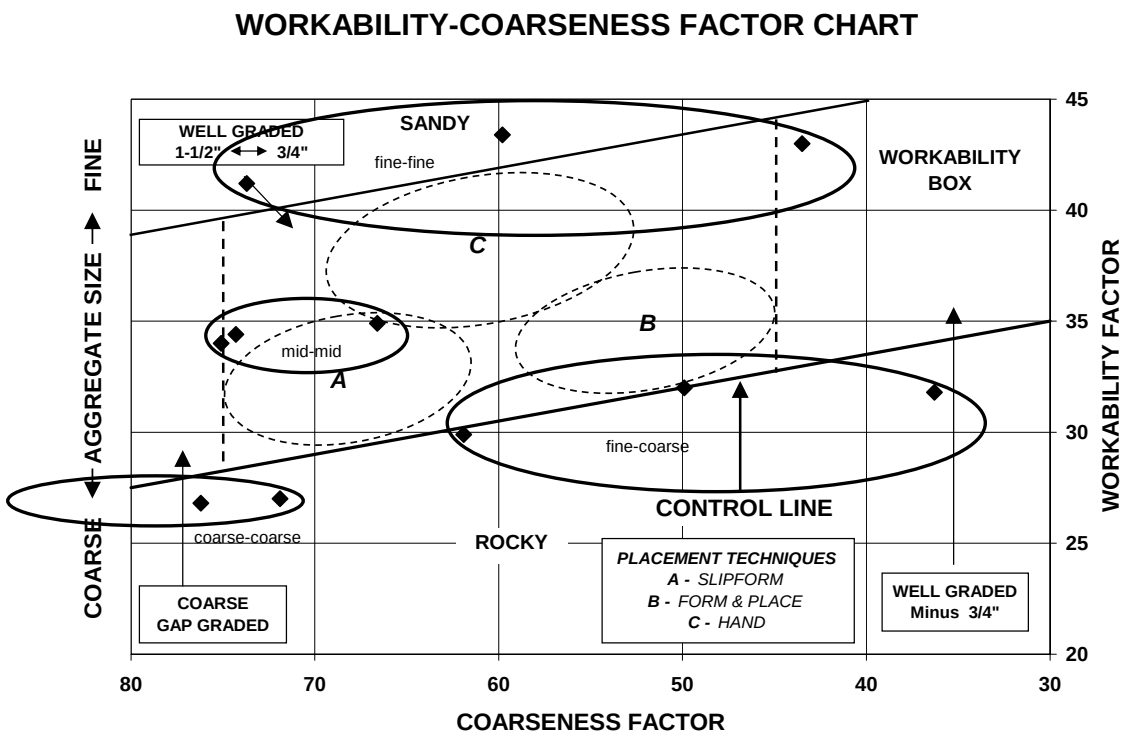

Fig. 55- Summary of MoDOT gradations on USAF Guide.

There is general agreement between the three charts in regard to expected behavior. All three gradations that ran on the coarse side of both the sand and all three coarse aggregates plotted in the rocky zones, as did the three fine-side coarse aggregate/coarse-side sand gradations. The three coarse-side coarse aggregate/ fine-side fine aggregate and the fine-side coarse aggregate/ fine-side sand plotted in or near the sandy areas. The middle mixes plotted in or near the USAF zone A, indicating good slip form paving behavior. However, two of the three middle mixes plotted somewhat close to the area of gap-graded mixes, indicating that daily fluctuations in gradation could cause “good days” and “bad days “ as the mix became increasingly or decreasingly rocky. This might be expected to affect smoothness pay factors.

SUMMARY AND CONCLUSIONS

For almost 100 years, efforts have been made to achieve desired concrete properties through adjustments in aggregate gradation. Initial efforts dealt with the concept of maximum density with the idea that a denser gradation would contain fewer voids necessary to be filled with cement paste. Unfortunately, mixtures formulated with few voids tended to be harsh. Still recognizing that the surface area of the aggregate particles that needed to be coated with paste was a key to behavior, some form of gradation measure was explored including surface area calculation techniques and some measure of gradation such as Fineness modulus. The Fineness Modulus concept has been shown to not always be unique to a given gradation because the same FM can be calculated from different gradations. However, the FM of the sand is still used in the commonly specified ACI 214 method of mix design. It was recognized early that gradations should be well-graded and specifications reflected this understanding.

At some point, the intermediate size of the overall aggregate gradation started to be removed for use in other products, and typical practice evolved into the use of two distinct aggregate fractions, coarse and fine, for routine production of concrete. Many times this left the gradations in a gap-graded state. In the early 1970's, Shilstone began to propose that the industry revert to a more well-graded set of materials. He developed and promoted the evaluation of total gradations by the following: 1) on a volume basis, not a weight basis, 2) the individual percent retained plot, 2) the Coarseness Factor Chart, and 4) the 0.45 power

gradation plot. The use of aggregate fractions that would supply the missing intermediate (3/8 in. to #30) material was highly recommended. The use of aggregates that would not necessarily meet ASTM C 33 specifications was put forth as a possibility. Although certain state DOT's (Iowa, Minnesota, Kansas, Washington) as well as other specifying agencies (ACPA, MCIB, USAF) have formally adopted some form of the concept of optimization of aggregate gradations, a number of other states are in the stages of considering optimization and allowing it on an experimental, case-by-case basis. Based on discussions on the internet, private industry seems to have moved forward more quickly than the public sector. Several commonly used specifications contain language permitting/ encouraging/recommending the use of aggregate gradation optimization, including ASTM C 33, ACI 301, ACI 302, and ACI 304.

A side issue related to the general concept of optimization is the so-called "8-18" band. The concept is to keep the amount of material retained on the individual sieves between 8 and 18 percent on the sizes of about the #30 sieve up to about the nominal maximum size. Much controversy swirls about this idea. Opinions range from total adoption as a rigid requirement to outright antagonism and denial that it will ever be practical. The consensus, even among specifiers, seems to be that the 8-18 (or 8-22) should be used as a guide and an ideal to strive for, not a rule, knowing that absolute adherence may be too costly to be of practical use.

Concurrent with the Shilstone movement is the growing body of specifiers that want a return to coarser, higher FM sands to get away from water demand-related shrinkage issues.

Most reports of the use of aggregate optimization point out the benefits of using a more well-graded material, including less paste and hence less concrete shrinkage, greater strengths, better pumpability, and enhanced finishability. Well-graded mixtures tend to not have as many problems as gap-graded mixes do in terms of pavement edge slump, segregation during vibration, finishing, raveling at joints, and wear-resistance. One of the main benefits of characterizing the mix as a single point on a Coarseness Factor-type chart is the ability to adapt to changing gradations in a timely manner.

Concern about the practicality of producing optimized aggregates centers on the difficulty in producing the gradations, especially coarser sands, in quantities large enough for typical jobs. Extra equipment may have to be purchased, extra handling may be involved, extra shipping costs may be present, and some natural sources of materials may not be conducive to providing the missing sizes.

When discussing aggregate gradation optimization, the great preponderance of the literature focuses on Shilstone-like analyses. Very little mention is made of the aggregate packing model developed under the SHRP research program. The one report not connected with the research project indicated that mixes produced

via the packing manual tended to be harsh, and more work was need for the manual to become useful.

One caution about trying to overcome a gap-graded mix by adding an intermediate size aggregate is that the particle shape must at least be compact, and preferably rounded. If the intermediate aggregate is flat and elongated, the result may be quite far from what was intended.

Guidance has been given in regard to achieving an optimized gradation, including the use of non-standard aggregates as a way of producing an overall optimized gradation. The concept of additional bins at material plants is a hurdle that the asphalt industry has surmounted, and the concrete industry needs to seriously consider.

A brief analysis of current MoDOT specified limits on gradations was undertaken. The fact that not all sieve sizes necessary for analysis are present in each of the MoDOT coarse aggregate specifications was considered. Depending on which side (fine or coarse) the gradations were running in relation to the limits, various combinations of sand and coarse aggregates A, B, or D were all over the Coarseness Factor chart, with behavior ranging from rocky to good to sandy.
In general, looking at the A, B, and D gradations, if actual gradations are allowed to run on the coarse side of the stone and the sand, the mixtures may be expected to be rocky and harsh. Conversely, gradations that run on the fine side of the sand and the coarse side of the stone may be sandy. Several of those that

run down the middle of the limits are borderline gap–graded, especially considering daily fluctuations in gradation. Some of the mixes could be expected to perform well, while some may do well subject to daily gradation changes.

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REFERENCES

ACI, (1996). United States Air Force Guide Specification, Military Airfield Construction, Rigid Airfield Pavement Surface. U. S. A. Force**:** 1-33.

Abrams, D. A. (1918). "The Basic Principles of Concrete Mixes." Mining and Scientific Press: 23-24.

Abrams, D. A. (1918). "Design of Concrete Mixtures." Bulletin No. 1, Structural Materials Research Laboratory: 1-22.

Abrams, D. A. (1919). "Correct Proportioning of Concrete Mixes." American Architect **115**(2265): 721-733.

Abrams, D. A. (1919). "Design of Concrete Mixtures." Concrete **14**(5): 191-195.

Abrams, D. A. (1919). "How to Design Concrete Mixtures." Engineering News Record **82**(16): 758-763.

Abrams, D. A. (1919). "Tests Do Not Bear Out the Surface Area Method." Canadian Engineer **36**(26): 566-569.

Abrams, D. A. (1922). "Scientific Methods of Making Concrete." Chemistry and Industry **42**(46): 1094-1098.

ACI (1985). Standard Practice for Selection of Proportions for Normal, Heavyweight, and Mass Concrete. Farmington Hills, Michigan, American Concrete Institute. **ACI 211.1:** 32.

ACI (1996). Guide to Concrete Floor and Slab Construction. Farmington Hills, Michigan, ACI. **302.1R-96:** 65.

ACI (1996). "Placing Concrete by Pumping Methods." **304.2R-96**: 25.

ACI (1999). Specifications for Structural Concrete. Farmington Hills, Michigan, ACI. **301-99:** 49.

ACI (2000). Guide to Measuring, Mixing, and Placing Concrete. Farmington Hills, Michigan, ACI. **304R-00:** 41.

ACPA (1989). Fast Track Concrete Pavements. Technical Bulletin TB-004.0 IT. Arlington Heights, Il.**:** 31.

Anderson, P. J. and V. Johansen (1993). A Guide to Determining the Optimal Gradation of Concrete Aggregates, SHRP-C-334. Washington, D.C., Strategic Highway Research Program, National Research Council**:** 200.

Anonymous (1990). "Doing More With Less: Optimizing Concrete Mix." Better Roads **6**(8): 18-25.

ASTM (1991a). Standard Method of Test for Unit Weight and Voids in Aggregate C-29. West Conshohocken, Pa., ASTM. **V. 04.02:** 4.

ASTM (1994). Specifications for Concrete Aggregates C-33. West Conshohocken, Pa., ASTM. **04.02:** 8.

Besson, F. S. (1935). "Case Against Surface Area and Fineness Modulus." Engineering News Record **114**(7): 248-249.

Blanks, R. F., E. N. Vidal, W. H. Price and F. M. Russel (1940). "Properties of Concrete Mixes." American Concrete Institute Journal **11**(5): 433-475.

Casteel, W. (2004). Arkansas DOT**:** Personal Communication.

Cox, K. P. (1993). "Evaluation of the Stretegic Highway Research Project Packing Handbook." Pacific Rim Transtech Conference Proceedings: 405-417.

Cramer, S. M. and A. J. Carpenter (1999). "Influence of Total Aggregate Gradation on Freeze-Thaw and Other Performance Measures of Paving Concrete." Transportation Research Record **1668**: 1-8.

Cramer, S. M., M. Hall and J. Parry (1995). "Effect of Optimized Total Aggregate Gradation on Portland Cement Concrete for Wisconsin Pavements." Transportation Research Record **1478**: 100-106.

Crouch, L. K., H. Sauter and J. A. Williams (2000). "92-MPa Air-Entrained HPC." Transportation Research Record **1698**: 24-29.

Dirks, D. (2004). Illinois DOT**:** Personal Communication.

Dunagan, W. M. (1940). "The Application of Some of the Newer Concepts to the Design of Concrete Mixes." Proceedings, American Concrete Institute **36**: 649-673.

Edwards, L. N. (1918). "Proportioning of Mortars and Concretes by Surface Area of Aggregates." Proceedings, ASTM **18**(Part II): 235-283.

Egan, B. (2004). Tennessee DOT**:** Personal Communication.

Frost, R. J. (1967). "Rationalization of Trial Mix Approach to Concrete Mix Procedure and Concrete Construction." American Concrete Institute Journal **64**(8): 499-509.

Fuller, W. B. and E. Thompson (1907). "The Laws of Proportioning Concrete." ASCE Transactions **LIX**: 67-118.

Gilbert, L. C. and H. F. Kriege (1930). "The "Missing Link" in Concrete Aggregate." Rock Products: 55-65.

Goldbeck, A. T. (1928). "The Effect of Gradation of Crushed Stone on Percentage of Voids." Crushed Stone Journal **4**(9): 1-5.

Goldbeck, A. T. (1928). "Gradation and Character of Aggregates as a Workability Factor." Engineering and Contracting **67**(5): 270-272.

Goldbeck, A. T. (1929). "Further Tests on Crushed Stone and Gravel Concrete." Crushed Stone Journal **5**(5): 3-9, 28.

Goldbeck, A. T. (1931). "Design of Concrete for Workability." Pit and Quarry **22**(5): 36-42.

Goldbeck, A. T. (1946). "Proportioning of Concrete." Concrete **54**(5): 18-20.

Goldbeck, A. T. (1950). "Concrete-Its Proportioning and Properties." Miunicipal Engineers Journal **36**: 73-91.

Goldbeck, A. T. (1968). (11).

Goldbeck, A. T. (1968). "Method for Proportioning Concrete for Compressive Strength, Durability, and Workability." National Crushed Stone Assoc., Inc. Bulletin(11).

Goldbeck, A. T. and J. E. Grey (1942). "Method for Proportioning Concrete for Compressive Strength, Durability, and Workability." National Crushed Stone Assoc., Inc. Bulletin(11): 3-20.

Goldbeck, A. T. and J. E. Grey (1965). "Method for Proportioning Concrete for Compressive Strength, Durability, and Workability." National Crushed Stone Assoc., Inc. Bulletin(11): 34-38.

Hanson, T. D. (1996). Improved Aggregate Gradation for Portland Cement Concrete Mixes, Iowa DOT. **Research Project HR-563:** 18.

Harrison, P. J. (2004). "For the Ideal Slab-on-Ground Mixture." Concrete International **26**(3): 49-55.

Hewes, L. I. (1924). "Analysis of Grading Curve for Concrete Aggregates." Engineering News Record **93**(6): 222-262.

Hobson, K. R. (2004). QA and IAS Manager. Oklahoma City, OK, Oklahoma DOT**:** Personal Communication.

Holland, J. A. (1990). "Mixture Optimization." Concrete International **12**(10): p. 10.

InDOT (2004). Supplemental Specifications, Concrete Pavement, Section 500, Indiana DOT**:** p.502.

IowaDOT (2002). Supplemental Specifications for Quality Management Concrete SS-01015, Iowa DOT**:** 6.

IowaDOT (2003). "Quality Management and Acceptance of PC Concrete Pavement IM 530." 5.

IowaDOT (2004). "Aggregate Proportioning Guide for PC Concrete Pavement IM 532." 8.

Joel, R. N. (1990). A Method for Controlling Concrete Workability Using Aggregate Gradation Control. Rolla, Missouri, University of Missouri-Rolla. **MS:** 318.

KansasDOT (2004). "Aggregates for Concrete, Special Provisions, Section 1102." 10.

KansasDOT (2004). Optimized Portland Cement Concrete, Special Provisions, Sections 402/502/1102, Kansas DOT**:** 3.

KansasDOT (2004). "Portland Cement Concrete Pavement, QC/QA, Division 500." 14.

Kennedy, C. T. (1940). "The Design of Concrete Mixes." American Concrete Institute Journal **36**: 373-400.

Kosmatka, S. H., B. Kerkhoff and W. C. Panarese (2002). Design and Control of Concrete Mixtures, 15th Ed. Skokie, Illinois, Portland Cement Association**:** 358.

Lafrenz, J. L. (2001). Material Selections to Minimize Early Cracking Of Concrete Pavement Panels. 2001 Missouri Concrete Conference, Rolla, Missouri.

MCIB (2000). Concrete Standards, Sections 3-1 and 4-4. Kansas City, Missouri, Mid-West Concrete Industry Board**:** 10,14.

McMillian, F. R. (1929). "Basic Principles of Concrete Making." Engineering News Record **102**(15-19): 580-583, 625-632, 673-679, 705-709, 748-752.

Meininger, R. C. (2003). 8 to 18 Percent or Fight. Rock Products Website, Rock Products**:** 2.

Mercer, L. B. (1948). "The Fineness Modulus Fallacy." The Commonwealth Engineer: 316-320.

MnDOT (2004). "Concrete Paving, Section S-112, Special Provisions." 11.

MnDOT (2004). "High Perfomance Concrete Paving, Section SP-111,Special Provisions." 11.

MoDOT (2004). Aggregate for Concrete, Section 1005, Standard Specifications. Jefferson City, Missouri, Missouri DOT**:** 4.

MoDOT (2004). Concrete, Section 501, Standard Specifications. Jefferson City, Missouri, Missouri DOT**:** 10.

Muszynski, L. C. (1996). Engineering Technical Letter (ETL) 97-5: Proportioning Concrete Mixtures with Graded Aggregates-A Handbook for Rigid Airfield Pavements. U. S. A. Force**:** 1-50.

Parry, J. (2004). Wisconsin DOT**:** Personal Communication.

PCA (1925). Design and Control of Concrete Mixtures. Chicago, Il, Portland Cement Association. **1**.

Phelan, W. S. (2004). "Admixtures and Aggregates: Key Elements in "Athletic Concrete" Revisited." Concrete International **26**(9): 40-43.

Roy, D. M., P. D. Cady, S. A. Sabol and P. H. Licastro (1993). Concrete Microstructure: Recommended Revisions to Test Methods, SHRP-C-339. Washington, D.C., Strategic Highway Research Program, National Research Council**:** 107.

Roy, D. M., B. E. Scheetz, R. I. A. Malek and D. Shi (1993). Concrete Components Packing Handbook, SHRP-C-624. Washington, D.C., Strategic Highway Research Program, National Research Council**:** 161.

Russell, F. M., J. S. Peck and D. A. Abrams (1940). "The Design of Concrete Mixes." American Concrete Institute Journal **36**: 400-424.

Shilstone, J. M. (1989). "A Hard Look at Concrete." Civil Engineering: 47-49.

Shilstone, J. M. (1990). "Concrete Mixture Optimization." Concrete International **12**(6): 33-39.

Shilstone, J. M. (1990). Mixture Optimization for Fast-Track. 69th Annual Transportation Research Board Meeting, Washington, D.C.

Shilstone, J. M. (1993). "Research for SmartPlant." 24.

Shilstone, J. M. and J. M. Shilstone Jr. "Interpreting Mix Design Submittals in the seeMIX Format." Newsletter: 1-7.

Shilstone, J. M. and J. M. Shilstone Jr. "Rationalizing Concrete Paving Mixtures." Newsletter: 4.

Shilstone, J. M. and J. M. Shilstone Jr. (1987). Practical Concrete Mixture Proportioning Technology, Reference Manual, Shilstone Software Co.

Shilstone, J. M. and J. M. Shilstone Jr. (1989). "Concrete Mixtures and Construction Needs." Concrete International **11**(12): 53-57.

Shilstone, J. M. and J. M. Shilstone Jr. (1992). "Pending ASTM-ACI Changes." Newsletter No. 1: 1-10.

Shilstone, J. M. and J. M. Shilstone Jr. (1996). "Standards Changes In Process." Shilstone Software News(2): 4.

Shilstone, J. M. and J. M. Shilstone Jr. (1997). "Concrete Mix Analysis-Interpreting the Coarseness Factor Chart." Newsletter: 1.

Shilstone, J. M. and J. M. Shilstone Jr. (1997). "Concrete Performance Is Predictable -A Comparison of Two Mixtures." Newsletter: 1.

Shilstone, J. M. and J. M. Shilstone Jr. (1999). "The 8-18 Spec and Coarseness Factor Chart." Shilstone Software News(4).

Shilstone Jr., J. M. (2004). "The 8-18 Rule." Concrete Construction Online.

Shilstone Jr., J. M. (2004). seeMIX II for Windows User Manual. Dallas, Texas, The Shilstone Companies, Inc.

Talbot, A. N. and F. E. Richart (1923). "The Strength of Concrete and Its Relation to the Cement, Aggregate, and Water." Bulletin No. 137: 1-116.

Taylor, M. A. (1986). "Concrete Mix Proportioning by Modified Fineness Modulus Method." Concrete International: 47-52.

USAF (1997). United States Air Force Guide Specification, Military Airfield Construction, Rigid Airfield Pavement Surface. U. S. A. Force**:** 1-33.

Various (2002-2003). Q & A Forum, Aggregate Research Institute.

Walsh, H. N. (1933). "Simplified Concrete Mix Design." American Concrete Institute Journal **5**(2): 110-120.

WashingtonDOT (2004). "Combined Aggregate Gradation for Portland Cement Concrete, Standard Specifications, Section 9-03.1(5)." 1.

Weymouth, C. A. G. (1933). "Effect of Particle Interference in Mortars and Concrete." Rock Products **36**(2): 26-30.

Weymouth, C. A. G. (1938). "Designing Workable Concrete." Engineering News Record **26**: 818-820.

Whitten, B. N. (1998). An Improved Aggregate Gradation for Tennessee Portland Cement Conncrete Bridge Deck Mixtures. Cookeville, Tennessee, Tenessee Technological University. **M.S.:** 102.

Wig, Williams and Gates (1916). "Strength and Other Properties of Concrete as Affected By Materials and Methods of Preparation." Technical Papers of the Bureau of Standards(58).

Williams, G. M. (1922). "Some Fallacies in Concrete Proportioning Theories." Engineering Journal **5**(9): 465-468.

Wilson, G. (2004). Nebraska DOT**:** Personal Communication.

Wilson, P. and D. N. Richardson (2001). Aggregate Optimization of Concrete Mixtures. Rolla, Missouri, University of Missouri-Rolla**:** 18.

Young, R. B. (1919). "Some Theoretical Studies on Proportioning Concrete by Method of Surface Area of Aggregate." Proceedings, ASTM **19**(Part II): 444-509.

Young, R. B. (1921). "Three Methods of Proportioning Concrete." Engineering and Contracting: 87-91.