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NOTES ON THE EFFECTS OF AGGREGATE GRADATION VARIATION ON SLURRY SEAL MIX DESIGN TESTS

OR:

TOWARDS A MORE RATIONAL SLURRY DESIGN METHOD

BY:

C. ROBERT BENEDICT, CONSULTANT
ISSA DIRECTOR OF RESEARCH

C/O POLYMAC CORP., ALPHA LABS.
P.O. BOX 74; ALPHA, OHIO 45301
PHONE: 513-298-6647
FAX: 513-426-3368

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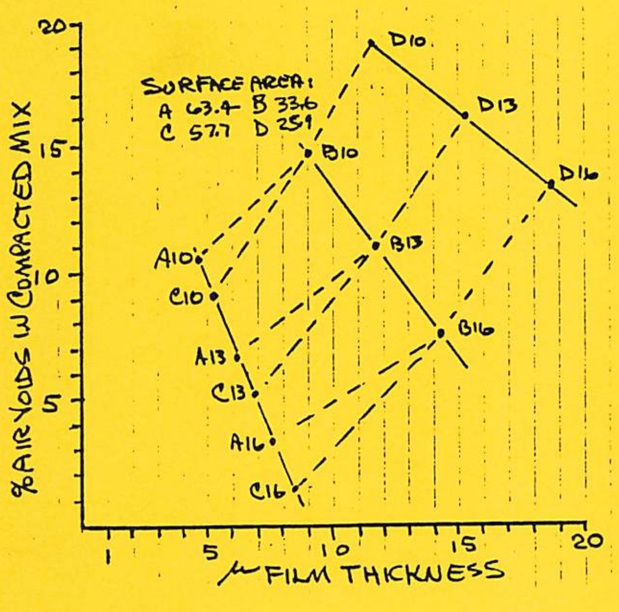

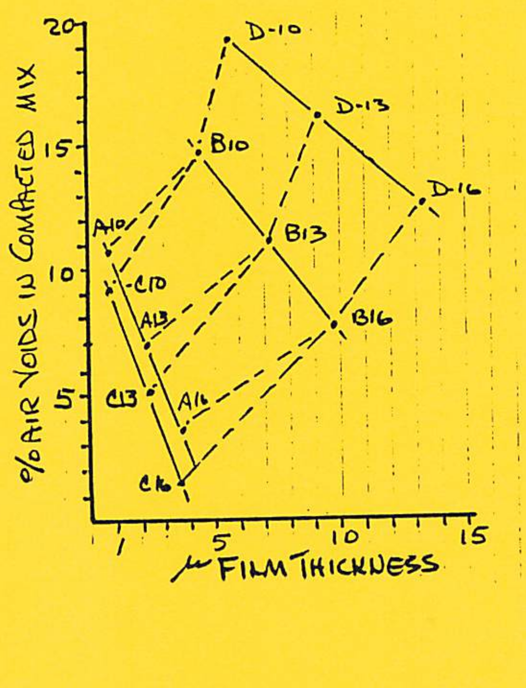

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INTRODUCTION

Since the beginning of the Slurry Technique we have searched for a method which would tell us, with precision, how much emulsion a given slurry should contain.

Through experience alone the old timers would say "---enough to stick it down and enough to keep it black". Too often, the "---it-looks-about-right" method of design failed to advance the industry. Kari and Coyne (1) with their development of the Wet Track Abrasion Test published in 1964 were the first to relate field performance to a laboratory test with the 75 g/SF WTAT loss to establish a minimum bitumen content. In 1962 Bernard and Raymond Young (2) produced their first "doughnut" Wet Track Machine which was used at Texas A & M in 1963 and 1964 for a study on fillers by Harper, Jimenez and Galloway (3) published in HRB Record #____1965.

Work proceeded in Kansas by Lynn Baldwin (4) and in California by Skog and Zube (5) and in Texas by Fiock (6) (6a) and at Bitumuls/ Chevron was continued by McCoy, Goodrich, Schmitz, Ed Rogers, et.al. (7) published in the late 60's and early 70's. More recently Scrimscher (8) at Caltrans presented new techniques using the Caltrans Shaker Test and Bolzan (9) has refined the method. All of this work was concerned with wear rates of slurry and used a variety of abrasion devices, where only MINIMUM asphalt contents were established. The tendency in that period was to use 18 to 20% emulsion contents, well above the MINIMUM requirements. Many of these slurrys were relatively rich.

In 1975 the author introduced the Loaded Wheel Test (10) which simulated the effect of rolling traffic and attempted to quantify the MAXIMUM safe bitumen content by noting surface tackiness and measuring sand adhered to the surface of a compacted specimen as related to the A-B test road results. (ISSA TB 109, 1976) (11).

By this time typical slurries were using coarser gradations of more discreetly selected aggregate sources. The typical emulsion contents dropped to the 15-17% range.

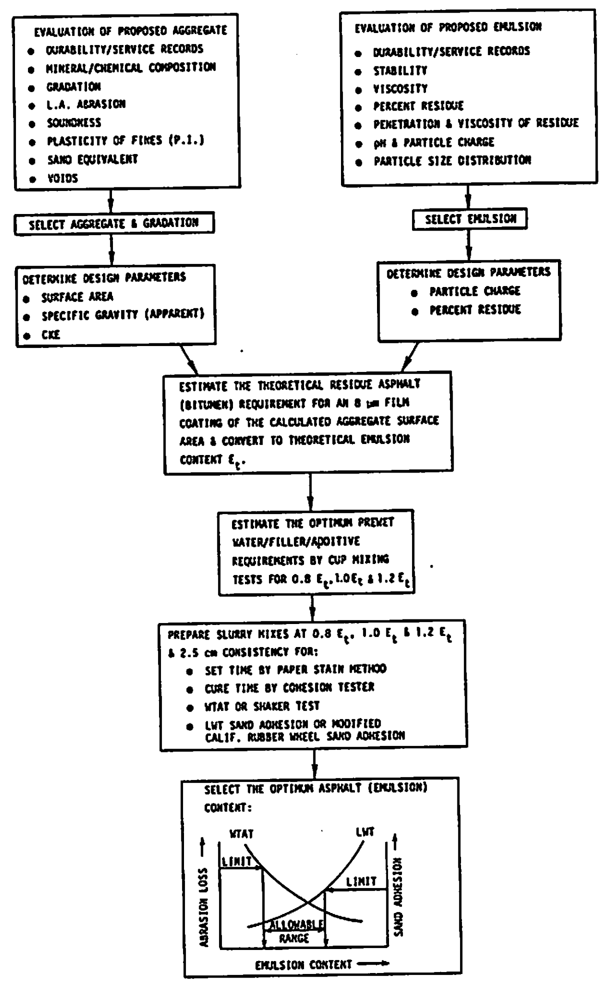
Also in 1975 when the Godwin (12) US Army Instruction Report WES S-75-1 (Surface Area Method of Slurry Design) was published, surface area analysis had already been discarded by many technologists with the 1974 A-B test road results where a 2.5 micron coating performed beautifully (13). Today, 15 years and 100 million vehicles later, enough of the test remains to verify these findings. 8.0 and even the 6.5 micron coatings suggested by Lee (14) can be greatly excessive.

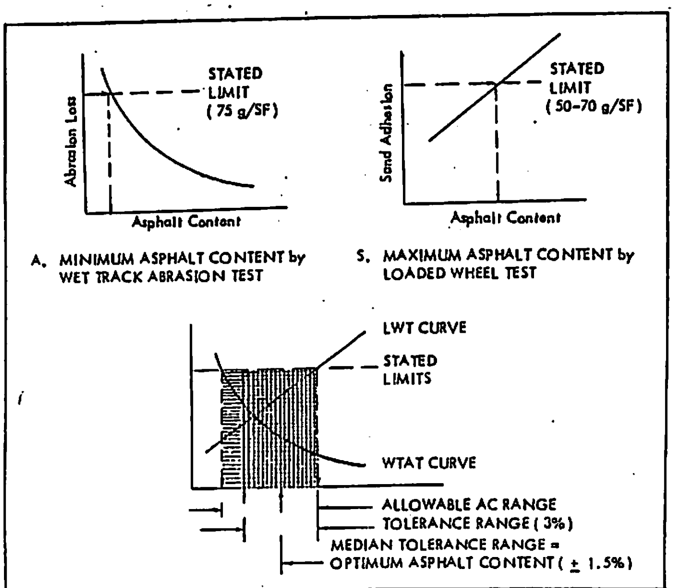
In 1977 ISSA Technical Bulletin #111 offered a comprehesive, emperical method of slurry design which incorporated the WTAT to establish a minimum and the LWT to establish the maximum emulsion. The optimum was selected between the two points as close to the maximum as field tolerances would allow (figure 1).

Lee, (14) published their "Laboratory Study of Slurry Seal" in 1978 which included with the same method but incorporated surface area design to establish the test specimen quantities. (Figure 2).

These new design techniques were successfully applied for the first time in 1977 to ODOT SR 42, SR 35 and SR 65 (15). The method has been used for many successful designs over the past 12 years.

Slurry Seal Design Flow Chart





GRAPHICAL DETERMINATION OF OPTIMUM ASPHALT CONTENT

In 1980 (16) and 1983 (17), new classes of high performance emulsifiers were introduced to the market place along with improvements in the selection of quality aggregates and improvements in proportioning, mixing and laying equipment. The result has been greatly improved systems which require a further reduction in bitumen to the 12-15% range and even as low as 9% emulsion (5.5% AC).

At the same time, new testing methods and laboratory equipment has become available and is being increasingly used in laboratories the world over. Communication among laboratories has been facilitated by ISSA papers presented notably at the Madrid (18), Guadalahra (19) and Geneva (20) World Congresses, have stimulated more design and research so that great progress has been made.

With these new materials and mixing methods the typical test values for the 1 hour soak WTAT no longer apply. The 1/4" LWT sand adhesion values of 10 years ago, no longer gives precise indications of optimum AC contents. Since the sand adhesion slopes are now typically too flat according to U (21) of the CEDEX lab in Madrid.

Wide variations in test results are seen and the designer is left up in the clouds to subjectively select the optimum emulsion contents.

Variations in field application as seen by extraction results (22) were quite perplexing and, to this day, sometimes still are, though great strides in the improvement of proportioning and mix uniformity have been made with the newer construction equipment.

Still, the problem of quarry and stockpile gradation variation and fines-coarse segregation is a daily occurance. Even in the laboratory where small samples are removed from sample buckets, even after repeated splitting or quartering, fines separation is quite common. The effect of this separation on small specimen test results can be a very serious matter. This segregation factor alone accounts for reduced precison and reproduceability of results. We have noted variations not only in lab samples but also in field samples from 5 to 18% 0/#200 and 10 to 50% in #4 to 3/8". We assume that similiar variations occur within the mid-range sizes.

The phone rings and the man says you designed this mix at 14% 0/200 and we're testing only 5 to 6% 0/200. How should we adjust the emulsion content?

The phone rings and the man says "I just spent $80,000 on a rut filling demonstration and its already re-rutting in spots-- bad. Why didn't we fix the ruts? We bucket blended chips with type 2 aggregate everything went down nicely. Extractions varied from lean to rich but within specs and the gradation varied, but everything was within spec."

The phone rings, more than I like to think about, and the man says, "My runway is shut down because the big stones come out. The asphalt acts like melted grease -- doesn't stick the stones down."

These problems were mostly due to gradation though everything was within the ISSA guidelines, the mix applications functioned as advertised.

There is an obvious problem in the current "State-of-the-Art" design technique since the test responses to the new materials no longer tell us reliably (if they ever did) what the precise optimum emulsion content should be.

We hasten to say that, in our opinion, the WTAT loss of 75 g/SF (24.5 grams) is as valid today as 25 years ago but the test is now only an evaluation tool, not a design tool. We also believe that the 1/4" LWT sand adhesion test is a valid test, but we've found out not a specific design tool; rather, it will clearly identify excess surface asphalt or asphalt surface flotation and to some extent the macrotexture characteristics of compacted specimens.

Recent studies (23) have used modified Marshall Stability and Flow, the Multilayer Loaded Wheel Test, Vertical and Lateral Displacements and the High Temperature British Wheel Tracking Test. The Marshall test is not a satisfactory tool for emulsion mixes, we believe, because it doesn't even come close to simulating field conditions. Many times we've found that the highest Marshall stabilities have the poorest field results. The LWT does simulate traffic more closely and does predict the effects of traffic compaction as well as optimizing the bitumen content when multilayer compaction curves are used (24).

Lee (25) and Ordemir (26) and Sang Soo Kim (27) have shown the relationship of bitumen content, mix voids and macrotexture. They each have suggested that analysis of voids and their relation to mix performance might bear fruit. (Figure 3).

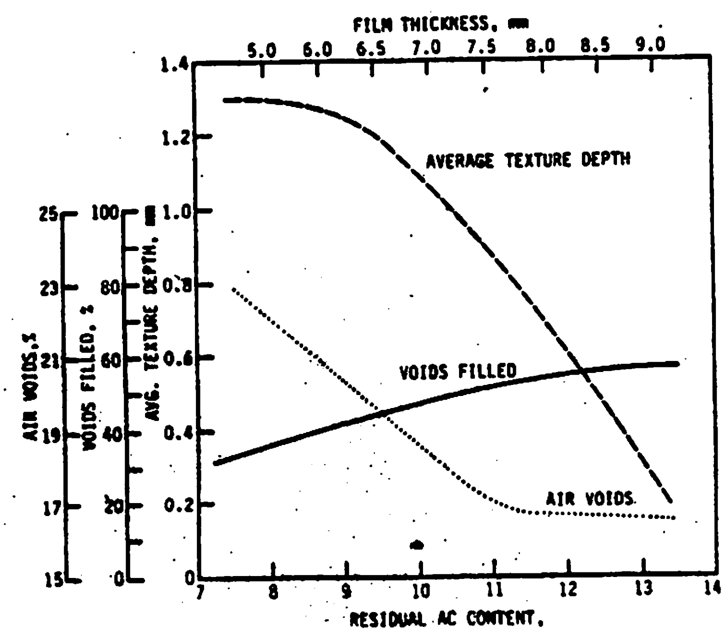


Fig. 4 : Relationship between residual asphalt content, film thickness, air voids, voids filled, and texture depth, Series II, L1.

Jones and Ng (27) reported here last year their correlation of 3 WTAT machines. Their testing program used 3 different aggregates but each of the some 180 specimens was graded to the identical gradation. Because of the care taken within sets, their reproducibility and repeatability was one rarely seen in most laboratories.

In a parallel study (28), we used a single aggregate, as received, for some 170 WTAT specimens. Though carefully split, we experienced a wider variation than did Jones and Ng: Ordemir and Kim also experienced wide variations with some 1000 WTATs.

One likely source of these variations is segregation in the aggregate samples.

OBJECTIVES OF STUDY

In the suspicion that aggregate gradation variation plays a role in our testing procedures, we performed a few laboratory tests and a few calculations to look at the effects of gradation, voids and surface area on a few of our laboratory design tests.

It was the purpose of these experiments to determine the effects of gradation variation on the slurry design tests which we use as standard procedure at our Alpha laboratory and to then to compare the results of our testing program with mix properties, some of which are not commonly used in slurry design as suggested by Lee, Ordemir and Kim.

The mix design tests were:

60 minute Wet Cohesion (ISSA TB 139) with trial mixes.
60C Cured Cohesion (ISSA TB 139 and ref #29)
1-Hour Soak Wet Track Abrasion Test (ISSA TB 100)
6-Day Soak WTAT (ISSA TB 100 & ref #30)
Loaded Wheel Test 1/4" C109 Sand Adhesion (ISSA TB 109)
LWT Multilayer Vertical and Lateral Displacements (ISSA TB 109 and #( ) & ( )

Mix design Tests compared with other properties:

Compacted Bulk Specific gravity and Density
Voids in the Mineral Aggregate
Percent Voids Filled
Air Voids in the Compacted Mix
Surface area-calculated
Absorbtion by Centrifuge Kerosene Equivalent
Bitumen film thickness - micron coatings

For our initial experiments, we selected the extreme gradations allowed by the ISSA type 2 and type 3 specifications. These gradations are inclusive of most of the Slurries applied in the U.S. Our Sandusky, Ohio Dolomite reference aggregate was used in combination with 1% type 1 portland cement and a CSS 1h/CQS 1h production emulsion which used our #320 emulsifier and a Chevron "Oceangrade" (Paskagoola) blended-crude bitumen. The emulsion contained 62% residue.

AGGREGATE GRADATION & PROPERTIES:

Table 1 gives the gradation and properties while Figure 4 is a plot of these gradations on a .45 power maxium density gradation chart. A and C have 15% 0/200 while B and D have only 5% 0/200. B and C each have 10% #4-5/16". D has 30% #4-5/16" while A has none. We removed all 3/8" material and used only the 5/16" (8 mm) for the coarse fractions.

Figure 5 is a graph comparing the properties tabulated in Table 1. Note the obvious wide variations in densities between the fine and coarse gradations. VMA is reduced in the high fines gradations while VMA increases with reduced fines and increased coarse aggregate.

U.S. SIEVE NO.	PERCENT PASSING A 2f	B 2c	C 3f	D 3c
3/8"	100	100	100	100
5/16"	100	100	100	100
1/4"	---	---	---	---
#4	100	90	90	70
8	90	65	70	45
16	70	45	50	28
30	50	30	34	19
50	30	18	25	12
100	21	10	18	7
200	15	5	15	5
325	--	--	--	--
SAND EQUIVALENT	67	83	67	83
APPARENT SPECIFIC GRAV.	2.65	2.65	2.65	2.65
BULK GRAVITY, COMPACTED	2.03	1.94	2.07	1.88
UNIT WEIGHT, PCF COMP	126.0	121.0	129.2	117.3
BULK GRAVITY, LOOSE				
UNIT WEIGHT PCF LOOSE				
VOIDS IN MINERAL AGG.	23.4	26.8	21.9	29.1
SURFACE AREA, SF/LB	63.4	33.6	57.7	25.9

TABLE 1 AGGREGATE PHYSICAL PROPERTIES

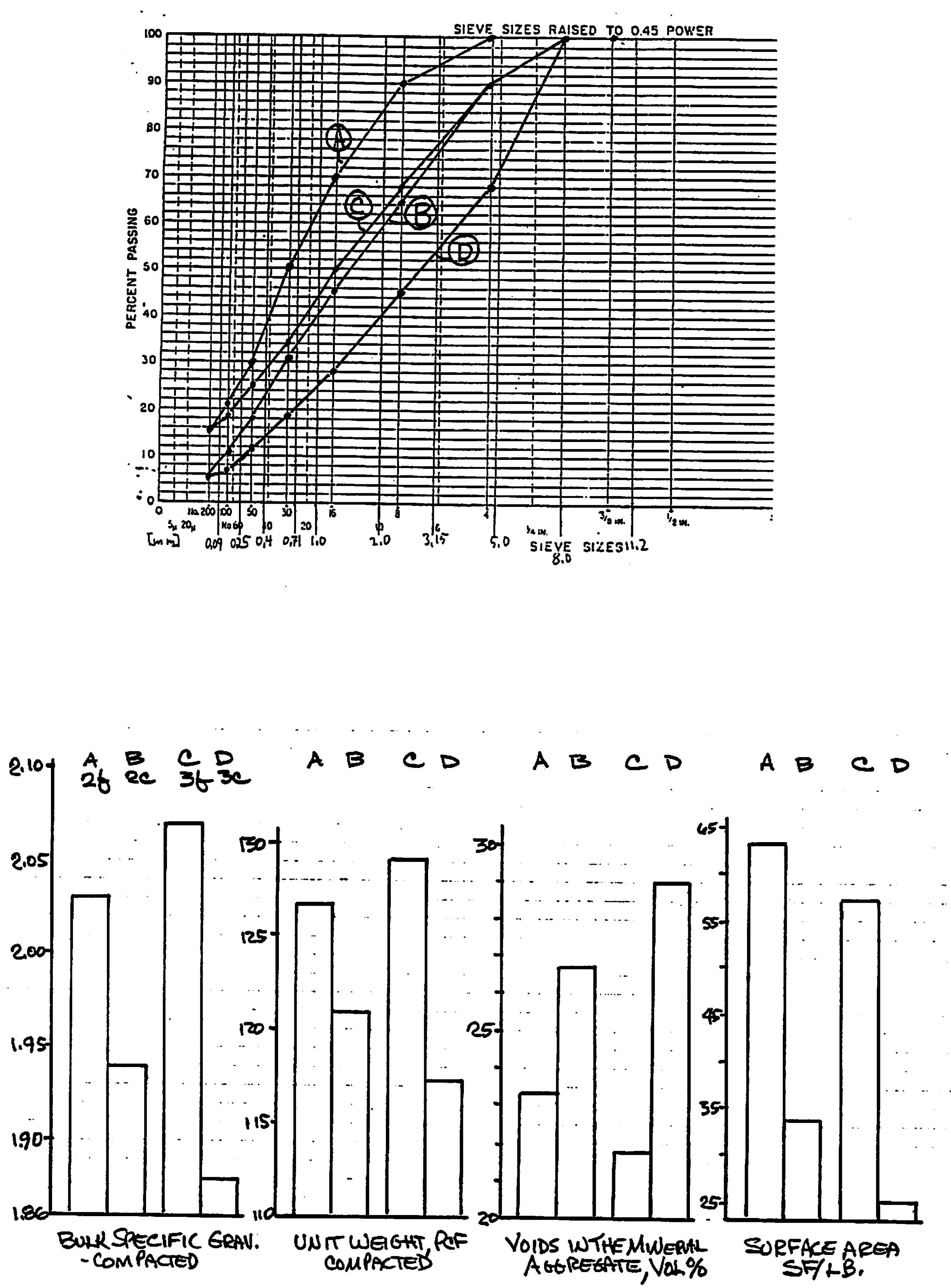


FIGURE 5. AGGREGATE PROPERTIES

SURFACE AREA FILM THICKNESS DESIGN

R.A. Jimenez suggested in 1965 that his surface area design method for hot mix could be applied to slurry seal design (a very different animal). Much was researched and discussed but when we took surface area designs to the field, there were frequent failures due to richness. The US Army WES in their 1975 Instruction Manual S-75-1 (ISSA TB #118) uses this method still today for lack of a better method.

Our calculations for an 8 micron surface area design for aggregate gradations A B C & D are tabulated in Table 2. Figure 5 shows the really dramatic variations in bitumen required by surface area design, air voids in the compacted mix, percent voids filled and the compacted mix densities.

	A	B	C	D
SURFACE AREA, SF/LB.	63.4	33.6	57.7	25.9
CENTRIFUGE KEROSENE EQUIVALENT (CKE)	5.2	3.2	5.2	3.2
PURE ASPHALT REQ'D @ 8 MICRONS % ADDED	15.6	8.7	13.7	8.4
% AE REQ'D @ 62% RES.	25.2	14.0	22.1	13.5
AE, GALS/TON	59.8	34.5	54.2	32.3
VMA	23.4	26.8	21.9	29.1
% VOIDS FILLED	135.5	62.3	129.7	54.0
AIR VOIDS IN COMPACTED MIX	-35.5	11.1	-29.7	13.3
COMPACTED MIX DENSITY PCF,	146.5 + (150.1)	131.7	146.9 + (151.1)	125.7

TABLE 2 SURFACE AREA AND ABSORBTION DESIGN FOR 8 MICRON FILM THICKNESS

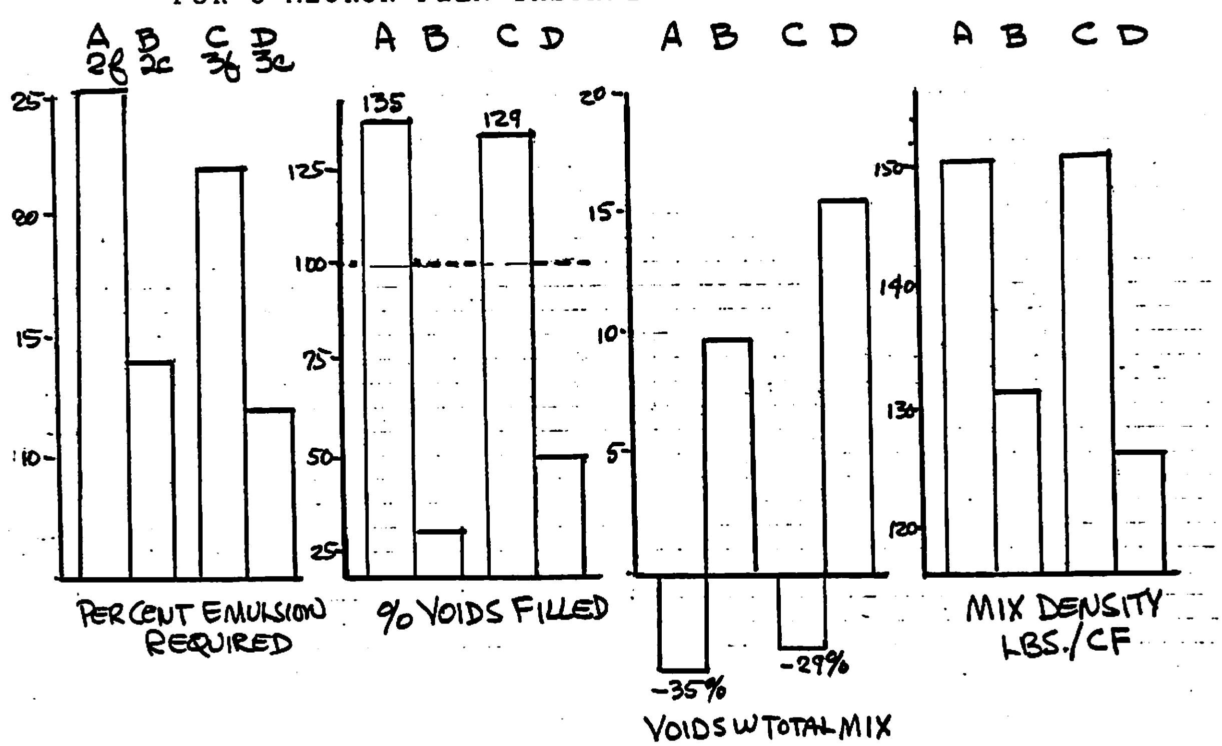


FIGURE 6. — MIX PROPERTIES OF AN 8μ FILM THICKNESS DESIGN / W.E.S. S-75-1 METHOD (ISSA TB 118)

While surface area design may work for hot mixes certain of the concepts are useful in special slurry design problems, it is quite clear from these examples that surface area design is inadequate for slurry design when standard ISSA gradations are used.

We will however compare our test results based on arbitrary 10, 13, and 16% emulsion with the calculated surface areas.

PROPERTIES OF EXPERIMENTAL MIXES

Tables 3 & 4 (appendix) tabulate our calculations for the properties while Figure 7 plots the compacted mix voids against the micron coatings, both by simple surface area and with an allowance for absobtion as determined by CKE (Centrifuge Kerosene Equivalent).

In our experiments with the 4 gradations and 3 emulsion contents, the range of coatings is about .5 to 20 microns and the compacted total mix voids range from (VTM) 1 to 19%.

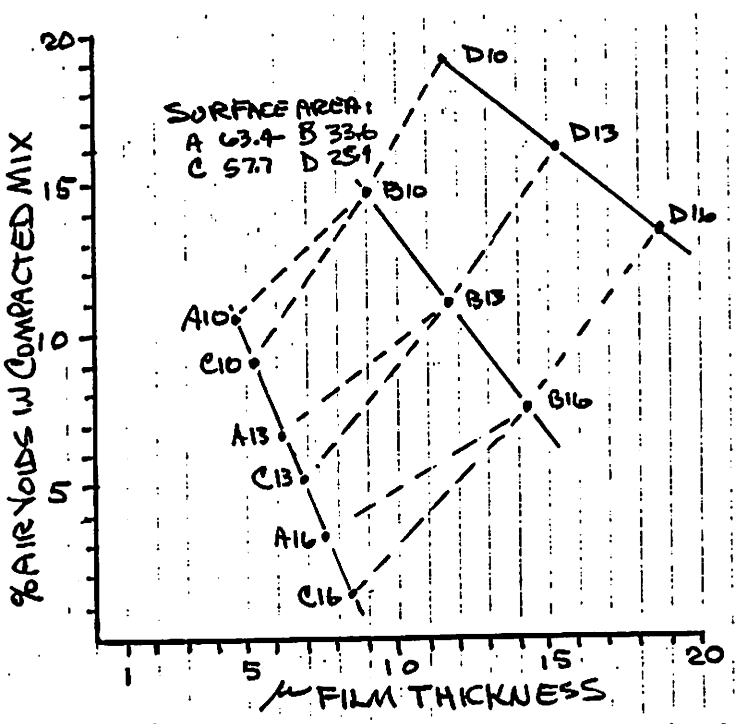


FIGURE 7a SIMPLE SURFACE AREA MICRON COATING VS. COMPACTED MIX VOIDS

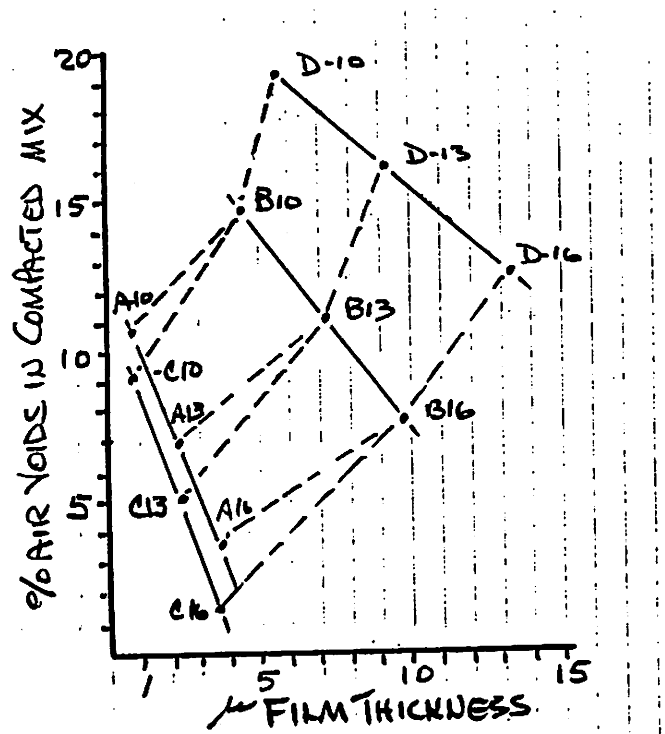


FIGURE 7b. SURFACE AREA + CKE ABSORBTION μ COAT VS. VOIDS

MIX DESIGN TESTS

60-MINUTE WET COHESION

Figure 8 shows that gradations A, B & C to respond to the 60 minute wet cohesoin test in nearly the same way, while D simply died. D has the least surface area, the least bulk gravity and the greatest VMA.

Emulsion reformulation will likely be required to accomodate gradation "D". In this case at least, gradation does affect the 60 minute wet cohesion.

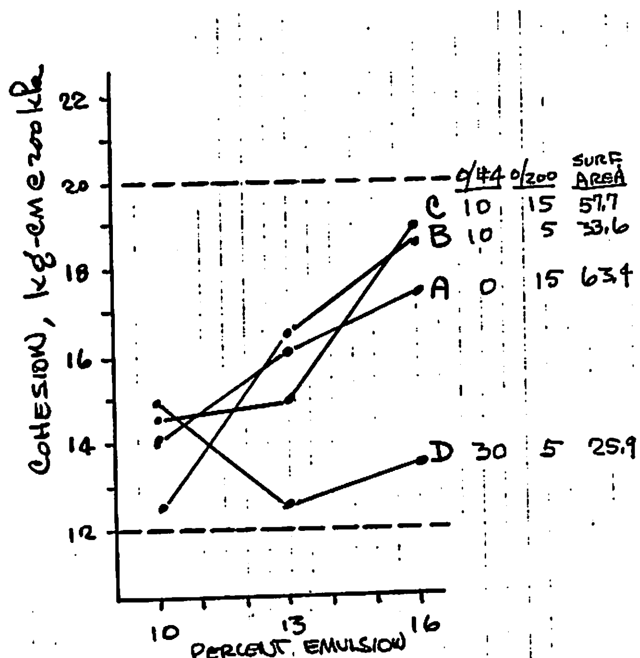


FIGURE 8. 60' WET COHESION

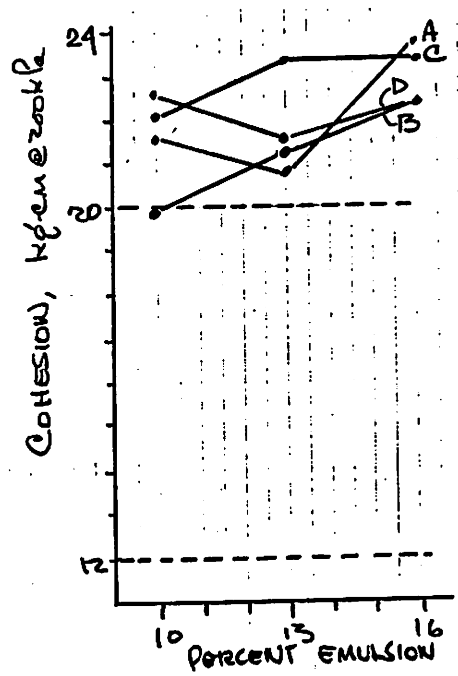


FIGURE 9. 60C CURED COHESION

60C CURED COHESION

Figure 9 results on 60C cured cohesion are inconclusive. This test was performed last and with a different emulsion since the original supply had expired. The values are all unusually high for an unmodified emulsion.

It is noted that at 16% emulsion content A & C and B & D are separately grouped or paired and correspond to the high fines and low fines gradations. The results are inconclusive, but it appears that higher fines contents tend to increase the 60C cured cohesion. This confirms our Geneva Paper on Effects of Filler contents ( ).

WET TRACK ABRASION TEST, ONE HOUR SOAK

Unfortunately, the system was too good for the one-hour soak WTAT to reveal anything interesting. (We find this more and more in our routine design and evaluation work) (Figure 10.)

WET TRACK ARASION TEST 6-DAY SOAK

The 6-day soak WTAT yielded much more interesting or meaningful results as shown in figure 11. The original C-10 specimen failed and was re-run with a different emulsion and still gave unexpectedly high 6-day soak losses. Both type 3's, C & D, showed high losses at the low 10% emulsion contents. A & C (high fines) showed increases in loss with an increase in emulsion content (!) while B and D (low fines) losses are greatly reduced and are essentially the same as the one-hour soak.

This same A-C (fine) and B-D (coarse) pairing as seen in the 60C cured cohesion test occurs in the 6-day WTATs.

There seems to be a relationship in loss increase at 16% AE with A & C (fine) and the very low mix voids of 1.4 and 3.4% compared to the loss decrease in B & D (coarse) at 7.7 and 13.2% mix air voids.

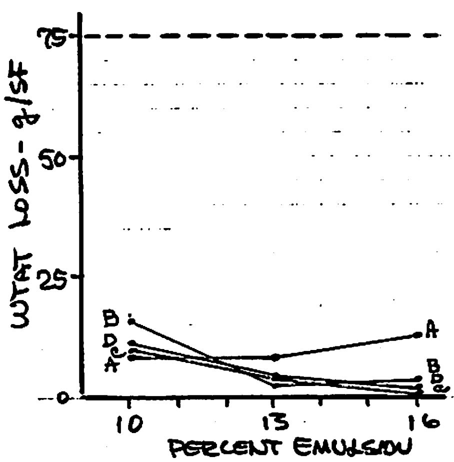


FIG. 10. WTAT - 1-HOUR SOAK

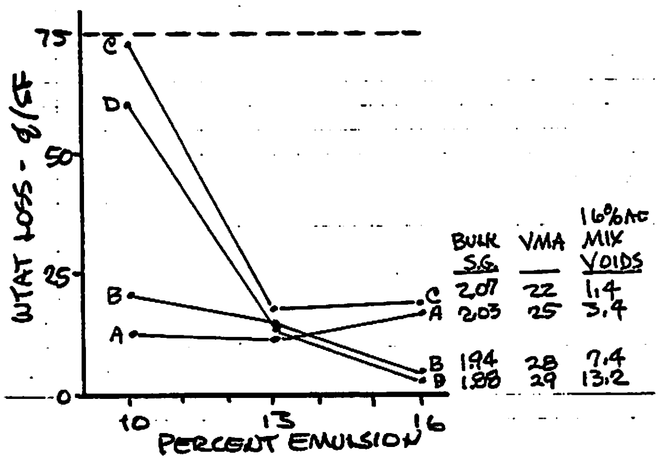


FIG. 11. WTAT - 6-DAY SOAK

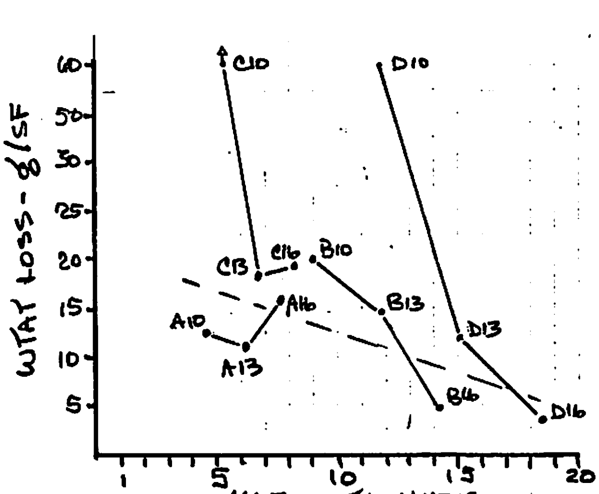


FIGURE 12. WTAT ABRASION LOSS vs. MICRON FILM THICKNESS

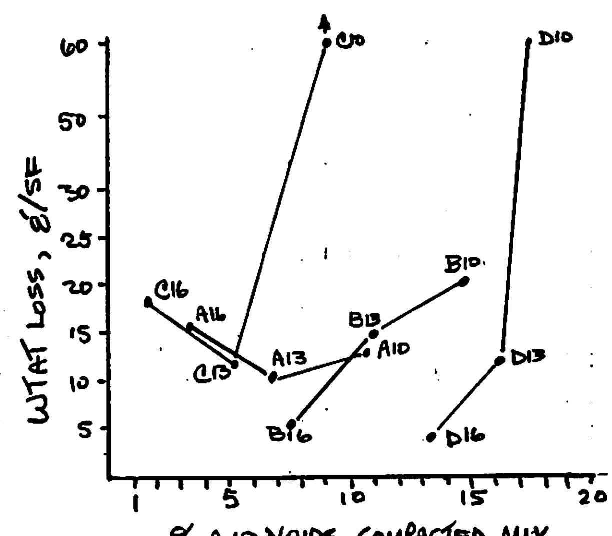


FIGURE 13. WTAT LOSS vs. MIX VOIDS

Figure 12. In general, WTAT losses decreased with an increase in film thickness. It is seen however that specific micron coatings cannot alone indicate a high or low loss; e.g., note the A-10 low loss at 4.5 micron and the very high D-10 loss at 11.5 microns. Note also the curious increase in loss of A-16 and C-16 with an increase in micron thickness. There seems to be a paring of A-C and B-D divided at the 8 to 8.5 micron coating.

Figure 13. There also appears to be a relationship between air voids and the 6-day WTAT loss. We see a general increase in loss with a decrease in voids at the 16% AE content. At 13%, AE loss is constant no matter what the void content and, at the 10% AE level, the reverse is true; i.e., losses increase with an increase in voids!

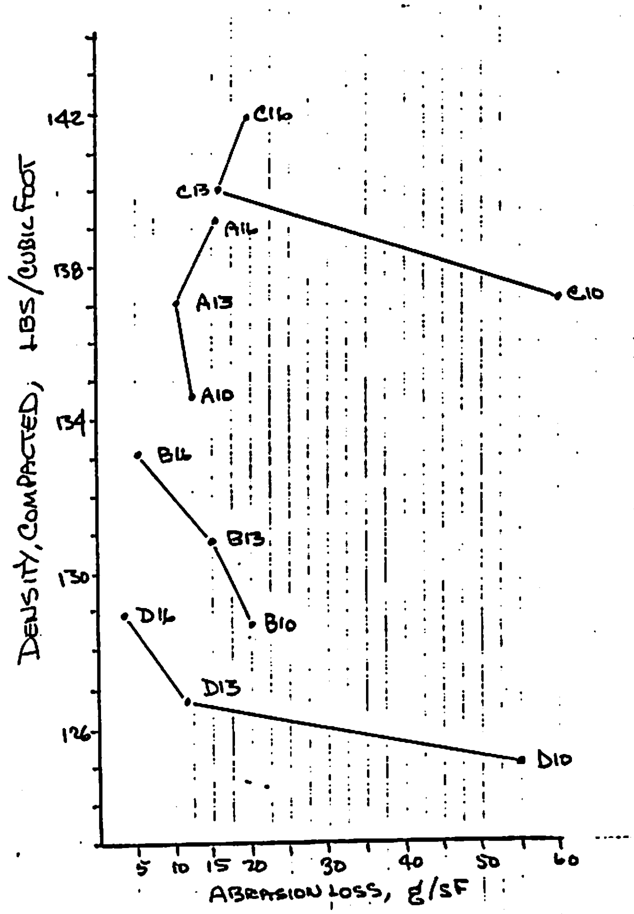


FIGURE 14. WTAT LOSS VS DENSITY

Figure 14 compares 6-day WTAT losses with the compacted mix bulk weight. Here we see again 2 distinct pairings of 126 to 134 lbs/CF and 134 to 142 lbs/CF. The A-C curves are non-linear and "hooked" while the B-D curves are more normal and linear. We suspect that compacted density may play an important role in slurry design.

LOADED WHEEL TEST 1/4" SPECIMEN, C-109 SAND ADHESION

The LWT sand adhesion is supposed to measure the relative amount of bitumen on the surface. ISSA TB 111 tentatively suggests that less than 50 grams/SF would indicate a safe amount for heavy traffic while 70 grams/SF would be a maximum for very light traffic.

The original work (   ) showed that there was no tackiness after 1000, 125-lb cycles at ambient at less than 50 grams/SF adhered sand and that this indicated a safe maximum emulsion content. The steep slope of the original sand adhesion-AE content curve has been shown to be atypical (U20, Cedex Lab, Madrid (   ). Our experiences in design work this past season has shown the same fact with one exception where our original, steep-sloped curves were duplicated because of excessive surface richness.

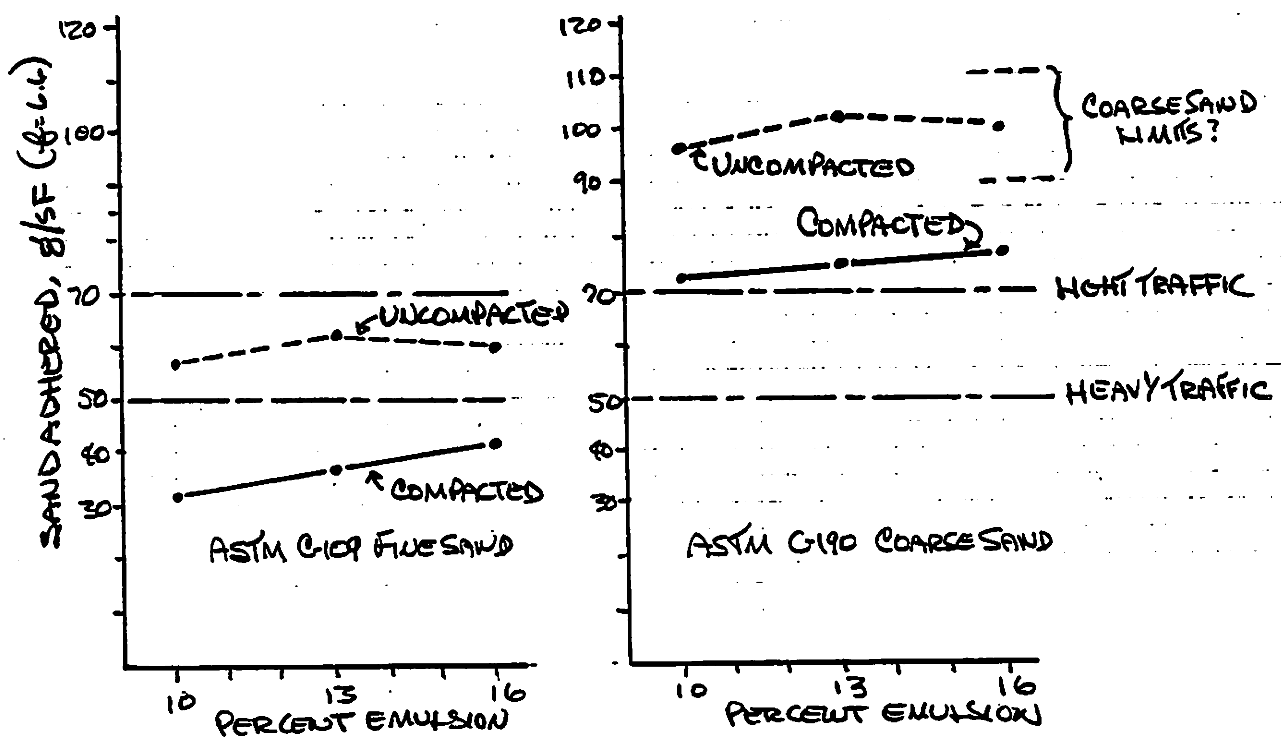


FIGURE 15. EFFECT OF OTTOWA SAND SIZE & COMPACTION ON 1/4" LWT SAND ADHESION VALUES

Figure 15 shows typical "flat curve" results with both fine and coarse sand. Both fine and coarse (ASTM C-109 & C-190) sand adhesion curves were identical but at 40 grams/SF (f=6.6) apart indicating that the heavy traffic coarse limit should be 90 grams/SF instead of the fine sand 50 gram limit. Note that the uncompacted sand adhesion curves are about 25 grams/SF higher than the compacted sand adhesion curves. This is due to coarser, "looser" uncompacted voids in the uncompacted specimens and possibly to the fresh, unworn surface.

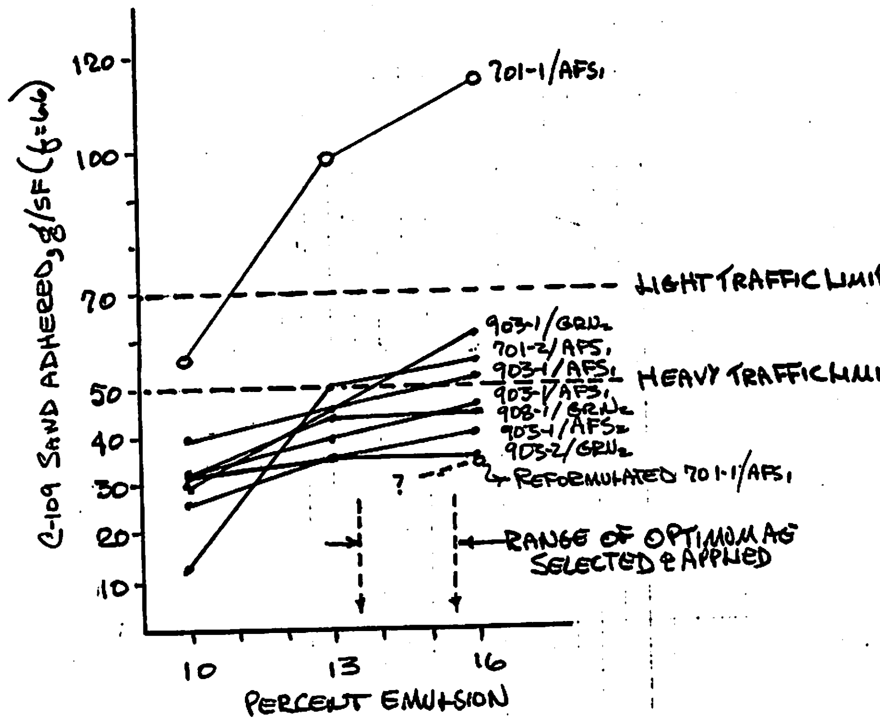


FIGURE 16. 1/4" LWT C109 SAND ADHESION LABORATORY DESIGN RESULTS-1988 6 EMULSIONS, 3 AGGREGATES

Figure 16 shows LWT sand adhesion results of 7 designs placed in the field under very heavy traffic. Optimum emulsion contents selected averaged at about 14.5% AE and the fine sand adhesion averaged about 45 grams per square foot.

Note the outlier #701-1/AFS curve which identified an incompatible system where excessive asphalt films were expressed to the surface. This curve is close to those we found in 1974 in our original work. Also this abberation indicates the value of the test in identifying excessive surface richness.

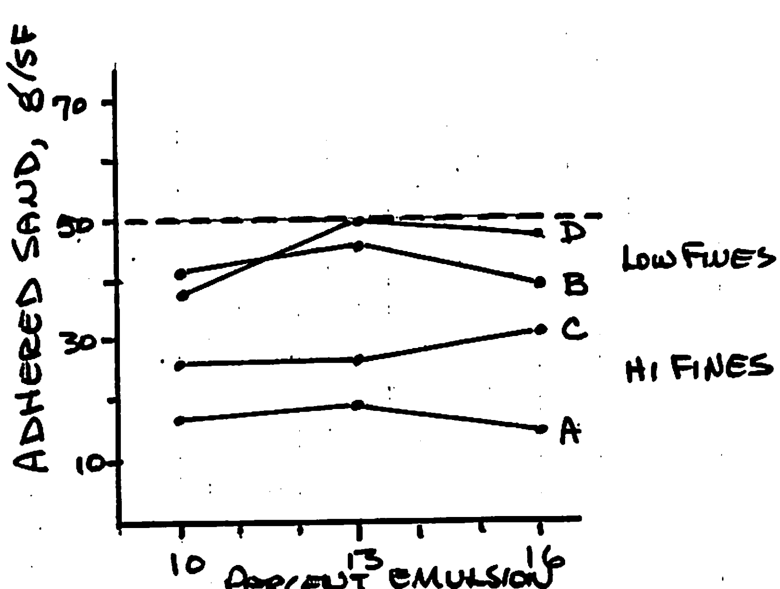


FIG. 17 1/4" LWT, C109 SAND ADHESION

Figure 17 plots the sand adhesion results of our A, B, C and D gradation slurries. The high fines A and C gave fine sand adhesion values that were much lower than the more "normal" values seen in Figure 16, while the B and D low fines sand adhesion values were more in line with the "normal" values. Sand adhesion values at the emulsion contents vary (widely) with the gradation. A-C & B-D are again paired.

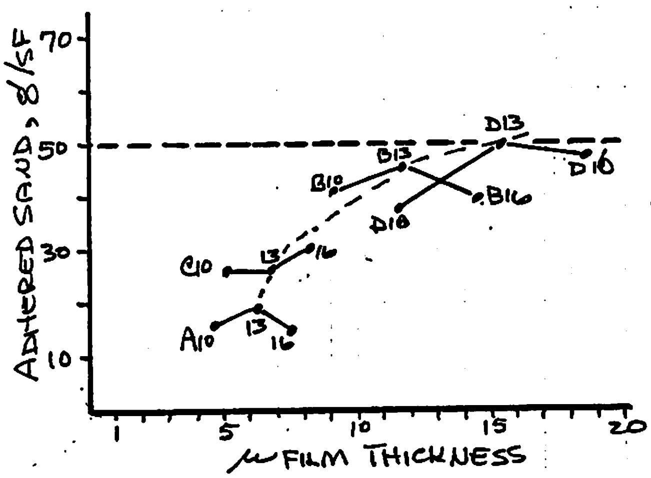


FIGURE 18. FILM THICKNESS VS. SAND ADHERED

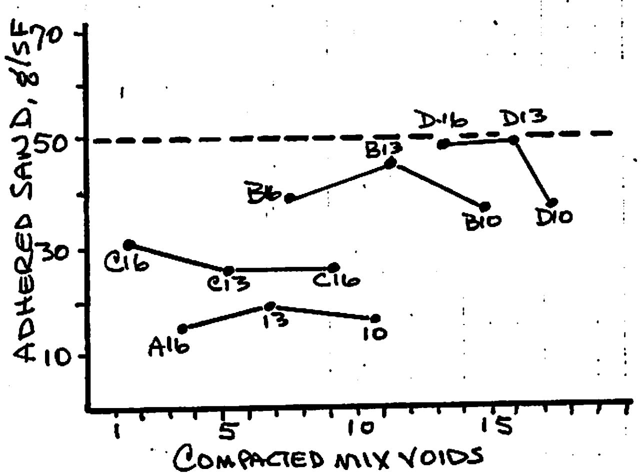


FIGURE 19. MIX VOIDS VS. ADHERED SAND

When the sand adhesion is plotted against the micron coatings (Figure 18) we see a sensible curve; i.e. adhered sand increases with film thickness as one might expect, but the curve is not linear as expected. At 13% a relatively smooth curve is formed, while at 10 and 16% the curves are erratic. A possible explanation for the slope differences between the A-C and B-D curves is that there is more space inside the mix so that the part of the thick films expected drained off the surface and into the void spaces in the mix.

Figure 19 plots sand adhesion against the void contents. Sand adhesion increases with void content increases, but not proportionately. With a decrease in voids, A to C, the sand adhesion increases (probably due to greater texture depth in C due to 10% + #4) while an increase in voids increase sand adhesion with the B and D high voids gradation.

Void contents also relate to sand adhesion. Again A-C and B-D are paired.

1/2" LOADED WHEEL TEST - MULTILAYER VERTICAL AND LATERAL DISPLACEMENTS

Figure 20. In the LWT ambient displacment test, 1/2" (13 -14 mm) thick LWT specimens, after oven curing are measured for central thickness and width, then compacted with 1000, 125-lb LWT cycles and then remeasured to determine the percent of vertical and lateral displacement.

Normal, plain or unmodified, systems display about 20% or more vertical and 5-10% lateral displacements. High quality modified systems vertical and lateral displacements are usually about 10-12% and 3-5% or less respectively at an optimum area of about 11 to 13% AE.

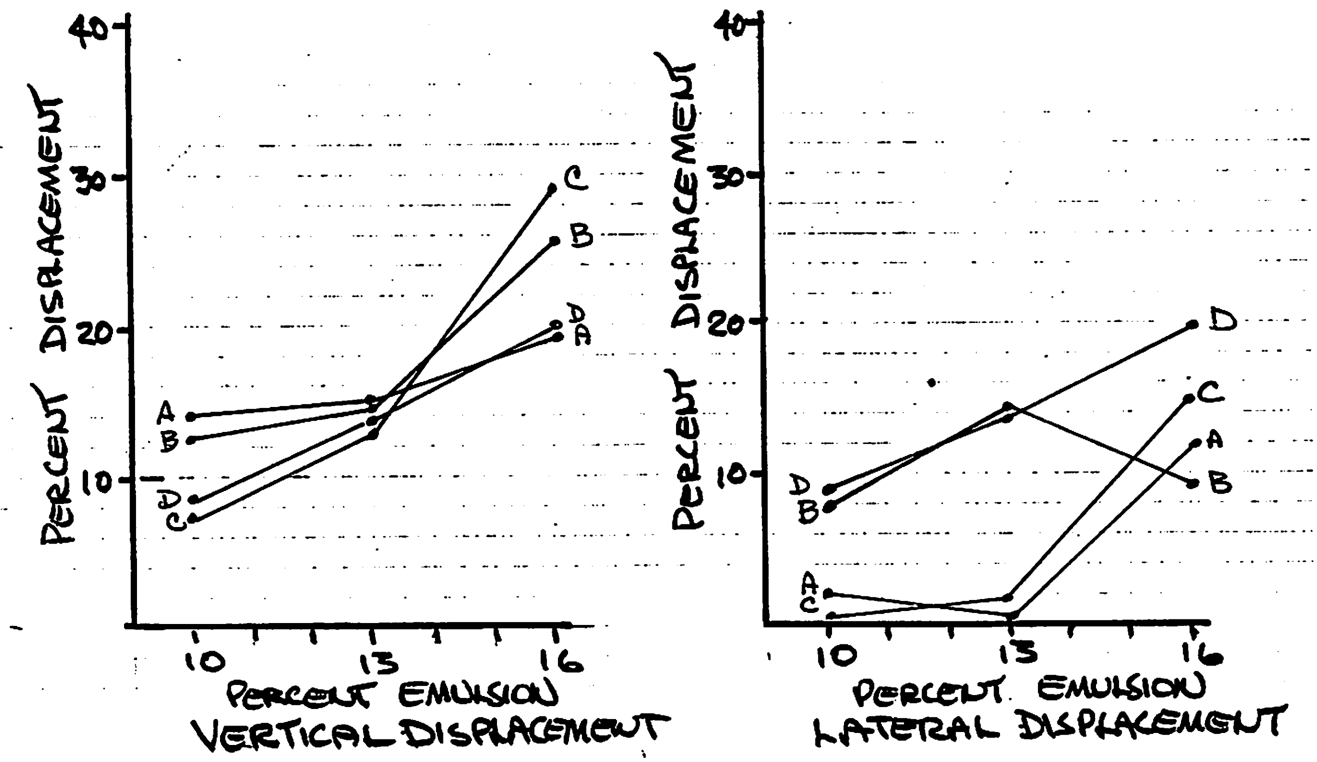


FIGURE 20. 1/2" (13mm) LOADED WHEEL DISPLACEMENTS 1000, 125 LB. CYCLES @ AMBIENT

These sytems are unusally good for unmodified systems with vertical displacements all at 12-15% at a near optimum of 13% emulsion content. The B and C gradations each have only 10% coarse fractions and exhibit much greater vertical displacements at 16% AE than the A and D system: A with high fines and no coarse and low fines and D with high coarse fractions.

The lateral displacements which may be related to Marshall flow, show a wide divergance between the B-D and A-C pairs at the optimum; the low fines B-D being the least stable laterally.

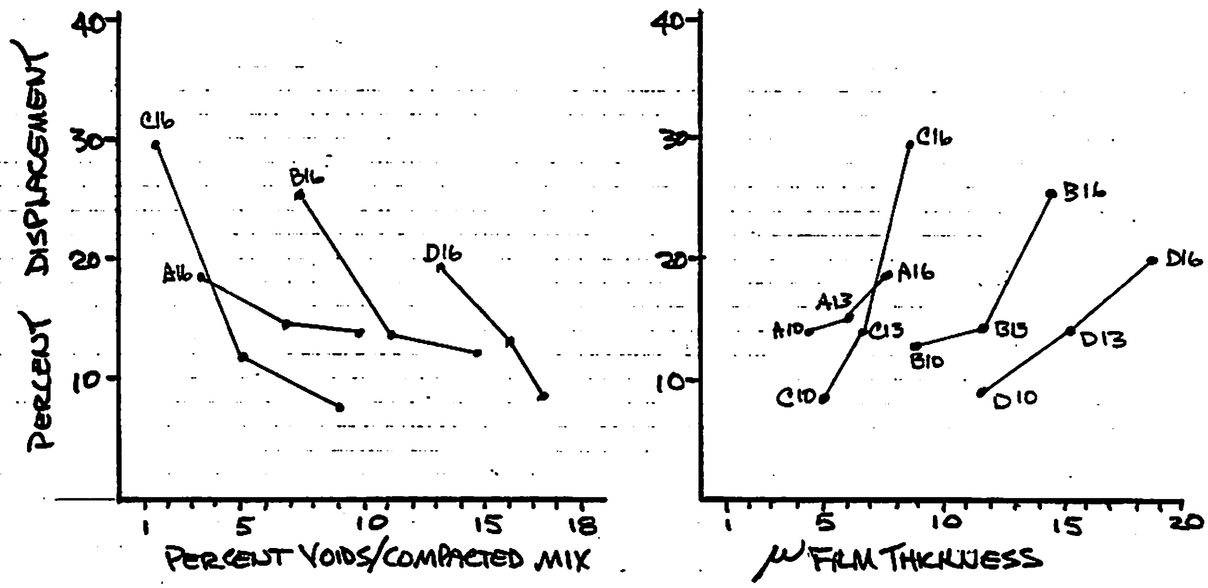


FIGURE 2. EFFECT OF MIX VOIDS & FILM THICKNESS ON 1/2" LWT VERTICAL DISPLACEMENT

Figure 21 compares the effects of micron film thickness and air voids content with vertical stability or resistance to vertical displacement.

At the 13% AE optimum, each gradation has nearly identical vertical displacements in spite of the wide variation in micron coatings from 6.5 to 15. The same is true of mix void variations from 5 to 16% these curious results should be studied further!

In general, vertical stability or resistance to compaction increases with a decrease in micron coatings while higher mix voids also give greater resistance to compaction.

SUPPLEMENTAL NOTES ON THE EFFECTS OF GRADATION VARIATION ON SLURRY DESIGN TESTS

If our observations are correct; that is , that the performance of a slurry in regards to gradation is best at some optimim density or mix voids, then it may follow that the ISSA gradation bands may require modification to accomodate these optimum compacted densities and mix voids.

The present experiments were based on maximum compacted laboratory densities of the aggregate. In practice these laboratory densities may not always occur in the field because of a resistance to compaction or equilibrium between the mix "stiffness" or resiliency and the compactive effort of the traffic.

In addition to gradation, these effects should be studied: (1) the quality, characteristics and quantity of the aggregate fines and fillers (2) the quality of the bitumen including the effects of residual emulsifiers' and additives' adhesion and cohesive strength and (3) the effects of polymer modification and their qualities, if present.

Several authors have discussed the effects of traffic compaction of slurry and the resulting density and voids. Harper, Jimenez and Galloway noted the relation of traffic compaction time on density and voids shown in table 5.

COMPACTION OF SLURRY SEAL BY TRAFFIC

Time	Density (gm/cu cm)		Voids[a] (%)	
	t = 1/8 In.	t = 3/16 In.	t = 1/8 In.	t = 3/16 In.
Init.	1.48	1.46	36.8	37.6
1 day	2.12	2.12	9.4	8.6
1 wk	2.19	2.21	6.4	5.6
1 mo	2.22	2.25	5.1	3.8
2 mo	2.23	2.26	4.7	3.4

[a]Based on computed maximum theoretical specific gravity of 2.34.

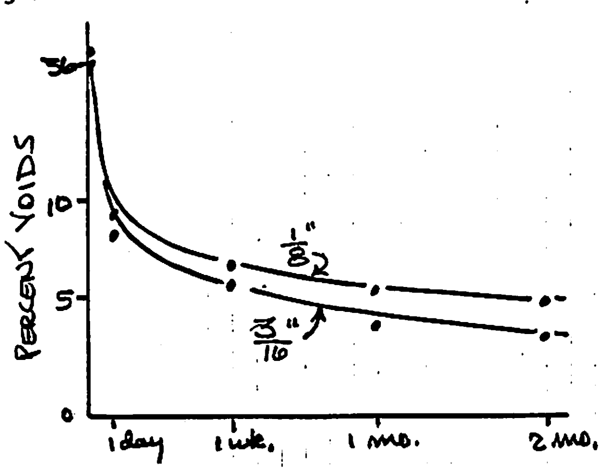
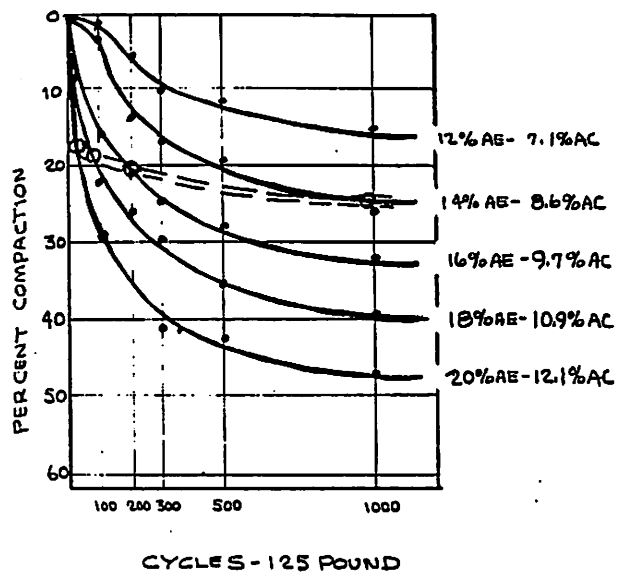


TABLE 5 PLOT of HARPER, JIMENEZ, GALLAWAY 1965 DATA

Benedict showed LWT compaction curves related to emulsion content and bitumen consistency and later in the A-B road study and the SR 33 where bitumen content was also related to skid numbers and accumulated traffic. In Geneva 1987, the author reported maximum optimum densities of multilayered slurries about 2.10 or 131 lbs/CF at the LWT compaction curve peak. (Figures 22-25).



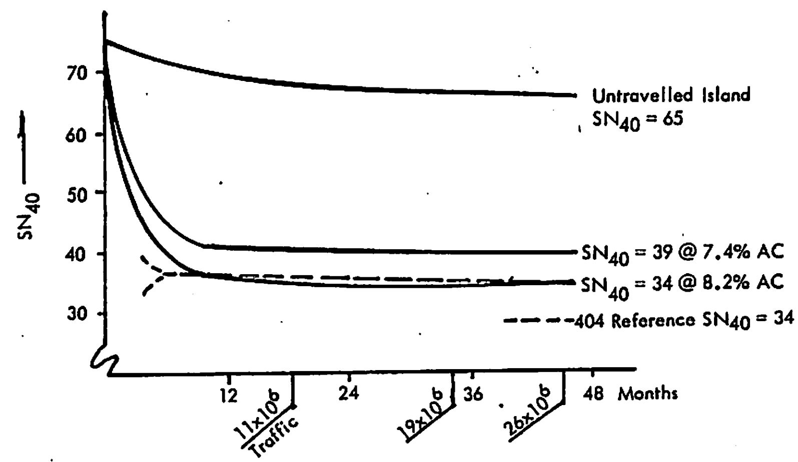
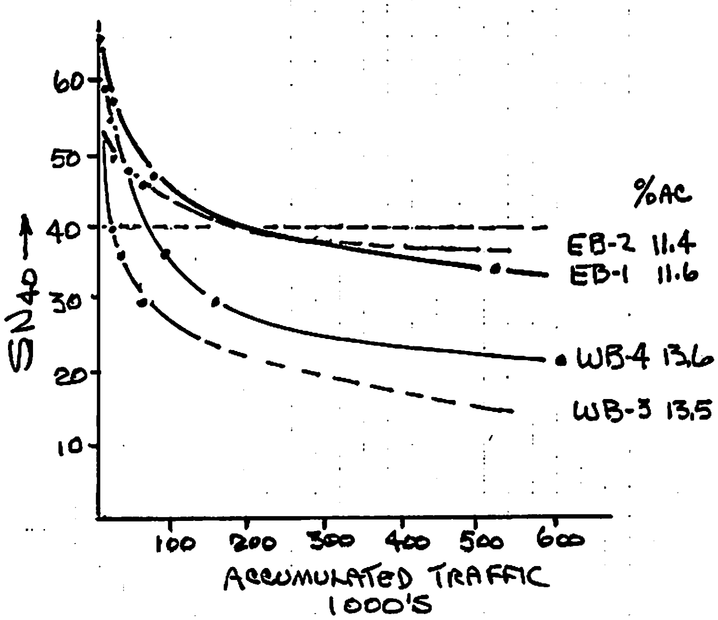
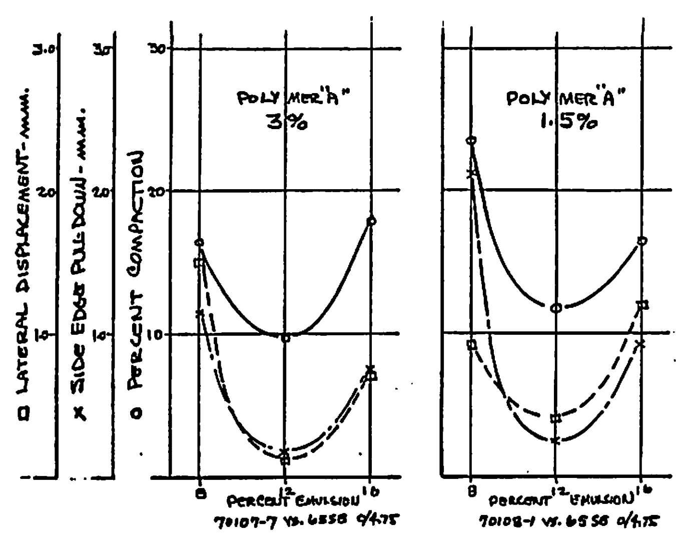


Figure 1. Effect of Asphalt Content on A-B Road Test Skid Numbers after 45 Months and 25,000,000 Accumulated Traffic

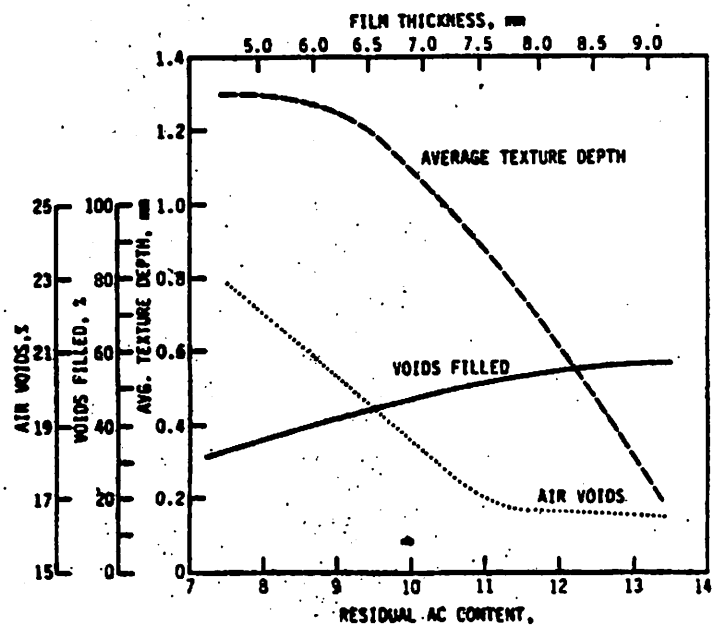


FIG, EFFECT OF TRAFFIC COUNT ON SKID NUMBER OF AN OVERLY RICH, TYPE 3 SLURRY SEAL - 15000 ADT (ODOT SR33 - 1983)



FIGURES 19&20 DIMENSIONAL CHANGES AFTER 1000 CYCLES LOAD WHEEL TEST AT 57KG & 22°C

Lee and Ordemir published in 1984 their analysis of the relationship between residual content, film thickness air voids, voids filled and macrotexture depth (Figure 26). Texture depth is related not only to gradation but also to higher air voids, lower bitumen content and thinner films.



Relationship between residual asphalt content, film thickness, air voids, voids filled, and texture depth, Series II, L1.

At an ASTM Syposium in Emulsions in 1988 and in this meeting Ballou and Reinke et. al. (33) report densities and voids from multilayered field cores in the same range as our findings reported here in this gradation study. (Table 6).

These scant clues add up to optimum or maximum field mix voids of 8 to 10%; (More than those normally associated with hox mixes) and traffic compacted densities of about 132 lbs/CF vs. more normal hot mix densities of 144 lbs/CF.

MARSHALL DATA

(Joplin Chat 7.0 Bit)

Materials	Stab @ 140 F	Flow .in	Density PCF	Voids %
Control AC 20	2533	16	131	6
3.5 SBR A	3164	17	133	8
3.5 SBR B	3353	18	132	8
3.5 SBR C	3190	17	132	8
3.5 Chloroprene D	1920	14	129	9
3.5 Chloroprene E	2265	11	130	9
3.5 Natural Poly Isoprene	3190	17	132	8

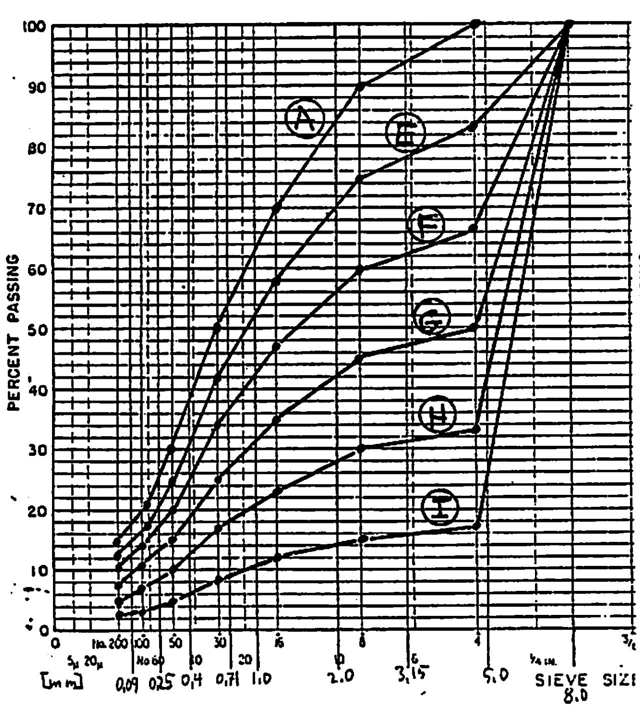
Packing characteristics of broken solids such as our aggregates, fillers and even our emulsion particle sizes have been studied by science and industry for it would seem, millenia. Volumes and whole sections of libraries would seem to be devoted to the subject. A thorough literature search should be done on the subject. In addition to gradation, the effects of fillers and bag house fines on bitumious mixes should also be searched (as reported here in Maui in 1985 (see: Kandhal (31) and Anderson (32).

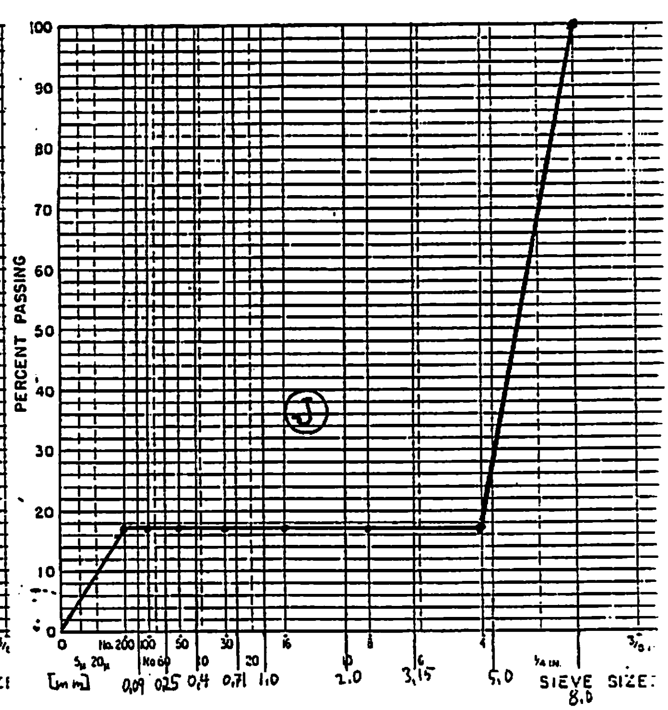
Lacking the benefits available from an extensive literature search, we offer a few observations from some additional laboratory experiments on the effect of gradation variation.

It is a common field practice to field blend "Chips" with type 2 to make a type 3 aggregate gradation. Because there was a field problem this past year where this was done, we started our experiment by adding in 1/6 increments of #4 - 5/16" chip to our fine type 2 "A" gradation. Figure 27 shows a change in density voids and surface area with the addition of each increment of chips. As chips increase, the density is reduced, the surface area is reduced while the voids increase. There is some experimental error here but the essential trend is unchanged. Essentially, as chips increase there is more space for asphalt and less surface to coat (60SF down to only 10 SF/lb!)

All these gradations contained various portions of intermediate sizes which also effect the densities.

	A	E	F	G	H	I	J
5/16	---	100	100	100	100	100	100
# 4	100	83	67	50	33	17	--
8	90	75	60	45	30	15	--
16	70	58	47	35	23	12	--
30	50	42	34	25	17	8.5	--
50	30	25	20	15	10	5.0	--
100	21	17.5	14	10.5	7	3.5	--
200	15	12.5	10.5	7.5	5	2.5	17





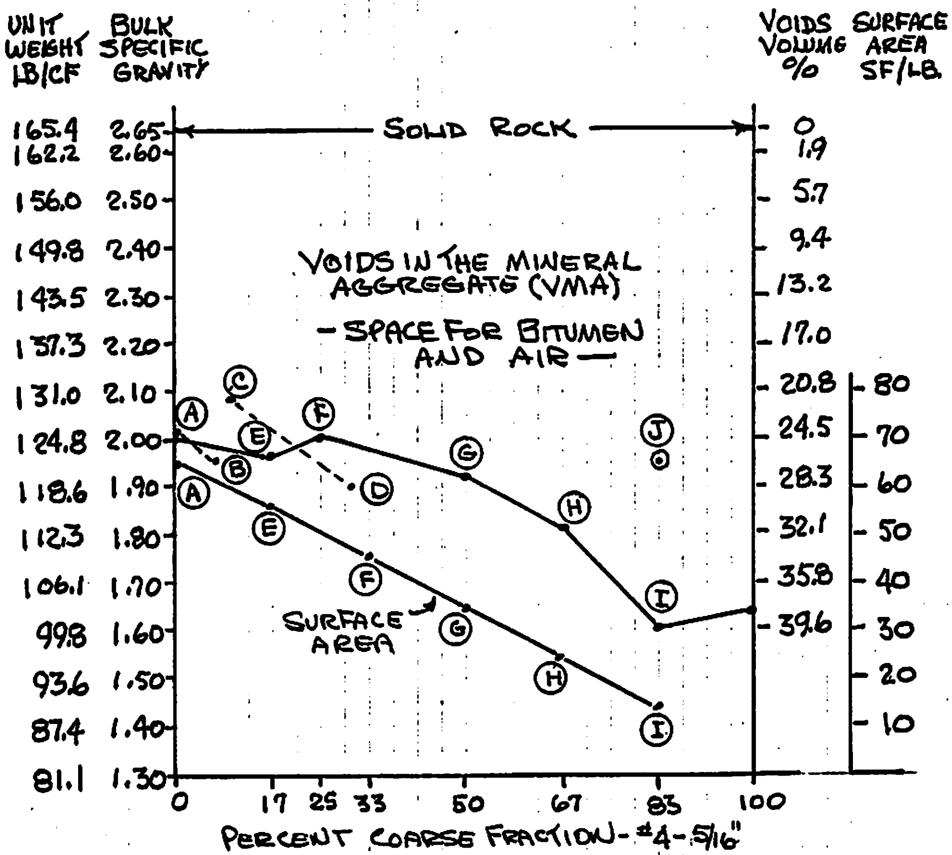


FIGURE 2: VOIDS, DENSITY & SURFACE AREA OF CHIP BLENDS WITH TYPE 2 AGGREGATE

We then looked at the effect of moisture on the compacted and loose weights. 4% moisture was added to each fraction and the densities determined. Figure 28 shows the bulking effect of 4% moisture content as the coarse aggregate increases (and fines decrease) the 2 curves merge so that the "bulking" due to the fines vanishes into the space created by the increased voids in both compacted and loose conditons. The bulking effect of moisture is less important with coarser gradations, a fact overlooked by Fiock (6) in his 1969 analysis.

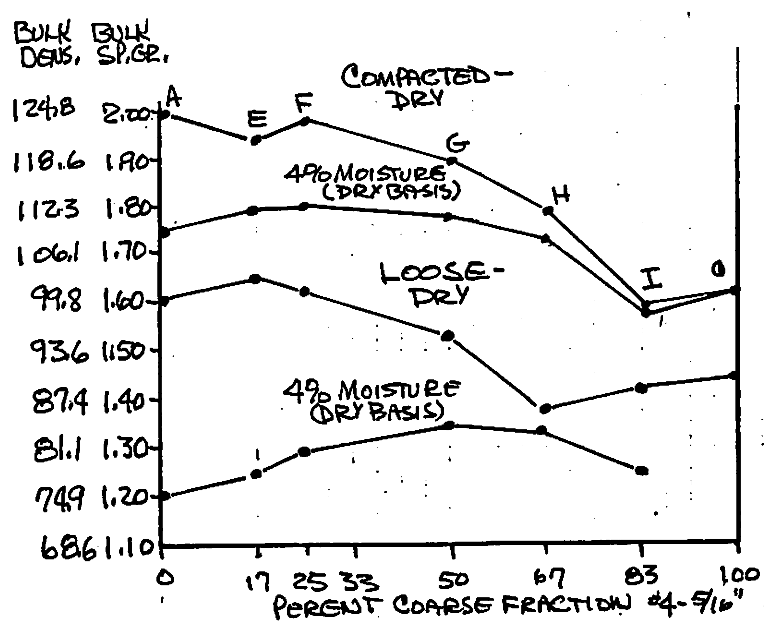


FIGURE 28, EFFECT OF MOISTURE ON BULK DENSITY OF CHIP BLENDS

We then determined the bulk specific gravity of each compacted separate fraction and found that each fraction varied somewhat but the bulk gravities were about 1.5 to 1.60 or 40 to 43% VMA or about double the voids of a typical slurry gradation. (Figure 29)

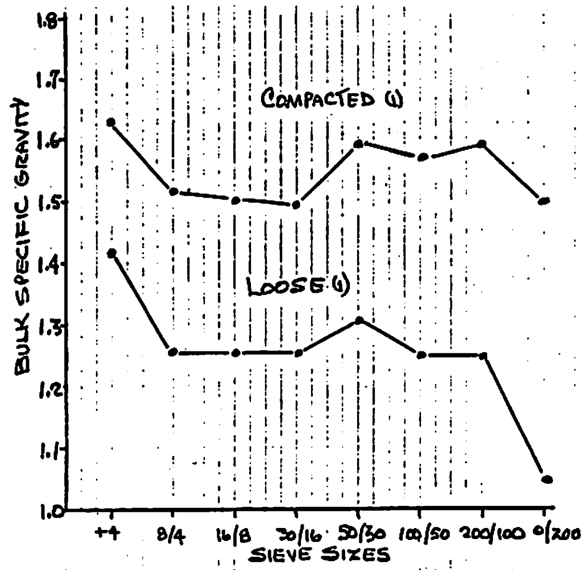


FIGURE 29, BULK SPECIFIC GRAVITY OF SLURRY AGGREGATE FRACTIONS

G. Lee's (34) in his 1970 AAPT paper on Rational Gradation Design, relates his work to the Furnas curve, figure 30, which relates the voids and size composition to size ratios. Starting with an infinitely large and an infinitely small size (size ratio of "0") the minimum void of 25% is reached with 67% large size and 33% small size.

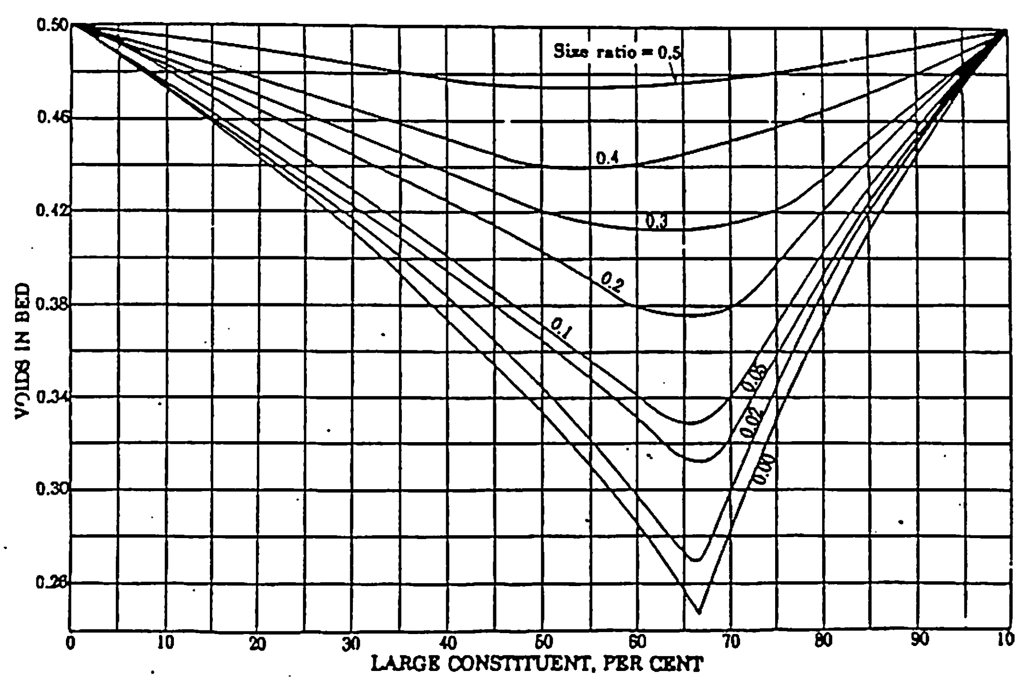


Fig. 1. Relation between Voids and Size Composition (Normal Voids = 0.50) (Furnas 1928).

We then attempted to verify this Furnas curve using 1/4" - 5/16" one size and 0/200 fines (figure 31). Though our curves are more rounded, we get the same peak at 67% coarse aggregate and 33% fine aggregate. At least, this truth has not changed for 61 years!

Additionally, we combined 1/3 each of 5/16", #16, and 0/200 sizes and determined that this gradation packed tighter (more densely, and very close to slurry gradation's compacted densities.

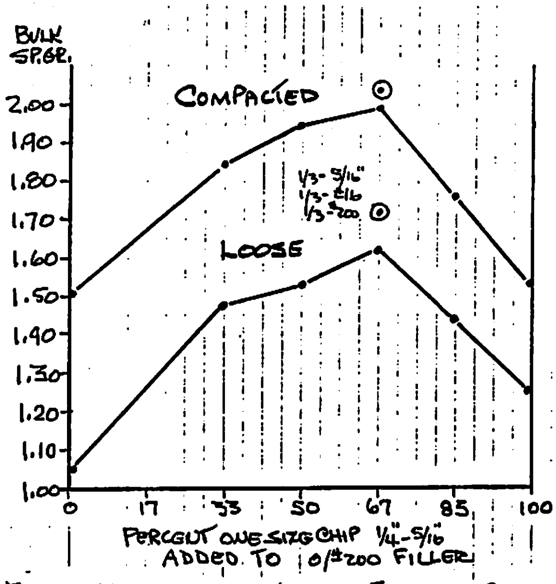


FIGURE 31. SIMILARITIES TO FURNAS CURVE

In general, the hot mixed asphalt concrete industry limits the amount of filler/fines (0/#200) to about 5%. In slurry, we start at that point and allow as much as 20% filler/fines in our mixes; typically 12-15% 0/#200 is used or weight percents of 0/#200 usually equaling or exceeding the weight of the bitumen in the mix by as much as 200%.

We often find that as much as 85% of the 0/#200 fraction will pass the 0/#325 and that 75% of the 0/#325 is 16 um and smaller while 50% of the 0/#325 is 8 um and smaller. We strongly suspect that at least the 0/16 um sizes are incorporated INTO the bitumen, thus the removing these aggregate particles from the aggregate gradation thereby increasing the voids in the mineral aggregate and at the same time increasing the volume of the bitumen as well as severly altering the properties of the bitmen and the resulting mastic or matrix which "holds" the larger particles of aggregate together.

If this motion is true, then a 15% 0/#200 gradation which has 25% VMA may "loose" 10% of 0/#200 and increase the VMA to by about 5% to 30% and the volume of the bitumen at 8.0 weight percent will increase the volume of AC in the mix by about 38%!

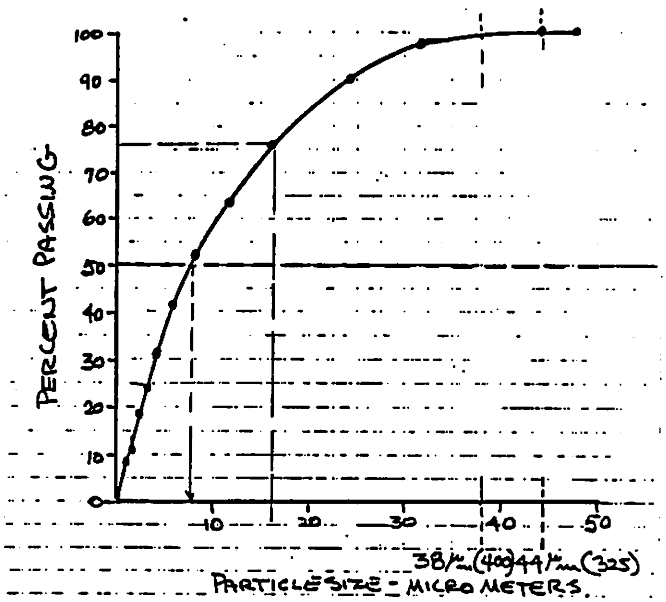
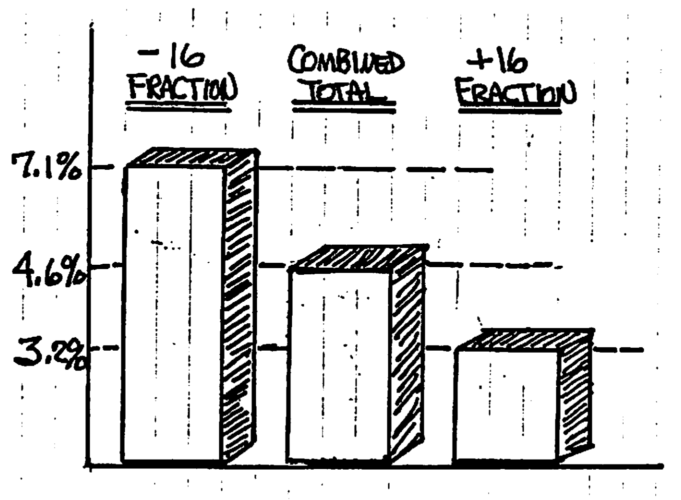


FIGURE 8. 0/44μm (0/325) PARTICLE SIZE DISTRIBUTION BY WATER & ALCOHOL LASER GRANULOMETER



FINE FRACTIONS CONTAIN MORE MOISTURE THAN COARSE FRACTIONS

The ability of the mix water (with or without additives) and the continuous phase of the emulsion to "wet" each of these fine particles and to separate agglomeration of these fines (micro - balls) may have a very large influence on the properties of the filler - matrix which in turn importantly influences the properties of the total cured mix.

We have also noted that mix water added to a dry slurry aggregate will preferentially be drawn to the 0/200 fines until they are saturated and only then will the larger fractions become "wet". This same phenomenon can be observed when emulsion is added to the mixture or when hot AC is added to hot aggregate in the pug mill. The "wetness" or wetting ability of the slurry liquids is important for several reasons but, regarding gradation and voids, the total liquids added to the mix should be less than the space available to hold the liquid, i.e., the loose voids. When the total liquids added exceed the voids available, then the aggregate becomes submerged in liquid and rich surface films will likely be deposited. We then see that mix liquids should not exceed mix voids. The amount of mix liquids required is related to the fines wetting ability of the mix systems.

A final note: Hudson and Davis in their 1965 AAPT paper found that minimum VMA was required for durable hot mixes figure 32. This finding may or may not be applied to thin layered slurry mixes. Many slurry gradations fall below the Hudson Davis limits.

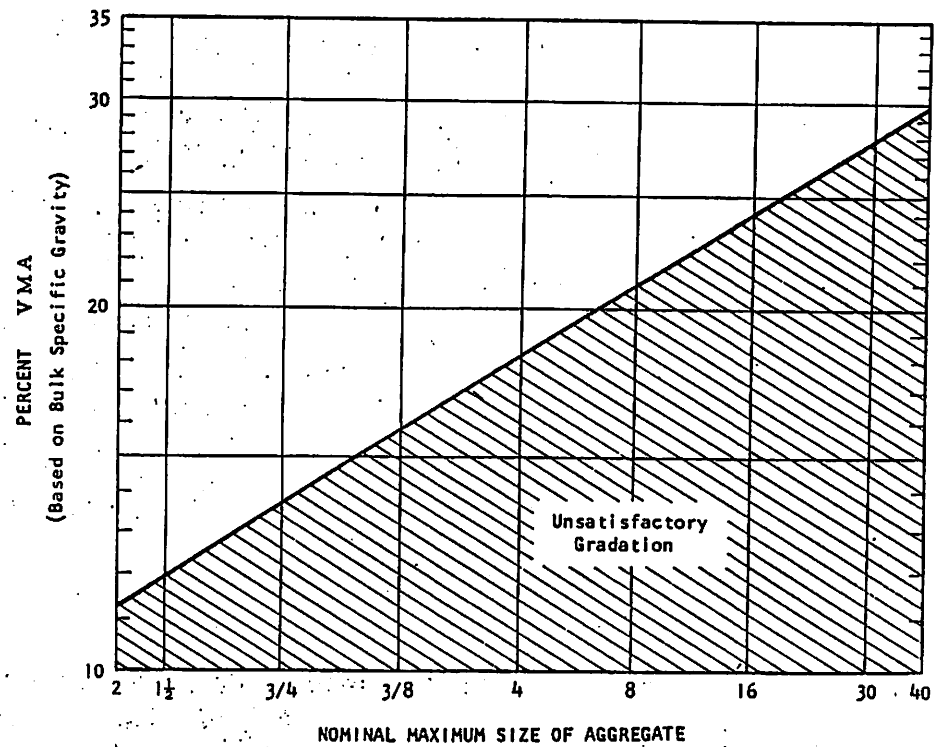


Fig. 4. Minimum VMA Requirements for Durable Mixture

The point of these exercises has been to stimulate thought about our ISSA gradations and that optimum densities or VMA, if there is such a thing, may be achieved with gradations, widely different from the standard ISSA gradations.

CONCLUSIONS

1. Gradation does affect the design tests performed in these very limited experiments and with the single system tested.

2. Bitumen or Emulsion content designs based on a specific micron coating thicknesses such as 6.5 or 8 microns for all gradations within the ISSA type 2 and 3 gradation bands can lead to disastrously rich or disastrously lean designs.

   It is recommended that surface area design as specified by WES S-75-1 (ISSA TB 118), be abandoned.

3. An "Optimum" emulsion content of about 13% gave the best overall performace irrespective of gradation or other factors. The true optimum was not determined and may have been found at 11 or 12% AE.

4. Generally, low voids and high densities did not perform in design tests as well as did higher voids and lower densities.

5. There appears to be an optimum at some point between low voids-high density and high voids-low density.

6. Slightly higher voids and lower densities may accommodate more emulsion and result in longer service life and better sealability.

7. Gradations outside the conventional ISSA type 2 and type 3 gradations maybe found beneficial and may give surface textures that may not available when using standard ISSA gradations.

8. The effects of relative density and mix voids on the permeability and macrotexture at various layer thickness of a variety of gradations has not been studied here. Future research should include an analysis of these factors.

9. In the field certain material combinations may never reach maximum density. Field voids would then be higher than anticipated. The effects of layer thickness on compaction or ultimate field density and voids and the resultant macrotexture and permeability should be included in future studies.

10. Each system is its own thing. "Results in this study are scant at best and cover only a single system and should be taken as such."

11. A case has been made to include voids and density analysis in future slurry design studies.

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Calculations:

10% AE × 62% = 6.2 + 100; 6.2/106.2 = 5.8% AC extracted
13% × 62% = 8.1 + 100; 8.1/108.1 = 7.5% AC extracted
16% × 62% = 9.9 + 100; 9.9/109.9 = 9.0% A extracted

	(A) 10%	13%	16%	(B) 10%	13	16
AE%	10%	13%	16%	10%	13	16
BSG	2.03			1.94×62.4	1.94×62.4	
VMA	23.4	23.4	23.4	26.8	26.8	26.8
% ADD	6.2×	8.1×	9.9	6.2×	8.1	9.9×
AGG WT.	126.7	126.7	126.7	121.1	121.1	121.1
AC WT	7.9	10.3	12.5	+7.5	+9.8	12.0
Den LBS/CF	134.6	137.0	139.2	128.6	130.9	133.1
AC WT.	7.9 / 62.4 =	10.3 / 62.4 =	12.5 / 62.4	7.5 / 62.4	9.8 / 62.4	12.0 / 62.4
AC VOL, CF	12.7%	16.5%	20.0	12.0	15.7	19.2
VMA	23.4	23.4	23.4	26.8	26.8	26.8
% VOIDS FLD	54.3%	70.5%	85.6%	44.8	58.6	71.6
	23.4 − 12.7	23.4 − 16.5	23.4 − 20.0	26.8 − 12.0	26.8 − 15.7	26.8 − 19.2
AIR VOIDS	10.7	6.9	3.4%	14.8	11.1	7.6
SURF AREA:	63.4 SF/LB.			33.6		
WT. % AC ADD. ÷ SA * f.	6.2 / 63.4× .02047 =	8.1 / 63.4× .02047 =	9.9 / 63.4× .02047 =	6.2 / 33.6× .02047 =	8.1 / 33.6× .02047 =	9.9 / 33.6× .02047
μ (1)	4.77	6.24	7.62	9.01	11.77	14.39
	CKE = 5.2; 6.2 − 5.2 ÷ 63.4× .02047 ÷ =	8.1 − 5.2 = 2.9; 63.4× .02047 ÷ =	9.9 − 5.2 = 4.7; 63.4× .02047 ÷ =	6.2 − 3.2 = 3.0; 33.6× .02047	8.1 − 3.2 = 4.9; 33.6 .02047	9.9 − 3.2 = 6.7; 33.6 .02047
μ (2)	.78μ	2.23μ	3.6μ	4.36μ	7.12μ	9.74μ

* NO CORRECTION

Calculations: 2

	(C) 10% AE	13%	16%	(D) 10% AE	13%	16%
B.G.	207	207	207	1.88	1.88	1.88
VMA	21.9	21.9	21.9	29.1	29.1	29.1
AC% ADD	6.2x	8.1x	9.9x	6.2x	8.1x	9.9x
AGG WT.	129.2=	129.2	129.2=	117.3=	117.3	117.3
AC WT.	8.0	10.5	12.8	7.3	9.5	11.6
LB/CF	137.2	139.7	142.0	124.6	126.8	128.9
AC WT	8.0÷	10.5	12.8	6.2=	8.1	9.9
	62.4	62.4	62.4	62.4	62.4	62.4
AC VOL	12.8%CF	16.8%	20.5=	9.9	13.0	15.9
	21.9	21.9	21.9	29.1	29.1	29.1
% VMA FLD.	58.4	76.7	93.6	34.0	44.7	54.6
VMA	21.9	21.9	21.9	29.1	29.1	29.1
AC VOL %	12.8	− 16.8	− 20.5	9.9	13.0	15.9
MIX AIR VOIDS	9.1	5.1	1.4	19.2	16.1	13.2
SURF AREA	57.7 SF/LB.			25.9 SF/LB.		
	6.2÷	8.1	9.9	6.2	8.1	9.9
	57.7x	57.7x	57.7x	25.9x	25.9	25.9
	.02047	.02047	.02047	.02047	.02047	.02047
μ(1)	5.24	6.85	8.38	11.69	15.27	18.67
	x9.1	x5.1	x1.4	x17.4	x16.1	x15.9
	47.7	34.9	11.7	203.4	245.8	246.4
	6.2 − 5.2 = 1.0 ÷	8.1 − 5.2 = 2.9 ÷	9.9 − 5.2 = 4.7	6.2 − 3.2 = 3.0	8.1 − 3.2 = 4.9	9.9 − 3.2 = 6.7 ÷
	57.7x .02047 =	57.7 x .02047	57.7 ÷ .02047 =	25.9x .02047 ÷ =	25.9 x .02047 ÷ =	25.9x .02047 =
μ(2)	.85μ	2.45μ	3.55μ	5.65μ	9.24μ	12.63μ

2/4/89 Calculations : 3

8" dia.

	(A)	(B)	(C)	(D)
	2.65 x 62.4 =			2.65 x 62.4
	165.4 PCF	165.4	165.4	165.4
BSG.	2.03 x 62.4 =	1.94 x 62.4	2.07 x 62.4	1.88
	126.7	121.1	129.2	117.3
	2.65	2.65	2.65	2.65
	− 2.03	− 1.94	− 2.07	− 1.88
	.62 =	.71	.58	.77 =
	2.65	2.65	2.65	2.65
VMA	23.4	26.8	21.9	29.1
	126.7 x	121.1 x	129.2 x	117.3 x
	15.6 =	8.7 =	13.7	8.4 =
lbs. AC	19.8 =	10.6 =	17.7 =	9.8 =
	62.4	62.4	62.4	62.4
% ACF	31.7	16.7 =	28.4 =	15.7 =
− VMA%	23.4	26.8	21.9	29.1
	8.3 =		6.5	54.0
	23.4		21.9	
% filled	135.5	62.3	129.7	54.0
	126.7	121.1	129.2	117.3
	+ 19.8	+ 10.6	+ 17.7	+ 8.4
MPCF	146.5	131.7	146.9	125.7

BR = (CSA x 8 x .02047) + HA

(25.9 x 8 x .02047) + 3.2

4.241
3.2
8.4

VTM	(B)	(D)
	121.1 / 165.4 = 73.2%	117.3 / 165.4 = 70.9
	+ 16.7	15.7
	89.9	86.6
	= 11.1	= 13.3