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16. Abstract

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# FINAL REPORT

# EXPERIMENTAL MIXES TO MINIMIZE RUTTING

C. S. Hughes
Senior Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Transportation and the University of Virginia)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

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## ABSTRACT

This report describes the materials and construction details involved in the design and placement of four experimental mixes on I-95 (Richmond-Petersburg Turnpike) in 1985 and follows the performance for 48 months. The mixes were designed to resist rutting and to provide several years of service before failing from fatigue or the intrusion of water. The results indicate that the gradation chosen is more important in minimizing rutting than are the asphalt cement-additive combinations used. However, some strength tests point to the value of using an AC-30 asphalt cement as opposed to an AC-20 asphalt cement. Controlling traffic for a sufficient time to allow the pavement to cool to a temperature at which traffic will not prolong the compaction process is critical. The minor rutting that has occurred was attributed primarily to consolidation. Ruts on one test section that averaged almost 1/4 in apparently resulted from a low voids in mineral aggregate of the mix used on that section.

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FINAL REPORT

# EXPERIMENTAL MIXES TO MINIMIZE RUTTING

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## INTRODUCTION

Two S-5 mixes placed on the Richmond-Petersburg Turnpike in 1984 displayed either inadequate stability or slow setting characteristics. Ruts as deep as 2 1/2 in occurred within several months of placement. Investigations by the Virginia Department of Transportation's (VDOT) Materials Division and the Asphalt Institute identified possible causes of the problems in both mixes. Some of these causes were a high asphalt content, ruts in underlying pavement, lack of density, a relatively high mica content in the aggregate, and the allowing of traffic on the fresh pavement too soon.

Because the turnpike is subjected to an extremely high traffic volume (59,390 vehicles per day, roughly 30,000 in each direction) and heavy loads, it was agreed that mixes placed in 1985 should be selected and designed to include experimental variables likely to enhance the strength of the mix and provide information useful in the future design of mixes that must be subjected to heavy traffic.

Button and Epps (1) summarized mix characteristics and construction procedures that contribute to tender mixes and that, conversely, are necessary for high strengths. Table 1 shows the characteristics that influence tenderness.

This report discusses the experimental design and installation that were included in the installation report (2) and documents the performance of the four test sections from 1985 through 1989. Although all test sections have performed adequately, one has ruts significantly deeper than the other three.

## DESIGN OF EXPERIMENT

The new mix design was chosen to be similar to Virginia's nominal 3/4-in top size mix except that tolerances were specified on more sieves and the gradation was moved toward the coarse side of the traditional gradation band to ensure that the job mix would not follow the maximum density gradation too closely and prevent an excess of -No. 30 +No. 50 size material, which can contribute to the tenderness of a mix. The master gradation band of the experimental mix is shown in Figure 1.

Table 1

RATING SCALE TO IDENTIFY TENDER MIXES

| Material or Mix Variable | Increasing Tenderness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1[a] | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| **Aggregate** | | | | | | | | | | |
| Shape | Angular | | Subangular | | | | Subrounded | | | Rounded |
| Texture | Very rough | | Rough | | | | Smooth | | | Polished |
| Maximum size | >3/4 in | | <5/8 in | | <1/2 in | | >3/8 in | | | <1/4 in |
| -No. 30 to +No. 100 | Suitable | | | | Excessive | | | | | Large excess |
| -No. 200 | >6% | | 5% | | 4% | | 3% | | | <2% |
| **Asphalt Cement** | | | | | | | | | | |
| Content | Low | | | | Optimum | | | | | High |
| Viscosity | High | | | | Medium | | | | | Low |
| Penetration | Low | | | | Medium | | | | | High |
| Hardening index | High | | | | Medium | | | | | Low |
| Temp. susceptibility | Low | | | | Medium | | | | | High |
| Setting characteristic | Fast | | | | Medium | | | | | Slow |
| Asphaltene content | >20% | | | | 10 to 20% | | | | | <10% |
| **Mixture** | | | | | | | | | | |
| Softening additives | None | | | | Some | | | | | Much |
| Moisture content | <0.5% | | | | 1 to 2% | | | | | >2.5% |
| **Construction** | | | | | | | | | | |
| Rolling temperature | Low | | | | Medium | | | | | High |
| C value | >50 | | | | 30-50 | | | | | <30 |
| Ambient temperature | <70 | | 80 | | | | 90 | | | >100 |

[a] A tenderness rating of 1 indicates the materials and mix variables that will produce the highest strengths.
Source: Button and Epps (1).

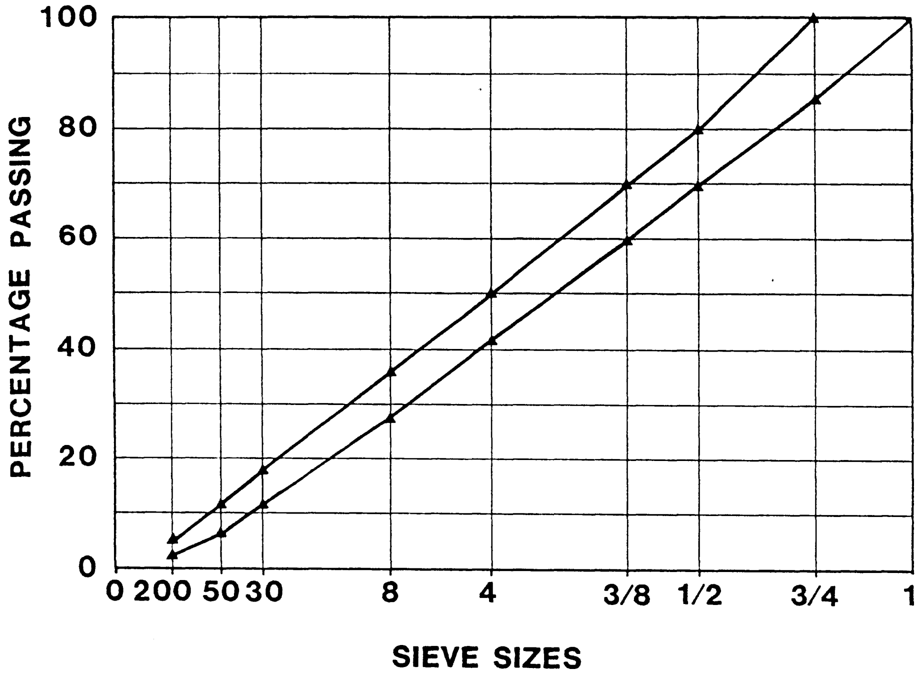


Figure 1. Master gradation band for experimental mixes.

Additional safeguards taken to produce a strong mix were (1) the use of an AC-30 asphalt cement, (2) the addition of 1% hydrated lime to act as a filler and as an antistripping additive, (3) the use of a 75-blow Marshall design, and (4) the requirement that all areas to be overlaid be milled to a 2-in depth. All of these actions were intended to produce a pavement that would resist rutting under the heavy traffic on the turnpike.

It was decided to hold the job-mix gradation constant and to vary the type of asphalt cement and the type of additive to minimize stripping. Lime was included as a variable because it has been used to improve asphalt mix characteristics in two ways: When it is placed on the aggregate, it can improve the aggregate-asphalt bond and thus enhance the antistripping characteristics of the mix. When it is added as a filler, it may combine with the asphalt to add stiffness to the mix. In this project, it should have served primarily as an antistripping additive because a relatively small amount (1%) was used merely to coat the damp aggregate before it was fed into the plant. However, there may have been enough lime available to combine with the asphalt and act as a stiffener.

Figure 2 shows the mix variables, including type of antistripping additive used, the lengths of the overlaid sections, the tonnages placed,

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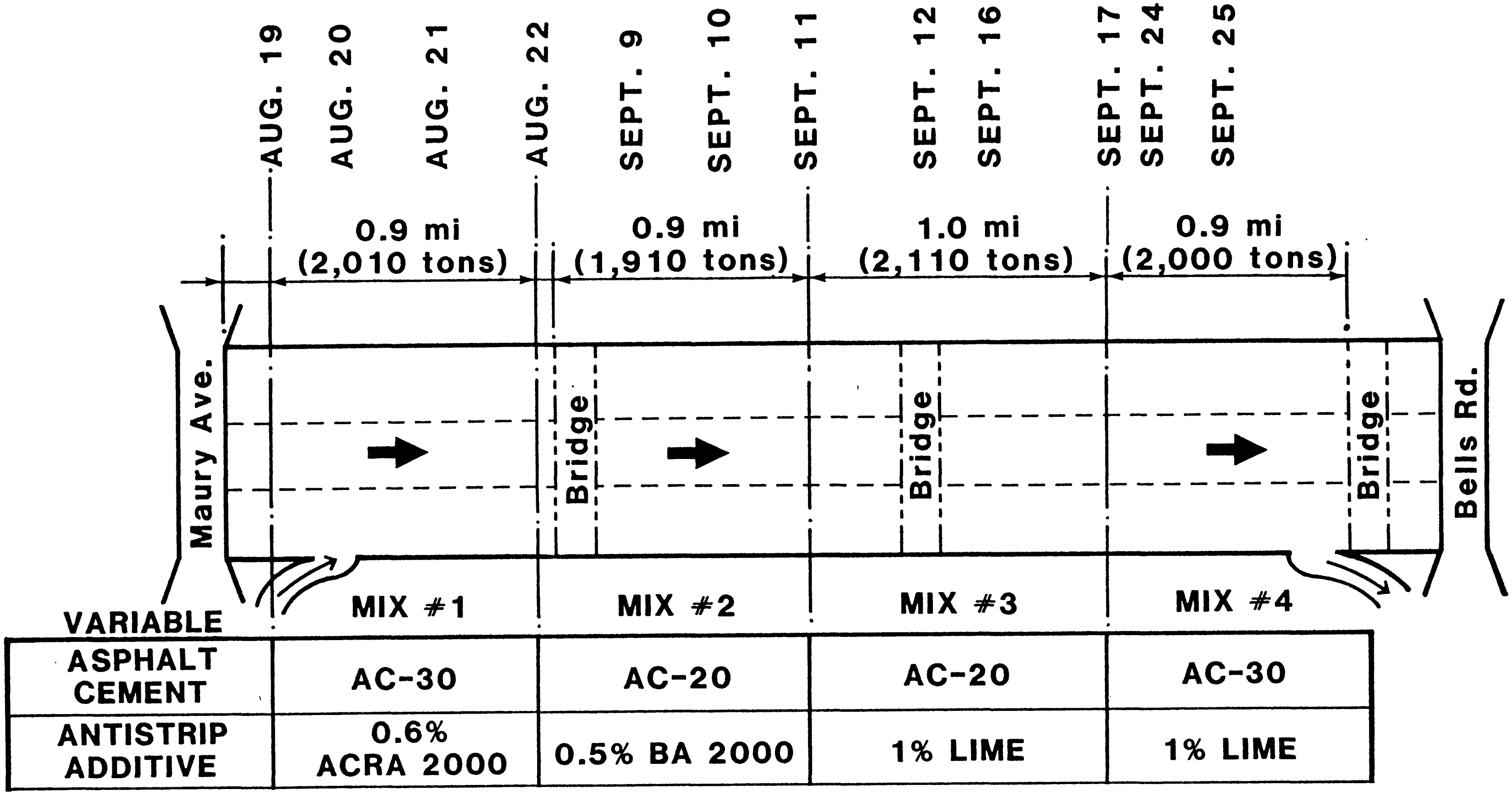


Figure 2. Test sections in southbound lane of Route I-95, the Richmond-Petersburg Turnpike.

and the paving dates for the experimental mixes. Mix 1 would indicate the effect of asphalt cement stiffness. Mix 2 was a control mix, inasmuch as it used both AC-20 asphalt cement and a liquid antistripping additive, two materials typically used in Virginia in 1985. If this mix performed well, it would indicate that gradation control alone is sufficient to provide a strong mix. Mix 3, using AC-20 asphalt cement and 1% lime, would provide an indication of the value of using lime in combination with a typical asphalt cement. It was thought that Mix 4, incorporating AC-30 asphalt cement and 1% lime, would be the most rut-resistant of the four mixes.

## MIX DESIGNS

The aggregate blend was primarily granite from Chesterfield, Virginia. The asphalt cement came from West Bank Oil Co.

The job-mix formula is shown in Table 2. Figure 3 shows the relationship between the job-mix formula gradation and the maximum density line. A deviation was created between the gradation and the maximum density line to ensure an adequate voids in mineral aggregate (VMA).

Two Marshall compactive efforts were used for each of the four experimental mixes: the 50-blow effort normally used in Virginia and the 75-blow effort specified for the experiment. This was done to gain experience in the use of the 75-blow compactive effort and to obtain a comparison of the two Marshall compactive efforts for the four mixes.

The designs for the four experimental mixes are shown in Figures 4 through 7. As the figures indicate, the properties of all four mixes were very similar for a given compactive effort. It is the recommended practice

Table 2

GRADATION FOR EXPERIMENTAL MIXES

| Sieve Size | % Passing |
|---|---|
| 1 in | 100 |
| 3/4 in | 100 |
| 1/2 in | 76.0 |
| 3/8 in | 60.0 |
| No. 4 | 47.0 |
| No. 8 | 32.5 |
| No. 30 | 13.0 |
| No. 50 | 8.0 |
| No. 200 | 3.5 |

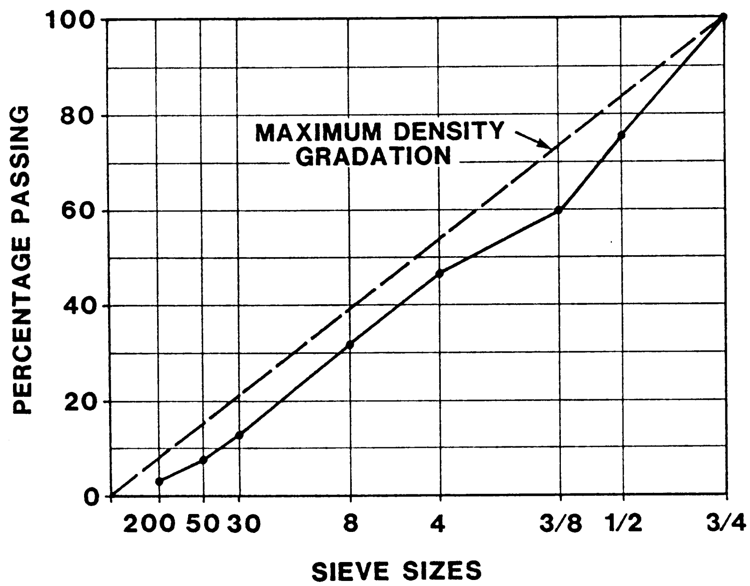


Figure 3. Experimental mix gradation plotted in relation to maximum density gradation.

in Virginia to specify the optimum asphalt content as that occurring at a voids total mix (VTM) of 4.0%, and this value is indicated by a dashed line on each design chart. Each property is then checked at the optimum asphalt content to ascertain whether the other design criteria are met. The criteria for the experimental mixes are given in Table 3.

As shown in Figures 4 through 7, the optimum asphalt content for the mixes varied from 4.5 to 4.6% for the 75-blow design and from 4.8 to 5.0% for the 50-blow design. It does not appear that either the liquid antistripping additive, lime, or grade of asphalt cement significantly affected the volumetric properties. The differences between stability and flow for the four mixes were probably due to testing variation. It appears from the mix design data that the gradation is more important than the binder and additive type; this verifies the theory of mix design and conforms to past experience.

Table 3

DESIGN CRITERIA FOR EXPERIMENTAL MIX

| | |
|---|---|
| Stability (lb) | 2,400 (minimum) |
| Flow (0.01 in) | 8-19 |
| VMA (%) | 14.8-19.0 |
| VFA (%) | 70-85 |
| VTM (%) | 3-5 |

## Marshall Design Charts

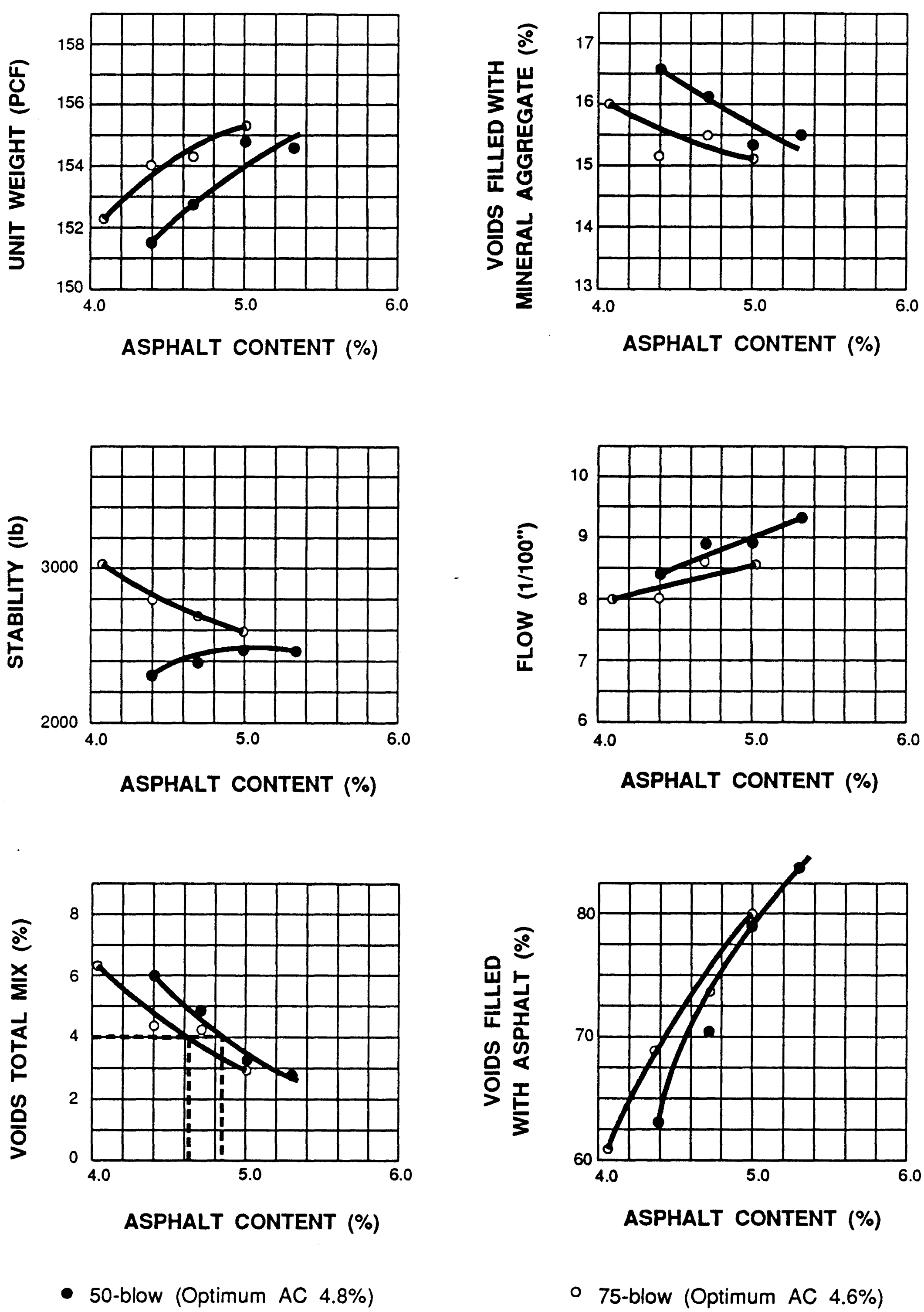


Figure 4. Design for Mix 1, AC-30 with 0.6% ACRA 2000.

## Marshall Design Charts

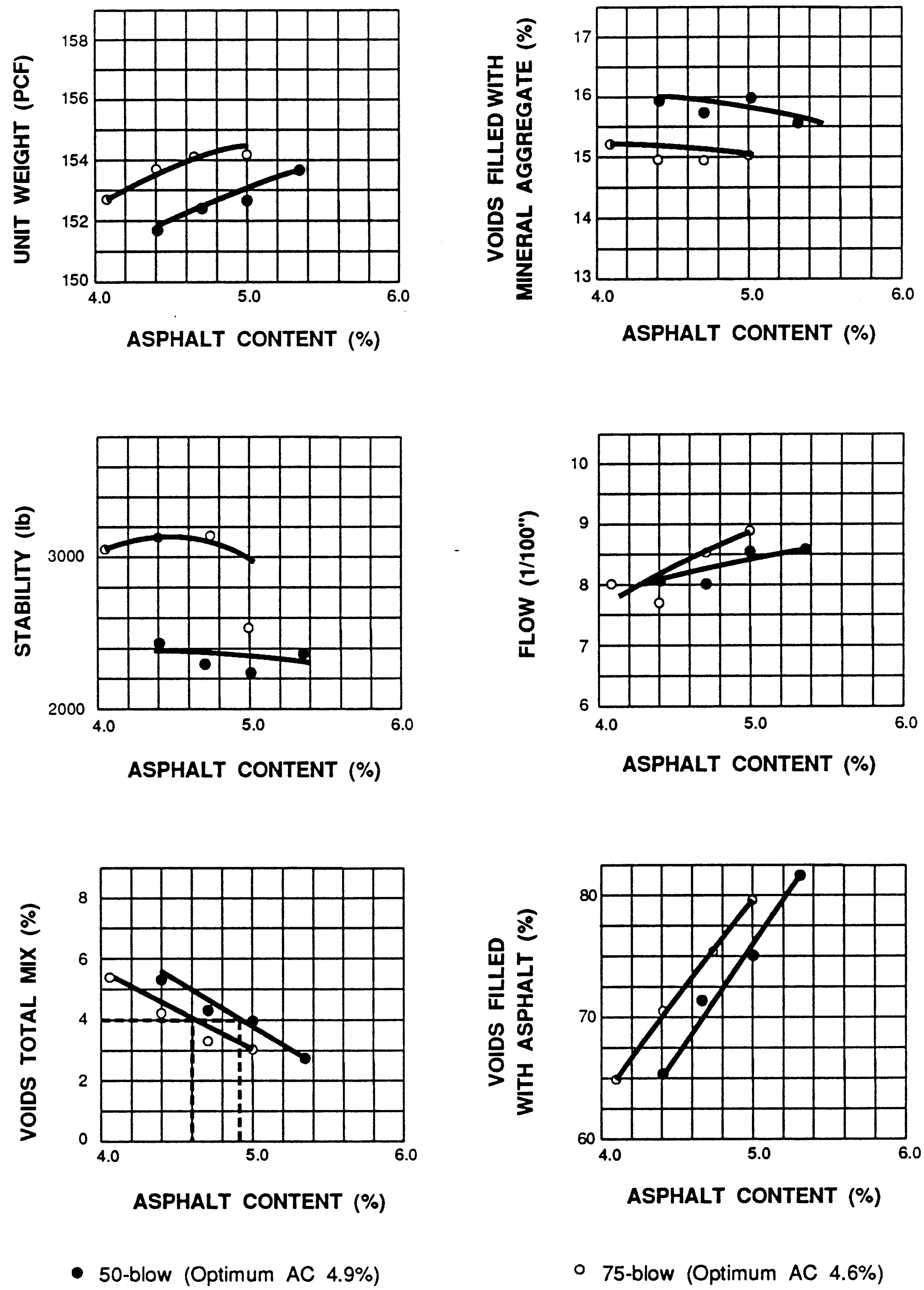


Figure 5. Design for Mix 2, AC-20 with 0.5% BA 2000.

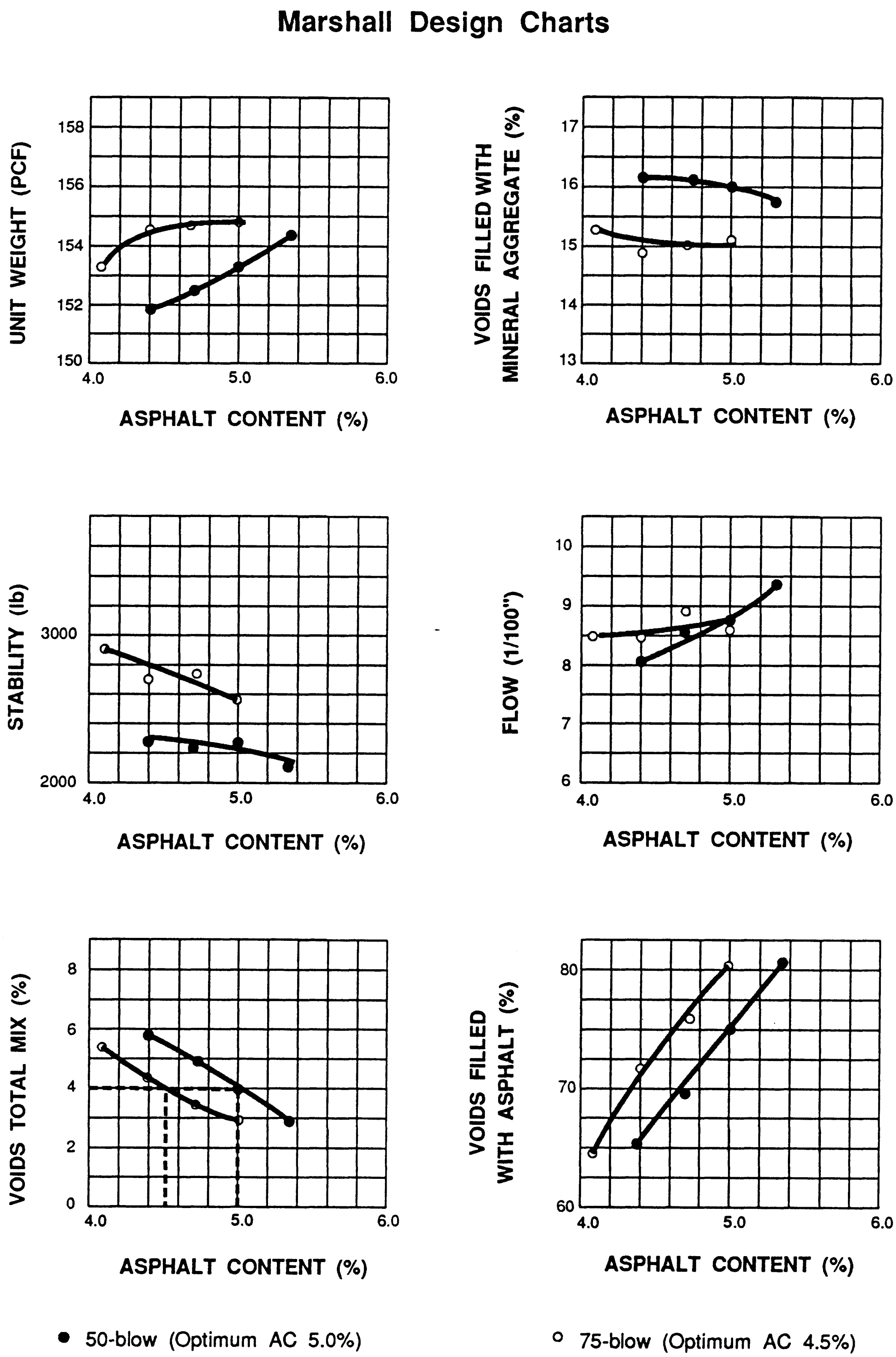


Figure 6. Design for Mix 3, AC-20 with 1% lime.

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## Marshall Design Charts

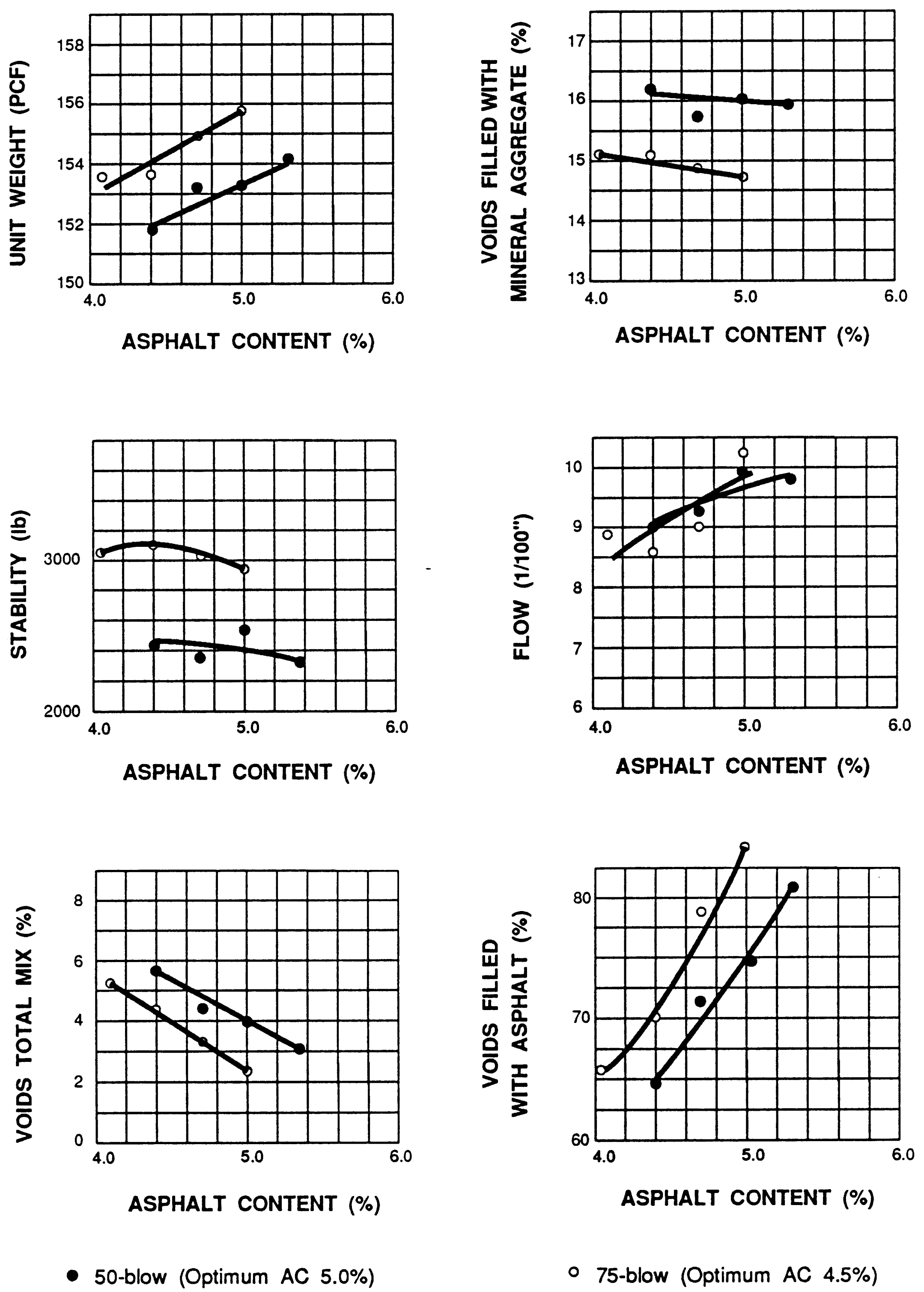


Figure 7. Design for Mix 4, AC-30 with 1% lime.

## PROPERTIES OF MIX INGREDIENTS

### Aggregates

Because of the previous rutting failures, there was concern that the mix gradation would not provide sufficient VMA to accommodate the asphalt and that this could result in flushing or instability. This concern led to an analysis of the specific gravity and absorptive properties of the aggregates to ensure that the void data were accurate. The results are listed in Table 4.

Table 4

AGGREGATE SPECIFIC GRAVITY AND ABSORPTION

| | |
|---|---|
| Bulk specific gravity | 2.76 |
| Apparent specific gravity | 2.78 |
| Effective specific gravity | 2.78 |
| Absorption (%) | 0.3 |

### Asphalt

The asphalt properties are given in Table 5. The viscosity of both asphalts at 140°F is slightly higher than the specification allows. The AC-30 asphalt cement appears slightly less temperature susceptible between 77°F and 140°F; but when its viscosity is plotted on a viscosity-temperature graph, it has about the same slope as the AC-20 asphalt cement above 140°F.

Table 5

ASPHALT PROPERTIES

| Property at Indicated Temperature | | AC-30 | | | AC-20 | | |
|---|---|---|---|---|---|---|---|
| | | Original | TFOT[a] | Ratio | Original | TFOT[a] | Ratio |
| Viscosity | 140oF (poises) | 3,612 | 10,038 | 2.78 | 2,465 | 5,946 | 2.41 |
| | 275oF (Cs) | 540 | 799 | 1.48 | 450 | 624 | 1.39 |
| Penetration | 77oF | 70 | 50 | | 69 | 46 | |
| | 66oF | 31 | 22 | | 30 | 23 | |
| | 50oF | 20 | 16 | | 19 | 14 | |
| | 45oF | 15 | 14 | | 13 | 12 | |
| | 39.2oF | 12 | 10 | | 9 | 8 | |
| Ductility | 77oF (cm) | 150+ | 133.5 | | 150+ | 150+ | |
| | 60oF (cm) | 65.5 | 10.5 | | 113.5 | 14.0 | |
| | 50oF (cm) | 9.2 | 4.8 | | 17.0 | 6.0 | |
| | 45oF (cm) | 5.8 | 4.0 | | 6.8 | 4.2 | |
| | 39.2oF (cm) | 4.2 | 3.2 | | 4.8 | 3.5 | |

[a]TFOT = thin film oven test.

In addition to the tests performed on the asphalts before construction, the Abson recovery procedure was used on samples of each mix. Table 6 gives a comparison of the averages for the original, thin film oven test (TFOT) and Abson results on asphalts and mixes sampled the same day. The values of the original and TFOT samples differ slightly from those shown in Table 5. The AC-20 asphalt cement with additive did not appear to harden as much in the plant as the TFOT predicted. The AC-30 asphalt cement with additive appeared to harden slightly more than this test predicted, and the AC-20 and AC-30 asphalt cements with lime hardened in the plant about as predicted.

Table 6

COMPARISON OF AVERAGES FOR ORIGINAL AND RECOVERED ASPHALTS

| Property | | Mix 1: AC-30, 0.6% ACRA 2000 | | | Mix 2: AC-20, 0.5% BA 2000 | | |
|---|---|---|---|---|---|---|---|
| | | Original | TFOT[a] | Abson | Original | TFOT[a] | Abson |
| Viscosity | $140^{o}$F (poises) | 3,356 | 9,987 | 13,990 | 2,489 | 6,427 | 4,689 |
| | $275^{o}$F (Cs) | 505 | 767 | 897 | 433 | 608 | 580 |
| Penetration | $77^{o}$F | 64 | 40 | 40 | 70 | 45 | 56 |
| % Loss | | | 0.2 | | | 0.2 | |

| Property | | Mix 3: AC-20, 1% lime | | | Mix 4: AC-30, 1% lime | | |
|---|---|---|---|---|---|---|---|
| | | Original | TFOT[a] | Abson | Original | TFOT[a] | Abson |
| Viscosity | $140^{o}$F (poises) | 2,564 | 6,024 | 6,296 | 3,573 | 9,767 | 10,931 |
| | $275^{o}$F (Cs) | 448 | 618 | 681 | 534 | 768 | 798 |
| Penetration | $77^{o}$F | 69 | 46 | 51 | 65 | 43 | 42 |
| % Loss | | | 0.1 | | | 0.1 | |

[a]TFOT = thin film oven test.

## INSTALLATION

Each mix required three days of paving (see Figure 2). The experimental mixes were placed in all three lanes of each section for a total length of the four sections of 3.7 mi. A total of 8,030 tons of mix was laid on the 78,000 $yd^2$ that was milled, for an average application rate of 205 $lb/yd^2$.

## TESTS ON FIELD SAMPLES

### Extractions

In addition to the normal samples taken and tested by the contractor and monitor samples tested by VDOT's Materials Division, samples were taken daily by the Virginia Transportation Research Council (VTRC) for determination of asphalt content and gradation. For convenience, the VTRC samples were taken initially from the paver hopper for Mix 1, whereas the contractor and monitor samples were taken from the haul truck at the plant. A difference in asphalt content (and the volumetric properties of the Marshall specimens) between the two sources sampled led to additional sampling by the VTRC from the haul trucks. It was believed that the truck samples were not representative of the asphalt content of the mix in the truck; therefore, the remaining mixes were sampled at both the plant and the road. The VTRC results are shown in Table 7, and the contractor and monitor sample results are shown in Appendix A. The averages and standard deviations of the contractor and monitor tests agreed very closely.

The average asphalt content from the plant samples was consistently lower than that of the samples taken from the paver. The addition of lime did not affect the gradation, particularly the -No. 200 portion. Although the asphalt contents of the samples obtained from the plant were consistently lower than those taken from the paver, the differences seen in the gradations would not indicate appreciable segregation.

Table 7

AVERAGE GRADATION AND ASPHALT CONTENT OF EXPERIMENTAL MIXES

| | Mix 1 | Mix 2 | | Mix 3 | | Mix 4 | | |
|---|---|---|---|---|---|---|---|---|
| Sieve Size | Road | Road | Plant | Road | Plant | Road | Plant | Job Mix |
| 3/4 in | 99.9 | 98.8 | 99.7 | 99.4 | 99.3 | 99.7 | 99.4 | 100 |
| 1/2 in | 79.5 | 71.3 | 74.9 | 76.7 | 74.8 | 76.8 | 73.3 | 76 |
| 3/8 in | 65.4 | 58.4 | 64.3 | 63.3 | 61.6 | 63.7 | 61.7 | 60 |
| No. 4 | 45.4 | 42.3 | 46.3 | 43.5 | 44.5 | 45.8 | 44.7 | 47 |
| No. 8 | 31.9 | 31.6 | 33.9 | 30.8 | 31.2 | 32.5 | 31.7 | 32.5 |
| No. 30 | 13.8 | 14.1 | 14.1 | 14.6 | 14.7 | 13.5 | 13.6 | 13 |
| No. 50 | 9.0 | 9.0 | 8.7 | 9.8 | 9.7 | 8.3 | 8.6 | 8 |
| No. 100 | 6.0 | 6.0 | 5.7 | 6.3 | 6.2 | 5.3 | 5.6 | - |
| No. 200 | 3.2 | 3.8 | 3.4 | 3.7 | 3.6 | 3.2 | 3.5 | 3.5 |
| AC (%) | 4.60 | 4.48 | 4.27 | 4.42 | 4.30 | 4.68 | 4.22 | 4.5 |

## Marshall Results

Marshall results for the mixes compacted with a 75-blow effort were determined on the samples taken daily and are shown in Table 8. The contractor and state Marshall results are given in Appendix B.

The lower asphalt content of the plant samples made a considerable difference in some of the volumetric properties. For instance, for Mix 2 it appears that the VTM values were too high and, conversely, the voids filled with asphalt (VFA) values too low. However, the results for the samples from the paver agreed very closely with the original design values. As the project progressed, the plant operator did attempt to change the operation of the discharge gates to try to reduce what was thought to be segregation and the resultant discrepancy in asphalt content. As anticipated from the design data, no differences were found in the Marshall properties among the mixes. Table 8 does provide an indication of typical variability in mix properties found in a project under good control. Mix 3 had an average VMA lower than desired.

Table 8

AVERAGE MARSHALL PROPERTIES FOR EXPERIMENTAL MIXES

| | Mix 1 | Mix 2 | | Mix 3 | | Mix 4 | |
|---|---|---|---|---|---|---|---|
| Property | Road | Road | Plant | Road | Plant | Road | Plant |
| AC (%) | 4.58 | 4.48 | 4.27 | 4.42 | 4.30 | 4.68 | 4.22 |
| Density (lb/ft$^3$) | 150.6 | 149.7 | 147.6 | 151.2 | 150.7 | 149.6 | 149.6 |
| Stability (lb) | 3235 | 2973 | 2755 | 3075 | 3216 | 3066 | 3325 |
| Flow (0.01 in) | 8.2 | 8.9 | 8.3 | 9.7 | 9.2 | 9.2 | 9.1 |
| VTM (%) | 4.0 | 4.0 | 6.3 | 3.3 | 4.0 | 4.4 | 4.6 |
| VMA (%) | 14.8 | 14.5 | 16.1 | 13.8 | 14.2 | 15.4 | 14.5 |
| VFA (%) | 73.0 | 72.4 | 60.1 | 76.1 | 71.6 | 71.4 | 68.3 |
| Maximum theoretical specific gravity | 2.518 | 2.508 | 2.528 | 2.512 | 2.520 | 2.512 | 2.516 |

## Resilient Modulus and Tensile Strength

It was known from the mix design that Marshall stabilities would not differ appreciably from one mix to another, so other measures of strength were used to try to discern a difference among mixes. The resilient modulus test (Schmidt device) was run with a load pulse of 0.1 sec at a stress level of approximately 2 lbf/in$^2$. Both resilient modulus and tensile strength were determined at 104$^o$F. The results of both tests are shown in Table 9. The compactive effort used was such as to simulate the VTM in the compacted pavement.

These results indicate that Mixes 1 and 4 were significantly stiffer than Mixes 2 and 3 at an α probability of 2.5%; they also show that AC-30 asphalt cement has a greater role in determining the mix stiffness than does the type of antistripping additive used.

Table 9

AVERAGE RESILIENT MODULUS AND TENSILE STRENGTH RESULTS

| Property | | Mix 1 | Mix 2 | Mix 3 | Mix 4 |
|---|---|---|---|---|---|
| VTM (%) | | 7.5 | 8.3 | 8.1 | 8.1 |
| Resilient modulus | $\bar{X}$ (lbf/in$^2$) | 33,000 | 17,000 | 20,000 | 28,000 |
| | $\sigma$ (lbf/in$^2$) | 300 | 300 | 200 | 400 |
| Tensile strength | $\bar{X}$ (lbf/in$^2$) | 46 | 31 | 33 | 42 |
| | $\sigma$ (lbf/in$^2$) | 3.5 | 7.2 | 3.8 | 4.0 |

## Initial Stripping Tests

Since one of the experimental variables was the type of antistripping additive used, an analysis of the stripping potential of the aggregate with and without additives was made. The aggregate used in the mixes has historically had a tendency to strip, as evidenced by the modified Lottman test (3), with tensile strength ratio (TSR) values in the high 40s.

Modified Lottman stripping tests made in 1985, however, showed that even without an antistripping additive, the aggregate had high values (see Table 10). The mixes containing no additive were tested prior to construction; the tests for those with additives were made on samples taken during construction.

There is a statistically significant difference between the TSR value for Mix 4 and those for the other mixes. The strength values from mixes with no additive (which were mixed in the laboratory) are significantly lower than for some mixes with additive, which were from plant-mixed samples. Although the TSR values of mixes with no additive are comparable to those of mixes with additive, the conditioned and dry strengths are not. These data indicate the need for a minimum conditioned or dry strength in addition to a minimum TSR. Although all TSR values were very high, stripping has been observed in all sections.

Table 10

STRIPPING TEST RESULTS (STRENGTH IN $LB/IN^2$)

| Asphalt | Additive | Conditioned | Dry | Tensile Strength Ratio |
|---|---|---|---|---|
| AC-20 | None | 78 | 87 | 0.90 |
| AC-30 | None | 76 | 83 | 0.92 |
| AC-30 | ACRA 2000 (Mix 1) | 108 | 120 | 0.90 |
| AC-20 | BA 2000 (Mix 2) | 89 | 96 | 0.93 |
| AC-20 | Lime (Mix 3) | 106 | 117 | 0.91 |
| AC-30 | Lime (Mix 4) | 97 | 118 | 0.82 |

## PERFORMANCE

The primary performance measure of interest is rutting. In addition to rutting measurements, changes in density and road roughness are possible indicators of rutting. In this section, the results of density tests and rut measurements taken during construction and the results of roughness measurements taken just after construction are compared to results of tests and measurements taken periodically after construction. Only rut measurements were taken at 1 and 3 months, and both rut measurements and cores were taken at 6, 12, 18, 24, 36, and 48 months after construction. The general performance of the mixes has been very good.

### Air Void Results

In the opinion of the author, adequate density is always necessary for good pavement performance. It was particularly important for the mixes used in the present project because if low air voids (6 to 8%) were not achieved during construction, heavy truck loads and high tire pressures certainly would consolidate the wheel paths and create ruts.

The results of the tests to determine air voids of the mixes taken at the time of construction and at the specified intervals are shown in Table 11. At the time of construction, sawed plugs were taken immediately after rolling from all three lanes on each mix. At the intervals of 6 to 48 months, cores were taken only from the traffic lane because of the heavy traffic condition. At the interval of 6 to 36 months, 6 cores were taken from each mix, but the fluctuations in averages and standard deviations contributed to a lack of definitive trends. Thus, 12 cores per mix were taken at the 48-month evaluation to increase the accuracy of the estimate of the average.

Table 11

AIR VOID RESULTS (%)

| | Mix 1 | Mix 2 | Mix 3 | Mix 4 |
|---|---|---|---|---|
| Initial[a] | 8.5 | 8.0 | 7.8 | 7.3 |
| 6 months[b] | 7.7 (1.6)[c] | 7.0 (1.7) | 7.3 (1.7) | 6.4 (0.9) |
| 12 months | 7.1 (2.3) | 6.6 (1.9) | 6.5 (2.1) | 6.0 (1.4) |
| 18 months | 6.0 (1.7) | 6.4 (1.8) | 5.7 (1.1) | 6.7 (2.0) |
| 24 months | 6.5 (2.1) | 5.4 (1.4) | 5.7 (1.6) | 5.9 (2.2) |
| 36 months | 5.5 (2.2) | 5.5 (2.3) | 6.6 (1.4) | 6.8 (1.4) |
| 48 months | 6.2 (0.9) | 5.5 (1.1) | 5.2 (1.5) | 5.9 (1.2) |
| Void difference Initial-48 months | 2.3 | 2.5 | 2.6 | 1.4 |

[a]All three lanes.
[b]Only traffic lane.
[c]( ) standard deviations.

These data indicate an interesting trend in the decrease in air voids. If smooth curves are used to estimate the air void trends (Figure 8), it can be seen that a decrease in air voids occurs for about the first 24 months and then the air voids tend to remain constant. (Mix 3 is somewhat of an anomaly in that the air voids continue to decrease even up to 48 months. The roughness and rut values are also different than those of the other mixes.) The decrease in air voids can be considered consolidation attributable to compaction under traffic, which accounts for the relatively minor rutting that has taken place in the mixes.

It does appear that in well-graded mixes most of the additional compaction from traffic and the subsequent decrease in air voids take place in the first 2 years of service. Furthermore, the decrease in air voids in these mixes ranged from about 1.5 to 2.5%.

The final air voids (48 months) are about 1 to 2% higher than the 4% air voids used to chose the optimum asphalt content. Although it is well understood that the Marshall design procedure used to select the optimum asphalt content is an empirical procedure, the data obtained in this report indicate that the 75-blow compactive effort provides a conservative estimate of the optimum asphalt content, at least as far as overfilling of the voids, which is a primary cause of plastic deformation, is concerned.

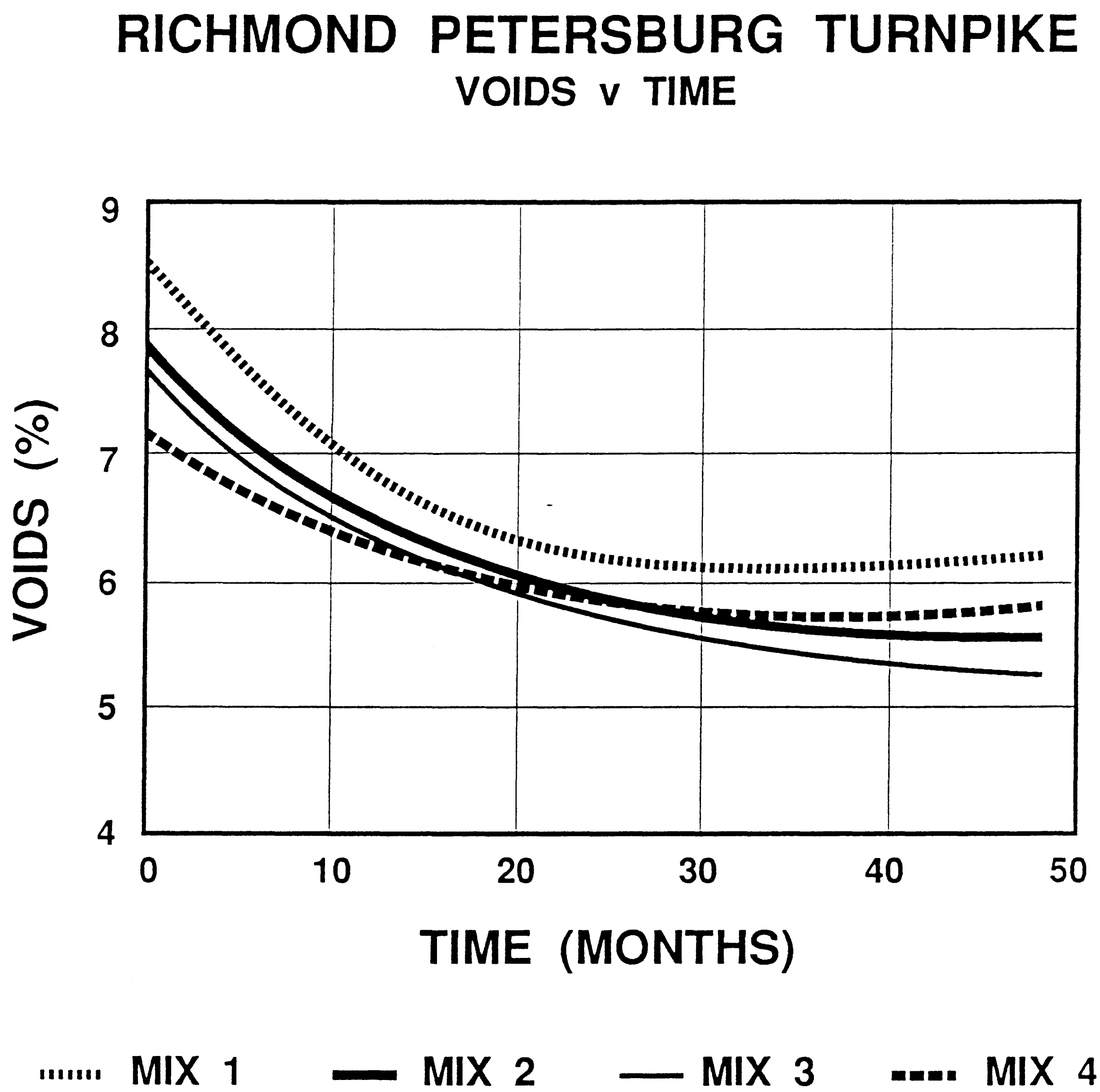


Figure 8. Smooth curves depicting voids vs. time.

## Pavement Roughness

Roughness tests were run with a May's meter soon after construction to establish a baseline against which future roughness values could be compared. It was not anticipated that significant differences attributable to mix type would be found. Roughness values are given in Table 12.

Table 12

AVERAGE ROUGHNESS RESULTS (IN/MI)

| Mix | Initial | 12 Months | 24 Months | 36 months |
|---|---|---|---|---|
| 1 | 90.2 | 85.8 | 85.9 | 87.2 |
| 2 | 84.0 | 79.9 | 82.2 | 81.7 |
| 3 | 80.9 | 75.6 | 77.3 | 79.0 |
| 4 | 87.2 | 82.1 | 84.1 | 82.9 |

The vehicle in which the May's meter was installed was replaced between the 36- and 48-month readings, and an adequate calibration was not obtained on the new vehicle so as to provide accurate roughness data at the 48-month interval.

The data for the 36 months measured show that all four mixes tended to become smoother within the first 12 months, after which the roughness tended to be fairly consistent. Again, Mix 3 was somewhat different in that the roughness increased slightly after 12 months. This trend by itself would not have much meaning, but as will be discussed later, this is the mix that has tended to rut more than the other three. It is possible that the tendency to become rougher is related to the rutting.

## Rut Depths

### Measurement

A 6-ft bow (Figure 9) was used for all rut depths. The bow was made to measure rut depths in 0.05-in increments. Because of the relatively coarse texture of the mix, a "within test" variability was found to have a standard deviation of 0.03 in. Thus, small differences (e.g., 0.005 in) are not significant.

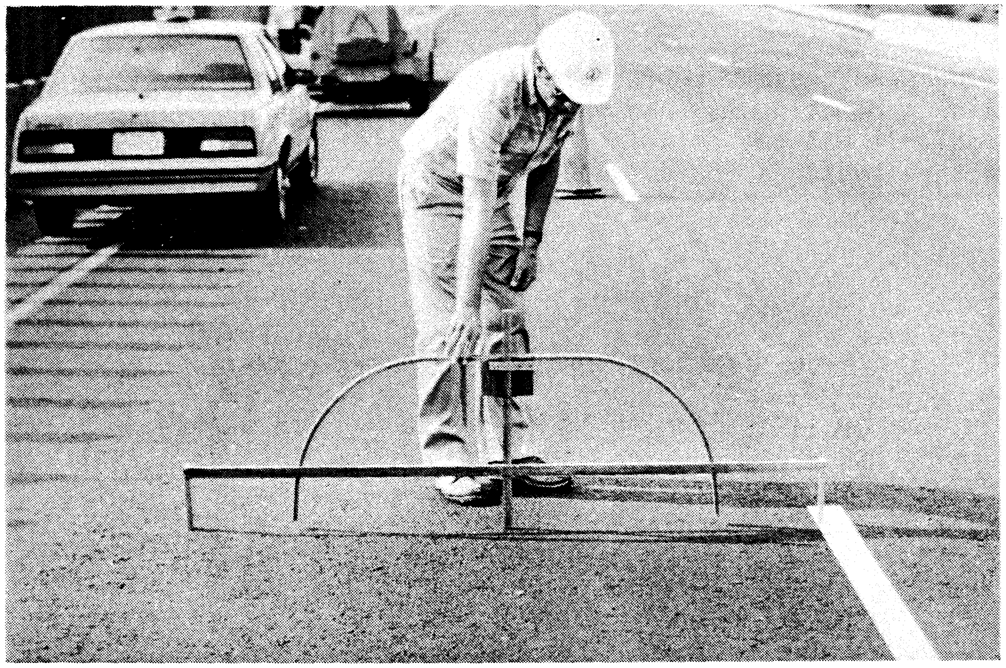

Figure 9. Six-foot bow used to measure ruts.

Rut Depths--1st 24 Hours

No ruts greater than 0.05 in were found after rolling was completed and before the lane was opened to traffic. The minor rutting that was found after one day's traffic appeared to occur most frequently in the inside and middle lanes and toward the end of the day where traffic was the heaviest and the temperatures warmest. Thus, the rutting that did occur was probably caused by early traffic, even though traffic was not allowed on the new pavement until its surface temperature was $150^{\circ}F$ or lower. The rutting was not a static condition but dynamic in that the ruts tended to change (move) slightly under traffic and on hot days. Although some of the change was probably due to the variability mentioned earlier, some rutted areas tended to "iron out," whereas others appeared to rut slightly more. This occurrence was associated with temperature rather than with type of binder or additive.

Rut Depths--1 to 48 Months

The 6-ft bow was used to measure rut depths in the right and left wheel paths of all three lanes approximately 1 and 3 months after construction. At 6 months and at all other intervals after construction, these measurements were repeated, but only in the traffic and inside lanes owing to considerations of safety.

## Rut Depth Analysis

The average rut depths for the inside and traffic lanes are shown in Table 13 and Figure 10. Other than for Mix 3, only very minor rutting occurred (i.e., approximately 0.10 in or less). The traffic lane of Mix 3 had appreciably more rutting than the other mixes. This rutting became noticeable at about 12 months and has continued to increase, reaching an average of almost 1/4 in at 48 months. Although 1/4-in ruts are not considered excessive, some ruts in this mix were measured at 0.6 in--deep enough to raise a concern. As Figure 10 shows, Mixes 1, 2, and 4 tended to level out at about 24 months, whereas Mix 3 has continued to rut. This is in agreement with the relationship of air voids and time.

The reasons for the greater degree of rutting in Mix 3 are not entirely clear. The gradation indicates a possible source of minor rutting in that the percentage passing the No. 30 sieve for Mix 3 is higher than for the other mixes, indicating that there may be slightly more sand in this mix than in the others. However, the slight increase in the percentage passing the No. 30 sieve did not cause a hump in the gradation curve, which is an indicator of a tender mix. Possibly associated with this higher percentage passing the No. 30 sieve is the VMA result, which averaged 13.8%, a lower than desirable value. Although the asphalt content was essentially the design content, the VTM of the mix was 3.3% and the VFA 76.1%. Both of these values are the extreme values for all mixes. This reinforces the thought that the gradation was at least part of the problem in that there was not sufficient room in the aggregate to accommodate the asphalt as called for in the design.

It is encouraging that even with the rutting that has taken place in Mix 3, the in-place air voids are still above 5.0 percent, indicating that consolidation (due to the mix more easily being compacted under traffic) is the cause of the rutting and that plastic deformation has not occurred.

Since Mix 3 has had a greater tendency to compact under traffic, it is theorized that it should have been readily possible to reduce the air voids below 7.8% at the time of construction. This would have reduced both the likelihood of and ability for the mix to compact as much as it has under traffic.

## Moisture Damage

Although the initial TSR results for stripping indicated little likelihood of moisture damage, cores taken at various intervals indicate that some stripping is occurring in all mixes. Moisture damage has been assessed by three procedures: Visual estimates of stripping have been made, TSR values have been determined using a conditioning procedure previously employed in this study, and a procedure similar to that developed by Maupin (4) has been used to compare "original," present, and future strengths.

Table 13

AVERAGE RUT DEPTHS (IN)

| Mix | Inside Lane | Traffic Lane |
|---|---|---|
| **Mix 1** | | |
| 1 Month | -.03 | -.05 |
| 3 Months | -.04 | .01 |
| 6 Months | .05 | .04 |
| 12 Months | .06 | .09 |
| 18 Months | .05 | .08 |
| 24 Months | .05 | .13 |
| 36 Months | .04 | .10 |
| 48 Months | .08 | .09 |
| **Mix 2** | | |
| 1 Month | .00 | -.03 |
| 3 Months | .03 | -.05 |
| 6 Months | .02 | .04 |
| 12 Months | .02 | .06 |
| 18 Months | .01 | .09 |
| 24 Months | .01 | .12 |
| 36 Months | .04 | .11 |
| 48 Months | .08 | .12 |
| **Mix 3** | | |
| 1 Month | -.04 | -.04 |
| 3 Months | -.05 | -.08 |
| 6 Months | .03 | .06 |
| 12 Months | .06 | .11 |
| 18 Months | .04 | .10 |
| 24 Months | .05 | .17 |
| 36 Months | .05 | .22 |
| 48 Months | .08 | .24 |
| **Mix 4** | | |
| 1 Month | .02 | -.01 |
| 3 Months | .01 | .02 |
| 6 Months | .01 | .02 |
| 12 Months | .04 | .05 |
| 18 Months | .00 | .08 |
| 24 Months | .02 | .08 |
| 36 Months | .02 | .06 |
| 48 Months | .06 | .10 |

+ = Rut.
- = Hump.

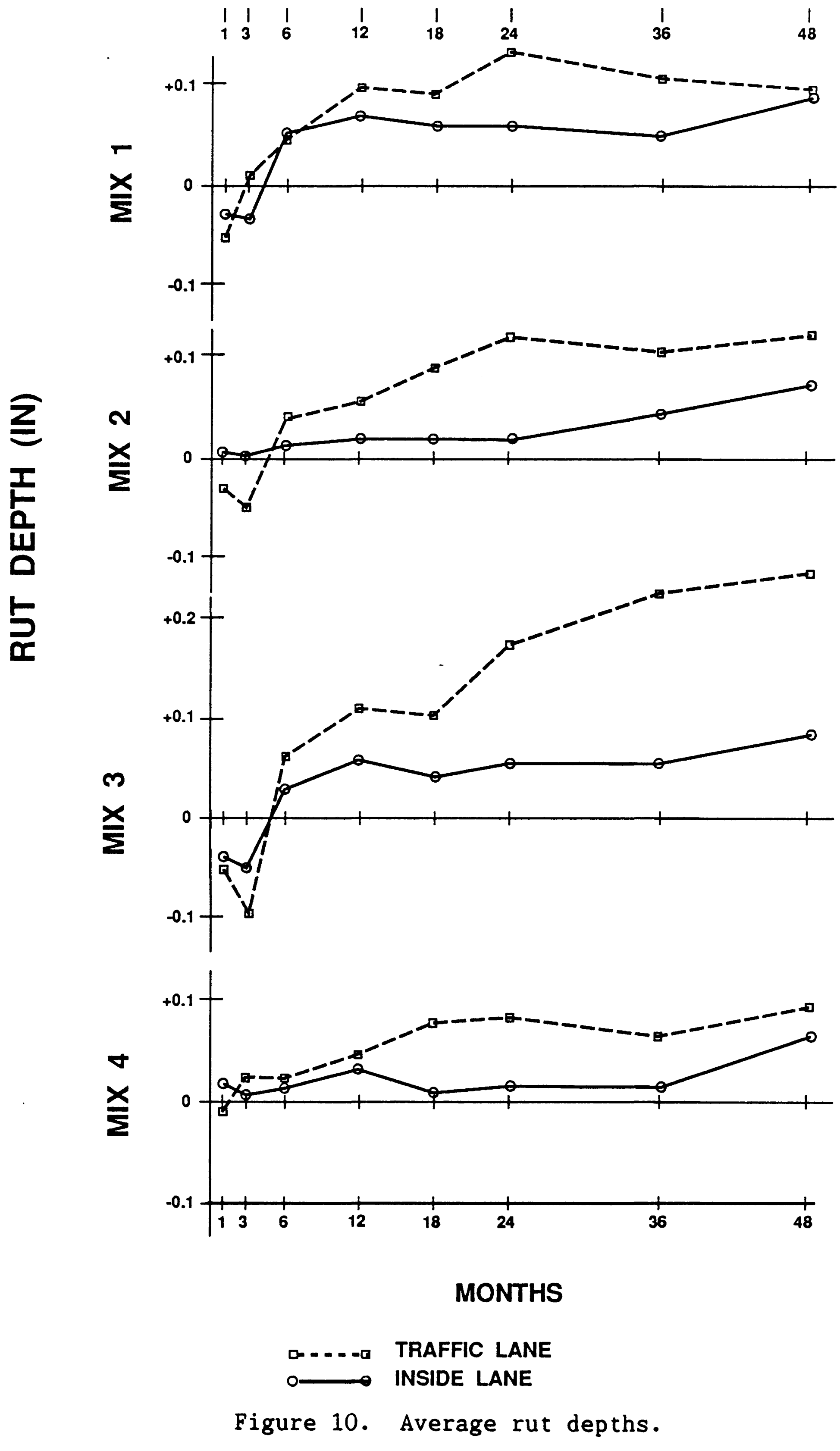


Figure 10. Average rut depths.

The visual estimates of stripping were made on cores soon after being taken, before they were allowed to dry and heal. These results indicate that all mixes had about 15% stripping. However, the stripping is limited to the coarse aggregate (Figure 11), which does not tend to produce a failure condition as quickly as if the stripping were in the fine aggregate matrix. Thus, although some stripping is taking place, widespread stripping failures are not imminent.

TSR values, determined using the modified Lottman procedure, are shown in Figure 12. This method of calculating TSR uses "dry" core strengths divided by "conditioned" core strengths, which predict future strengths. The conditioning consisted of vacuum saturating the cores, placing them in a $0^{o}$F freezer for 15 hours, and then placing them in a $140^{o}$F water bath for 24 hours. Thus, these TSR values are indicators as to what relative strengths the pavement may have in 5 to 10 years. These TSR values are all above the minimum of 0.3 recommended by Maupin (4), and this indicates that stripping will not be a predominant failure mode. Thus, for this mix, lime and the two liquid antistripping additives appear equally effective.

Figure 13 shows the results of the modification of a procedure developed by Maupin (4) to assess stripping. Cores are tested in three groups: (1) unstripped, (2) present, and (3) future. The unstripped and future indirect tensile strengths are the values discussed above as dry and conditioned, respectively. "Present" uses indirect tensile strength from cores tested soon after being taken (same as used for visual stripping). These results indicate that stripping is not likely to be a predominant failure mode in these mixes. This conclusion is based on a recommended minimum indirect tensile strength of 40 psi and a minimum TSR of 0.3.

## OBSERVATIONS AND DISCUSSION OF PERFORMANCE

The interaction between surface temperature and traffic had the greatest influence on early performance. When the surface temperature was reduced to a maximum of $150^{o}$F, the mix appeared to be sufficiently stable to resist rutting. However, this temperature guideline borders on the critical temperature for continued compaction. Although the surface temperature may only be $150^{o}$F, the interior of the 2-in mat is most certainly higher. Thus, keeping traffic off of the hot asphalt as long as possible is essential to eliminating initial rutting.

The only appreciable rutting (i.e., that exceeded 1/4 in) occurred with Mix 3. This is most probably related to the relatively low VMA of this mix. The viscosity of the asphalt-additive binder combination does not appear as important as the gradation, probably because the gradation was chosen to provide sufficient aggregate interlock to minimize the effect of binder viscosity. However, if sufficient aggregate interlock had not been obtained, binder viscosity would have been more important and, based on the Abson and resilient modulus results, the AC-30 asphalt cement with either lime or a liquid antistripping agent would have been beneficial.

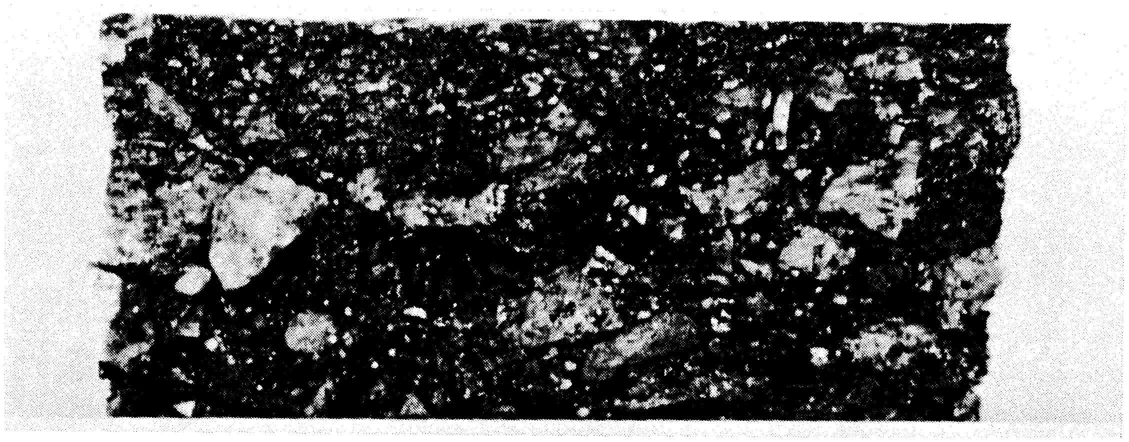

Figure 11. Typical stripping in coarse aggregate.

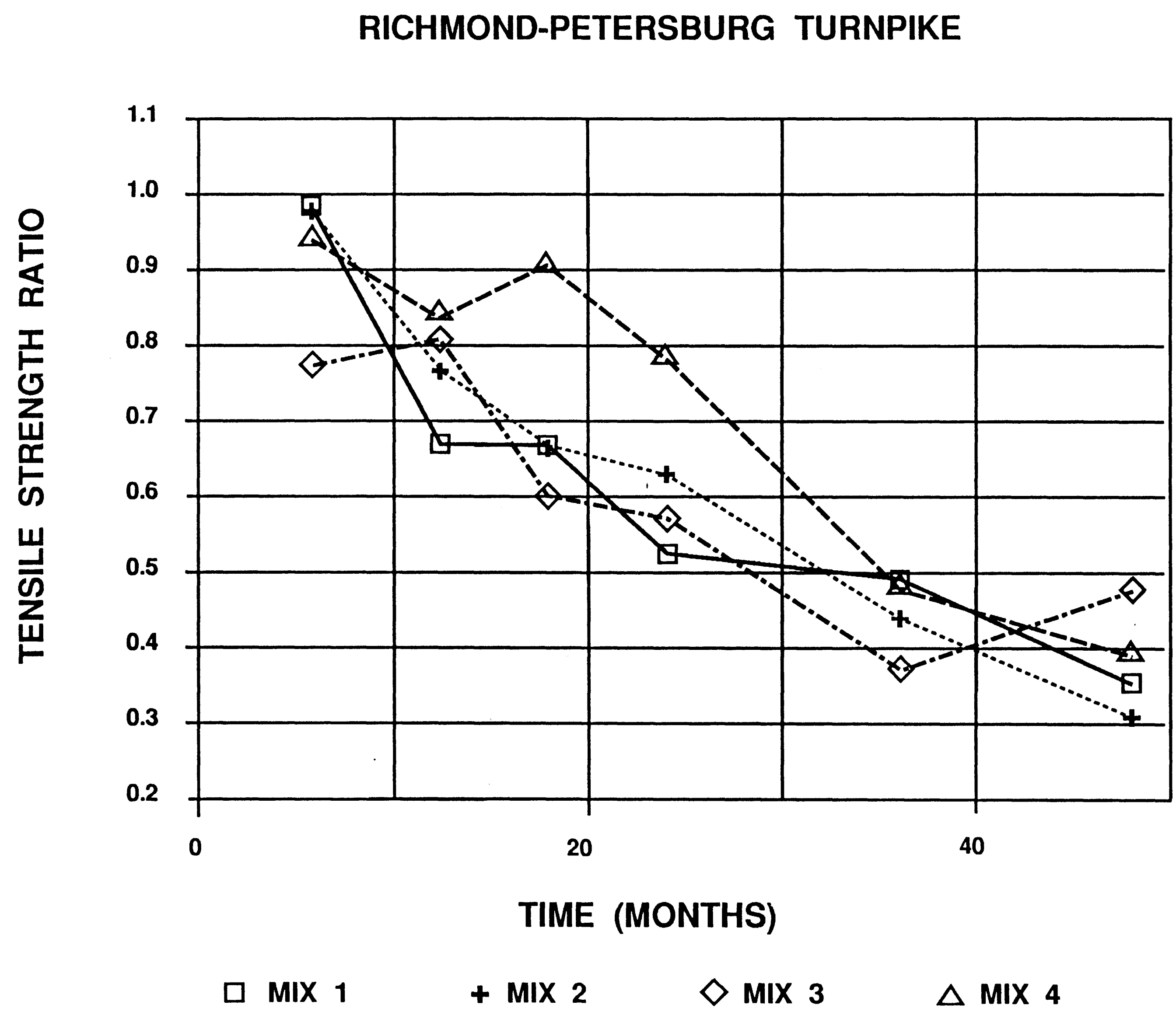


Figure 12. Tensile strength ratio vs. time.

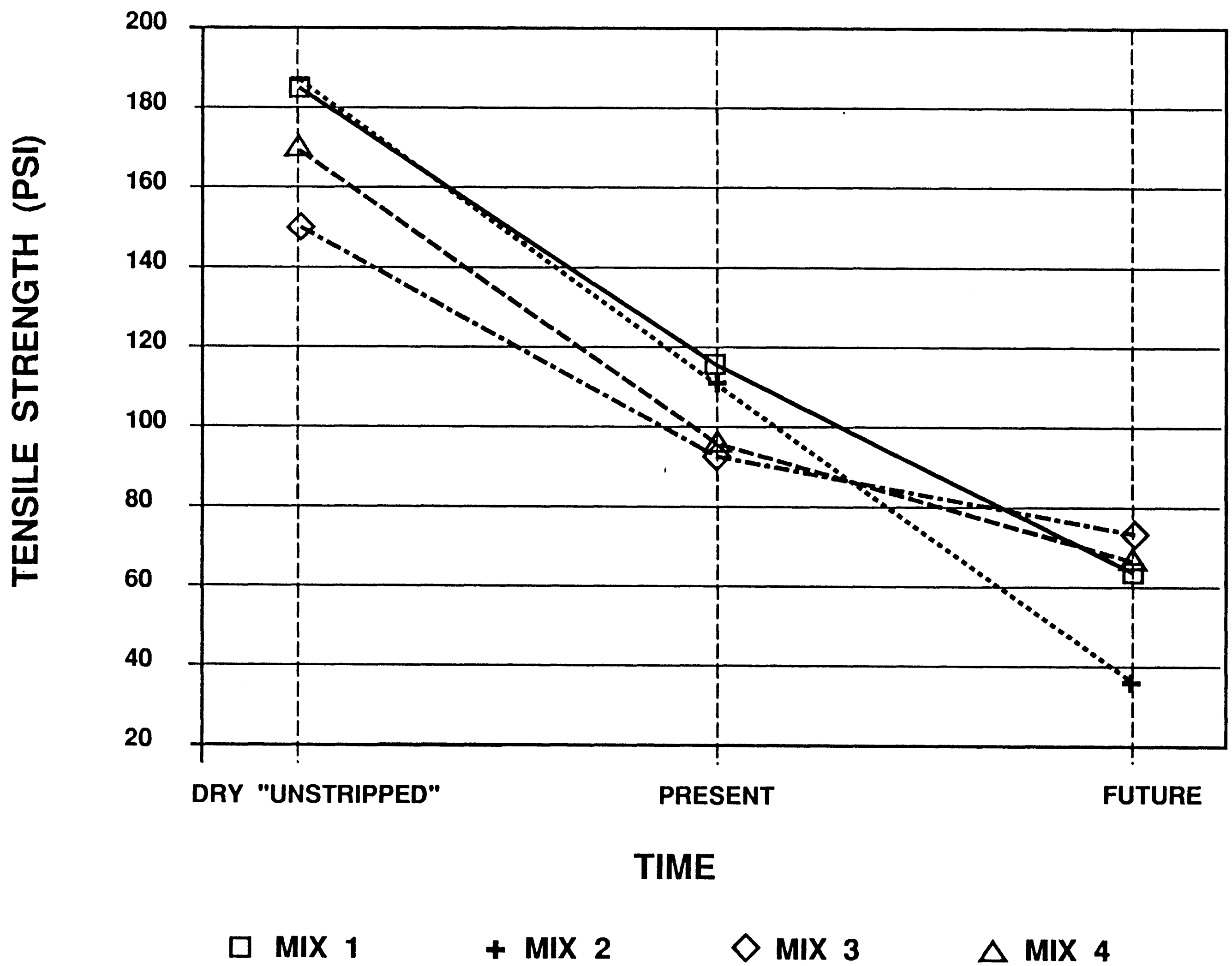


Figure 13. Tensile strength related to unstripped, present, and future condition.

Other than the rutting in Mix 3, very little other distress has been observed. There is some longitudinal cracking in Mix 1. Cores taken from the cracked areas indicate that stripping in the asphalt base, which is entirely unrelated to the experimental mix, is the cause of this cracking. Subbase fines pumped to the surface in those cracked areas is also an indication that the problem is deep seated.

## TRAFFIC ANALYSIS

The experimental sections are located in the southbound lanes of a three-lane roadway about 30,000 vehicles per day (VPD) in one direction. The traffic count in 1988 had increased to over 38,000 VPD. The test section starts adjacent to an on-ramp from a heavy industrial area and ends at an off-ramp to a heavy industrial area. In an attempt to estimate the daily 18-kip equivalent loads per lane, Table 2-7 in the Highway Capacity Manual (5) was used. Data from the table for the Lodge Freeway in Detroit were used to provide the vehicle count and was used with an equation by Vaswani and Thacker (6) to obtain the estimated 18-kip equivalents per lane as shown in Table 14.

Using a linear relationship with time of the estimated daily 18-kip equivalent loads to predict accumulated 18-kip equivalents for the traffic lane shows that 10.6 million 18-kip equivalent loads were placed on the traffic lane for the 4-year duration of this study. This is very heavy traffic and a tribute to the mix that it has withstood this traffic level and performed well.

Table 14

ESTIMATED DAILY 18-KIP EQUIVALENT LOADS

| | Traffic Lane | Middle Lane | Inside Lane |
|---|---|---|---|
| 1985 | 6,400 | 1,100 | 800 |
| 1988 | 8,100 | 1,400 | 1,000 |

## COSTS

The cost for each mix in place is shown in Table 15. Based on these figures, the average increase in cost of using 1% lime over that of using a liquid antistripping agent was $2.62 per ton, and the average increase in cost of using AC-30 asphalt cement over that of using AC-20 asphalt cement was $1.12 per ton.

Table 15

MIX COST

| Mix | Cost/Ton |
|---|---|
| 1 | $34.45 |
| 2 | 33.40 |
| 3 | 35.95 |
| 4 | 37.14 |

## CONCLUSIONS

The performance of four mixes designed to resist rutting was evaluated over 48 months of service. Based on the performance of these mixes, the following conclusions are offered.

1. The binder types and antistripping additives do not appear to be as important as the gradation in minimizing rutting. This conclusion is certainly related to the gradation used and possibly the type and shape of aggregate.

2. Early rutting (sooner than 1 month) appears to be influenced greatly by the temperature of the pavement when it is opened to traffic.

3. Rutting during the 48 months appears to be influenced by the air voids obtained during construction, which has an impact on the consolidation that takes place. A low VMA also appears to have influenced the rutting of Mix 3.

4. The air voids have a tendency to decrease for about 2 years and then stabilize. The decrease in air voids ranged from 1.5 to 2.5%, stabilizing at an air void content of about 5 to 6%.

5. The roughness of the pavement decreased slightly over the first year of service and has changed very little after that period.

6. Visual estimates, TSR, and indirect tensile strengths all indicate that moisture damage is taking place. However, major damage from this failure mode is not apparent. Lime and the two liquid antistripping additives appear comparably effective.

1808

## ACKNOWLEDGMENTS

This project was carried out under very difficult traffic conditions. Without the cooperation of everyone involved, the data collection would have been much more difficult. Thanks go to the contractor, APAC-VA, and Frank Fee of the asphalt supplier, Elf Asphalt, who was extremely cooperative in trying to produce asphalts with a reasonably low temperature susceptibility. The Turnpike personnel were also extremely helpful. The Materials Division, as usual, was most cooperative. Often, VTRC personnel are not acknowledged because the research is part of their job. But in this case, L. E. Wood went beyond what is normally expected in being on the job, collecting samples, and running the lab tests. Special thanks go to G. W. Maupin for his encouragement and advice.

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# APPENDIX A

## RESULTS OF PRODUCTION AND MONITOR EXTRACTION TESTS

Percentage Passing

| Sieve Size | Contractor[a] $\bar{X}$ | Contractor[a] $\sigma$ | Monitor[b] $\bar{X}$ | Monitor[b] $\sigma$ | Job Mix |
|---|---|---|---|---|---|
| 3/4 in | 99.1 | 1.1 | 99.5 | 0.8 | 100 |
| 1/2 in | 75.4 | 3.1 | 75.1 | 2.8 | 76.0 |
| 3/8 in | 62.7 | 3.2 | 62.1 | 2.8 | 60.0 |
| No. 4 | 46.1 | 2.6 | 45.1 | 2.4 | 47.0 |
| No. 8 | 34.1 | 2.4 | 32.8 | 2.1 | 32.5 |
| No. 30 | 14.7 | 1.4 | 14.3 | 1.1 | 13.0 |
| No. 50 | 9.3 | 1.1 | 9.1 | 0.9 | 8.0 |
| No. 200 | 3.6 | 0.6 | 3.1 | 0.5 | 3.5 |
| AC (%) | 4.33 | 0.17 | 4.30 | 0.17 | 4.50 |
| F/A | 0.82 | 0.10 | 0.71 | 0.11 | 0.78 |

[a]N = 35.
[b]N = 41.

1816

# APPENDIX B

## CONTRACTOR AND STATE MARSHALL RESULTS

1818

| | Contractor[a] | | State[b] | |
|---|---|---|---|---|
| | $\overline{X}$ | $\sigma$ | $\overline{X}$ | $\sigma$ |
| Stability (lb) | 3,140 | 280 | 2,900 | 310 |
| Flow (0.01 in) | 10.9 | 1.0 | 9.8 | 1.0 |
| VMA (%) | 14.4 | 0.8 | 14.9 | 0.8 |
| VFA (%) | 71.7 | 3.7 | 67.5 | 4.4 |
| VTM (%) | 4.1 | 0.7 | 4.9 | 0.9 |
| Maximum theoretical specific gravity | 2.520 | 0.02 | 2.512 | 0.01 |

[a]N = 33.
[b]N = 33.

1820