Properties of Fly Ash–Extended Asphalt Concrete Mixes

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Fillers added to asphalt concrete mixes have long been used as stiffening, extending, or otherwise void-filling materials, depending on their type and particle size. Fly ash, a by-product of the coal-burning process for power generation, is a filler that can serve one or more of the above-mentioned functions. The role of fly ash in asphalt concrete mixes has been investigated. Three sizes of fly ash (coarse, medium, and fine) were used. The effect of these fly ash sizes on the resilient modulus, rutting potential, and water resistance of these mixes was investigated. It was found that the medium-size fly ash was the best size for an asphalt extender.

Fly ash is a finely divided residue that results from furnace-burned pulverized bituminous coal. Electrical generation is the prime consumer of coal produced in the United States and, consequently, the prime producer of fly ash. In the United States, the annual production of fly ash increased from about 43 million tons in 1975 to about 60 million tons in 1979; the utilized amount during that time increased from about 5 million tons, or 10.6 percent of the production, to about 10.0 million tons, or 17.4 percent (*1*). From these figures, it is clear that there is a huge amount of unused fly ash that must be disposed of each year. This not only costs power companies money but also creates a disposal problem.

Asphalt pavement usually consists of three components: asphalt, aggregates, and air. Because nearly all asphalts used in road construction are of crude oil origin, the increase in crude oil prices in recent years has resulted in an increase in asphalt prices. The dwindling world resources of oil have increased concerns about the asphalt supply for highway pavements. In addition, a considerable portion of asphalt-type highways in the United States are deteriorating as a result of heavy loads and unfavorable weather conditions. All of this has led many researchers and agencies to look for ways of reducing the amount of the required asphalt and improving pavement resistance against loading and moisture damage.

One method that has recently received much attention is the partial substitution, or replacement, of asphalt with other materials. Some mineral fillers have been known to work as integral parts (extenders) of asphalt if thoroughly mixed with it, resulting in an increase in binder content and, therefore, decreasing the amount of asphalt required for optimum conditions.

Fly ash has been used successfully as a filler for asphalt mixes for a long time. It has the advantage of increasing the resistance of asphalt mixes to moisture damage. In addition to filling voids, fly ash reportedly works as an asphalt extender (*2*). It is the main purpose of this investigation to study the possibility of using wasted fly ash as an asphalt extender in bituminous paving mixes.

LITERATURE REVIEW

As finely pulverized bituminous coal is burned, particles of fly ash are suspended in the gas stream that reaches the boiler. As hot gases pass into the atmosphere, the particles of fly ash collect on the plates of electrostatic precipitators within the heating system. Fly ash is then processed or filtered and finally accumulated and stored (*3,4*).

Fly ash is characterized by its low specific gravity, which is a function of its chemical composition and varies between 2.3 and 2.6, averaging 2.4 (*5*). The particle size distribution generally depends on the collector used. It has been found that the ash collected by the electrostatic precipitator contains a greater percentage of very small particles ($<1.5\ \mu$) (*4*). In general, a typical fly ash particle size ranges between 0.5 μ and 100 μ (*4*). Fly ash particles are generally spherical (*4,6*); however, a minor fraction consists of irregularly shaped particles (*6*).

Most types of fly ash have been used successfully as mineral fillers in hot asphalt mixes (*4–6*). It has been reported that fly ash does not differ materially from Trinidad Asphalt's mineral filler (*7*). In another study, fly ash was used as a replacement for limestone dust in asphalt concrete mixes with good results (*8*). The suitability of fly ash as a filler in sheet asphalt mixes was investigated by the Detroit Edison Company and reported by Zimmer (*9*). It was found that stabilities of mixes containing fly ash are comparable to those containing limestone dust when proportions are based on weight, and that fly ash has virtually the same void-reducing properties as limestone dust.

The resistance of asphalt mixes containing fly ash to water action has been found to be equal or superior to those containing other types of filler (*6,10*). The strength retention for eight fly ashes ranges between 85 and 100 percent—all above the 75 percent figure considered to be the critical minimum.

A report by Rosner et al. indicates that the addition of up to 6 percent fly ash by weight of aggregate to asphalt concrete produces an acceptable mix (*11*). At the same time, asphalt requirements and voids in mineral aggregates (VMA) values are lower than those for mixes containing portland cement or hydrated lime.

Tons et al. investigated the use of fly ash as a replacement for asphalt cement in asphalt concrete mixes (*2*). The three

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types of fly ash used in the study were found to have positive effects on the physical properties of the evaluated mixes. Furthermore, the replacement of up to 30 percent of asphalt cement by fly ash improved most of the mix's physical properties when a practical asphalt content was used.

Concerning other types of fillers, Kallas and Puzinauskas found that 9 of the 11 fillers investigated were effective in replacing a portion of the asphalt required to produce minimum VMA (*12*). Other reports also point out that some mineral fillers can serve as asphalt extenders, and that they may actually decrease the stiffness of the asphalt (*13,14*). Baghouse fines, also, were reported to act as asphalt extenders (*15–18*).

Finally, it has been found that mixing fine fly ash particles (passing Sieve #325) with asphalt cement causes the highest increase in viscosity compared with coarser fly ash sizes (*19*).

STUDY OBJECTIVES

This investigation had two objectives:

1. To study the effect of fly ash particle size, aggregate gradation, and binder content on the resilient modulus and rut-depth characteristics of asphalt concrete mixes.
2. To evaluate the use of fly ash as an asphalt extender in asphalt concrete mixes.

EXPERIMENTAL WORK

Materials

Asphalt Cement

AC-20 asphalt cement was used for this study. It was obtained from Marathon Petroleum Company in Detroit, Michigan. The results of tests conducted on the asphalt are shown in Table 1.

Fly Ash

Fly ash used in this study was obtained from Consumer's Power Company, Michigan. The fly ash was dry-sieved on Sieves #270 and #325 for 15 min. Because fly ash has practically no particles finer than 1 μ, silica fume (microsilica), which is 100 percent finer than 0.5 μ, was mixed with the fly ash fraction passing Sieve #325 in a 50/50 ratio by weight to form the fine fraction. This was done to study the stiffening effect of very fine materials. Table 2 summarizes the specific gravities and particle size distribution of the three fractions.

Aggregate

The coarse aggregate was a crushed gravel obtained from Thompson-McCully Asphalt Paving Company in Whitmore Lake, Michigan. The fine aggregate was a concrete sand obtained locally.

The coarse aggregate was sieved and divided into different sizes as follows: ¾ in.–½ in., ½ in.–⅜ in., ⅜ in.–#4, #4–#8. Each size was then thoroughly washed, dried, and stored until usage. The fine aggregate was divided into the following sizes: #8–#16, #16–#30, #30–#50, #50–#100, #100–#200.

The coarse and fine aggregate fractions were combined with the desired proportions according to the gradation curves A, B, and C. The three gradations were chosen in such a way that the sand content was different for each one; however, they were all within the specification limits of the Michigan Department of Transportation. The fine gradation (C) represents the finest, and the coarse gradation (A) represents the coarsest. The medium gradation (B) falls between the two. An important property of these aggregate gradations is that they possess different surface areas. This is important because the larger the surface area of aggregates, the larger the amount of asphalt needed to coat such aggregates. The three gradation curves are shown in Figure 1, and their specific gravities and absorptions are shown in Table 3.

TABLE 1 SUMMARY OF ASPHALT CEMENT PROPERTIES

Test	ASTM Test Designation	Test Results
Specific Gravity (77/77° F)	D 70-76	1.022
Viscosity x 10^6, poises (77° F)	D 3570-77	1.504
Penetration (77° F) 0.1 mm, 100 g, 5 sec	D 5-73	74
Penetration (95° F) 0.1 mm, 100 g, 5 sec	D 5-73	(143)*
Softening Point, of (R & B)	D 36-76	122 (129)*
P.I.		(-0.7)*

* For Recovered Asphalt

TABLE 2 PROPERTIES OF FLY ASH FRACTIONS

Grain Size Analysis	Fly Ash Fraction Coarse	Fly Ash Fraction Medium	Fly Ash Fraction Fine*
Sieve Size:			
# 30 (595 μ)	99.9	100	100
# 100 (144 μ)	93	100	100
# 200 (75 μ)	64	100	100
# 270 (54 μ)	54	100	100
Hydrometer Analysis			
# 325 (44 μ)	47	100	100
30	36	94	97
20	25	79	90
13	18	54	77
9	13	41	70
7	10	30	65
3.5	4	10	55
1.5	0	2	51
1	0	0	50
0.5	0	0	50
0.2	0	0	48
0.1	0	0	35
0.084	0	0	25
.05	0	0	10
.01	0	0	2
Specific Gravity	2.012	2.383	2.259

50 percent by weight silica fume

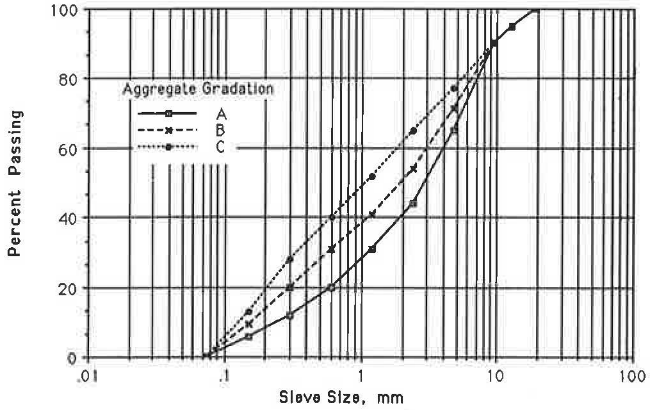

FIGURE 1 Particle size distribution of aggregates.

Test Variables and Specimens Preparation

A set of variables was chosen for this study. In addition to the fly ash sizes and aggregate gradations already mentioned, two other variables—asphalt content and percentage of replacement—were used.

Because asphalt content is not constant in the replacement process, the term "asphalt equivalent," which represents the asphalt content for control mixes, was used instead. Three asphalt equivalents were used in this study—namely, 4, 5, and 6 percent. The asphalt cement at each asphalt equivalent was replaced by an equal volume of fly ash in five replacement percentages: 0, 10, 20, 30, and 40 percent. The asphalt cement was partially replaced by fly ash so that the total volume of binder (asphalt + fly ash) was kept constant and equal to the original asphalt volume before the addition of fly ash.

All specimens used were Marshall size and were cast according to ASTM standards with 50 blows on each side of the specimen.

Either one or two specimens were prepared for each mix, as shown in Table 4. For control mixes (no fly ash), two specimens were prepared. This experimental design was used to reduce the quantity of materials needed and the time necessary for preparing and testing specimens.

CHARACTERIZATION OF MIXES

Resilient Modulus

Resilient modulus test before and after immersion was conducted on the same specimen; the nondestructive nature of the test made this possible.

Specimens were immersed in water at 140°F for 24 hr. Testing for resilient modulus was then done for the purpose of evaluating the effect of test variables (mainly fly ash size and quantity) on resistance of mixes to water action. By testing the same specimen before and after immersion, errors owing to material variability were eliminated. At the same time, a reduction in materials' quantities, time, and effort was achieved.

It should be mentioned that although only samples of the results are reported here, the conclusions were based on the results of the entire study (*19*).

Dry Resilient Modulus

Dry resilient modulus results for 6 percent asphalt equivalent are shown in Figure 2. These results show that, in general and for a given aggregate gradation and binder content, fine fly ash causes the most stiffening of the three fly ash fractions. This is consistent with the results of viscosity testing of asphalt–fly ash mixes (*19*), which show that the fine fly ash causes the highest stiffening effect among the three fly ash sizes. Medium fly ash ranks second; coarse fly ash gave the

TABLE 3 SPECIFIC GRAVITIES AND ABSORPTIONS OF AGGREGATE GRADATIONS

Parameter	Aggregate Gradation A	B	C
Bulk Sp. Gr.	2.599	2.600	2.600
Bulk Sp. Gr. (SSD)	2.645	2.643	2.640
Apparent Sp. Gr.	2.725	2.717	2.709
Percent Absorption	1.775	1.662	1.554

TABLE 4 MIX VARIABLES AND NUMBER OF SPECIMENS

	Aggregate Gradation								
	A			B			C		
	Fly Ash Size			Fly Ash Size			Fly Ash Size		
	F	M	C	F	M	C	F	M	C
Asphalt - Equivalent 4 Percent of Asphalt Replaced									
0 percent	2	2	2	2	2	2	2	2	2
10 percent	1	2	1	2	1	2	1	2	1
20 percent	2	1	2	1	2	1	2	1	2
30 percent	1	2	1	2	1	2	1	2	1
40 percent	2	1	2	1	2	1	2	1	2
Asphalt - Equivalent 5 Percent of Asphalt Replaced									
0 percent	2	2	2	2	2	2	2	2	2
10 percent	2	1	2	1	2	1	2	1	2
20 percent	1	2	1	2	1	2	1	2	1
30 percent	2	1	2	1	2	1	2	1	2
40 percent	1	2	1	2	1	2	1	2	1
Asphalt - Equivalent 6 Percent of Asphalt Replaced									
0 percent	2	2	2	2	2	2	2	2	2
10 percent	1	2	1	2	1	2	1	2	1
20 percent	2	1	2	1	2	1	2	1	2
30 percent	1	2	1	[illegible]	1	2	1	2	1
40 percent	2	1	2	1	2	1	2	1	2

lowest modulus values. This kind of behavior is expected because the fine fraction (contains an appreciable amount of submicron particles), when combined with asphalt, caused its viscosity to increase to values higher than those caused by the other two fractions. This translates into a high resilient modulus in asphalt–fly ash concrete mixes. As for coarse fly ash, given its large particle size, it creates more voids in the mix, hence producing a less stiff mix than the other two.

For a given aggregate gradation and asphalt equivalent, dry resilient modulus increases as the percent of replacement increases for fine and medium fly ash, but it remains the same or decreases for coarse fly ash. The increase in the resilient modulus in the case of fine fly ash appears to be logical, given its high stiffening effect. The ineffectiveness or the negative effect of coarse fly ash is mainly attributable to the increase in voids in mixes made with this fraction as its quantity increases.

For a given aggregate gradation, increasing asphalt equivalent from 4 to 6 percent has little or no effect on dry resilient modulus. The details of this effect can be found elsewhere (*19*).

In general, for a certain asphalt equivalent, changing the aggregate gradation from A to C shifted the resilient modulus values downward. This was more pronounced for mixes containing coarse fly ash and mixes with low replacement percentages. Grain interlock, which is more pronounced for Gradation A, could be the reason for this behavior.

Estimates of the main effects of the four independent variables on dry resilient modulus are shown in Table 5. These effects seem to strengthen the previous conclusions. These

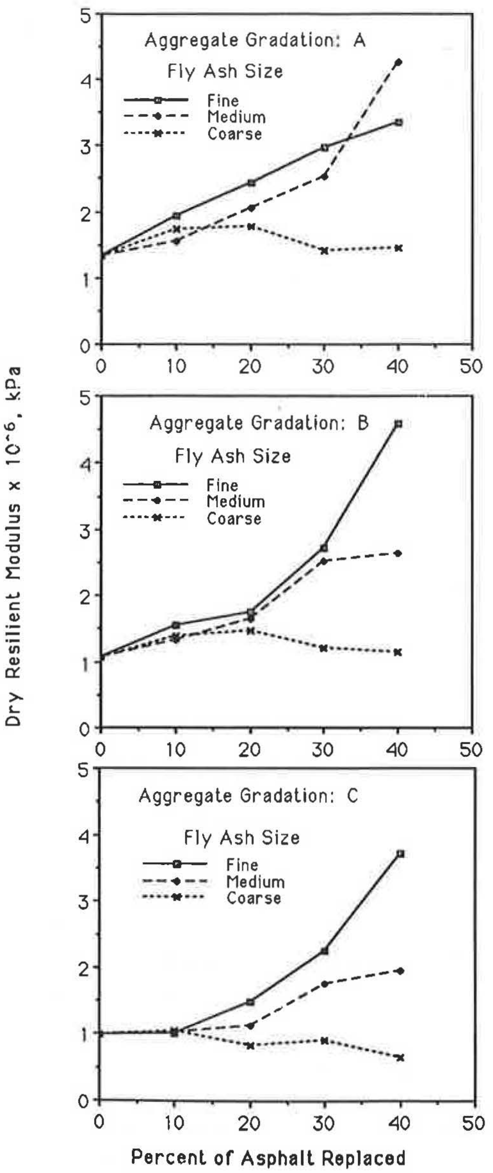

FIGURE 2 Dry resilient modulus versus percentage of asphalt replaced for 6 percent A.E.

effects are represented by α, β, γ, and λ in the prediction model shown below.

$$Y_{ijklm} = \mu + \alpha_i + \beta_j + \gamma_k + \lambda_l + \varepsilon_{ijklm} \qquad (1)$$

where

Y_{ijklm} = the predicted value of the dependent variable for a given set of levels of the independent variables,
μ = the grand mean (the constant in Table 5),
α_i = estimated main effect of the *i*th level of the asphalt equivalent,
β_j = estimated main effect of the *j*th level of the aggregate gradation,
γ_k = estimated main effect of the *k*th level of the percentage of asphalt replaced,
λ_l = estimated main effect of the *l*th level of fly ash size, and
ε_{ijklm} = an error term.

These parameters indicate the effect of each level of a given independent variable on the predicted values. A plus sign indicates a positive effect; a minus sign indicates a negative effect. A very low value (approximately zero) indicates little or no effect. In other words, the estimated main effects show the contribution of each level of the independent variable toward the predicted values. Table 5 also shows the standard deviation of these main effects.

Immersion Effect

To study the effect of water on asphalt–fly ash concrete mixes, the index of retained stiffness (IRS) was used. IRS is the ratio of resilient modulus after and before water immersion. It indicates the resistance of a given mix to water action.

Figure 3 shows a sample of the results of soaked resilient modulus. Corresponding IRS values are shown in Figure 4. Tables 6 and 7 show the statistically estimated main effects for soaked resilient modulus and IRS, respectively. These results show that, in general, IRS value gets lower as the aggregate gets finer and as the asphalt equivalent gets lower. However, much lower IRS values were obtained for mixes made with Gradation A and fine fly ash at 40 percent replacement. In fact, all mixes made with fine fly ash at 40 percent replacement show lower IRS values than those mixes made with medium or coarse fly ashes. This was expected, because these mixes were not completely coated with asphalt, allowing water to easily strip asphalt films from aggregate surface, thus reducing IRS values below those of other mixes.

Rut Depth Prediction

One of the major distresses that occur in bituminous pavement is permanent deformation, or rutting. Permanent deformation has received considerable attention from researchers and pavement technologists. Several methods have been introduced in pavement design to address the problem of rutting. These methods are divided into two main categories: indirect and predictive (*20*). Indirect methods are based on limiting layer thickness and component material strengths, stability, or density to a minimum, or limiting the vertical compressive strain on the subgrade surface to some maximum level. Predictive methods are based on predicting rut depth for a given set of conditions and redesigning the pavement if necessary until a satisfactory rut depth value is obtained.

A predictive method that relates pavement permanent deformation to creep test results was developed by Shell Oil Company Laboratories. Because of its simplicity as a tool for comparing different mixes and the availability of the needed equipment to run the creep test, this method has been adopted here to evaluate the rutting potential of asphalt–fly ash concrete mixes (*21*).

To predict rut depth, the static creep test—as suggested by Shell—was conducted on Marshall specimens representing

TABLE 5 ESTIMATED MAIN EFFECTS FOR DRY RESILIENT MODULUS × 10^6 (kPa)

Parameter	Estimated Main Effects	Standard Deviation
Constant	1.88	0.03
Asphalt Equivalent		
6 Percent	0.02	0.06
5 Percent	0.03	0.06
4 Percent	-0.06	0.06
Aggregate Gradation		
A	0.36	0.06
B	0.09	0.06
C	-0.45	0.06
Percent of Asphalt Replaced		
10 Percent	-0.48	0.06
20 Percent	-0.19	0.06
30 Percent	0.10	0.06
40 Percent	0.57	0.06
Fly Ash Size		
Fine	0.53	0.06
Medium	0.10	0.12
Coarse	-0.63	0.06

different mixes. Each mix was represented by either one or two specimens (see Table 4), which were made and tested at random. The test was performed for 1 hr in a temperature-controlled chamber maintained at about 104°F (40°C). The time-dependent deformation was measured using a pair of linear variable differential transformers (LVDTs) that were connected to a computer to take readings, calculate the mix stiffness, and store the data. Time-dependent mix stiffness (S_{mix}) was later plotted in a log-log scale against the stiffness of recovered asphalt (S_{bit}). The scale, obtained from a Van der Poel nomograph (*22*), was for the same conditions as those of S_{mix}.

For rut depth calculation, pavement must be divided into layers and sublayers; then, for a given air temperature, the asphalt effective viscosity is calculated for each sublayer. Effective viscosity, the slope of the S_{mix}-S_{bit} relationship, and traffic data were used thereafter to calculate the viscous part of the asphalt stiffness (S_{bit}, visc). This value was then used to obtain the viscous part of the mix stiffness from the S_{mix}-S_{bit} relationship.

The rut depth was then calculated using the following equation:

$$\Delta h_i = C_m h_i \frac{Z_i \times 6 \times 10^5}{S_{\text{mix},i}} \tag{2}$$

$$\Delta h = \sum \Delta h_i \tag{3}$$

where

Δh_i = rut depth in the ith sublayer,
Δh = total rut depth,
C_m = correction factor for dynamic effect,
h_i = sublayer thickness,
$S_{\text{mix},i}$ = mix stiffness for the ith sublayer, obtained from the S_{mix}-S_{bit} relationship, and
Z_i = proportionality factor between average stress and contact stress.

The factor Z in the equation is a function of mix stiffness in the high-stiffness region (short loading time), the sublayer thickness, the stiffness and the thickness of other sublayers, the modulus and thickness of the base course, and the subgrade modulus. The values of Z were calculated using the elastic layer theory and tabulated for different combinations of the previously mentioned variables.

The expected rut depth in each mix was calculated for the conditions shown in Table 8.

The results of the calculated rut depth are plotted in Figures 5 and 6. It is worth mentioning that most mixes made with Gradation C failed under the static load, some after only a few minutes of loading, so no data were obtained for thse mixes. As the results show, the general trend for all mixes containing fine and medium fly ash fractions is that the rut depth decreases as the replacement increases. Mixes made with Gradation A and coarse fly ash show similar results. However, mixes made with Gradation B and coarse fly ash show an increase in rut depth as the percent of replacement increases. The reason that the coarse fly ash increases the rut depth as the replacement increases for Gradation B and not A is probably that the aggregates' interlocking—and hence the mix's resistance to loading—is reduced by increasing the percentage of replacement in the case of Gradation B, which contains a larger amount of sand. On the other hand, Gradation A contains a small amount of sand; hence, even with

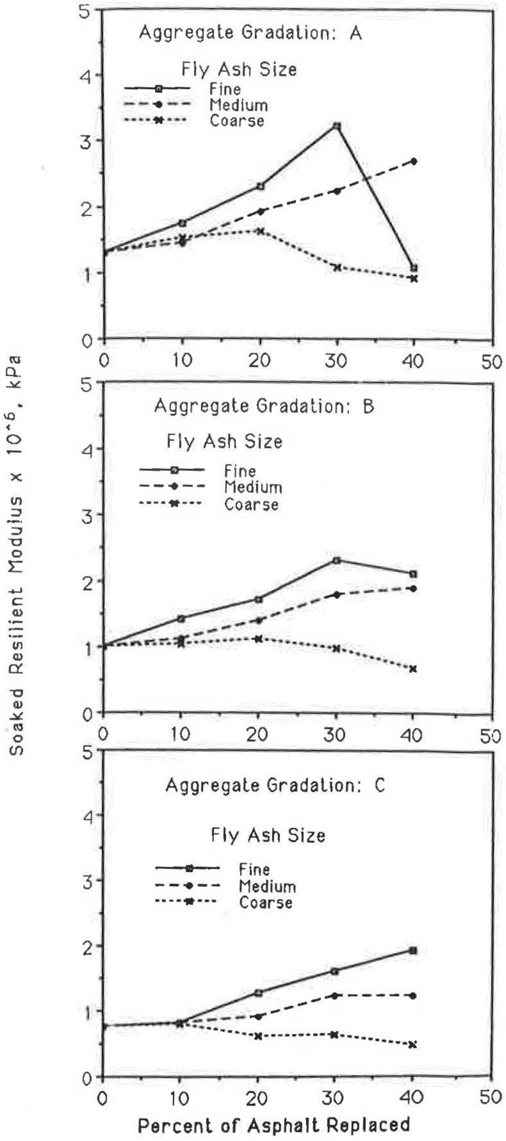

FIGURE 3 Soaked resilient modulus versus percentage of asphalt replaced for 6 percent A.E.

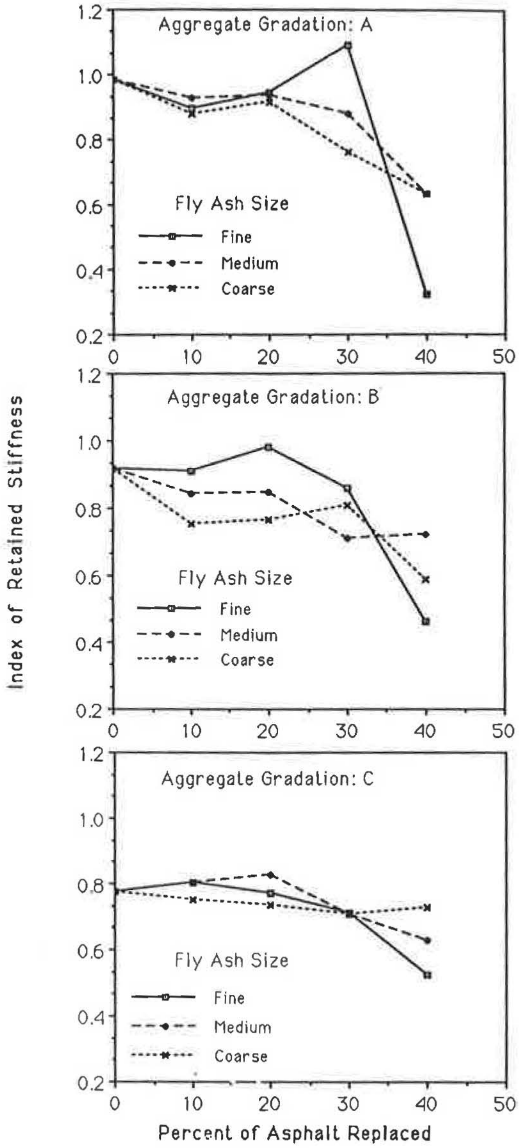

FIGURE 4 Index of retained stiffness versus percentage of asphalt replaced for 6 percent A.E.

the addition of coarse fly ash, the interlocking among large aggregate particles—and, in turn, the rut depth—is not much affected by the replacement process.

For a given aggregate gradation and asphalt equivalent, fine, medium, and coarse fly ash fractions gave the lowest, intermediate, and highest rut depth, respectively, when compared at the same percentage of replacement. However, there are a few exceptions. Ranking mixes containing the three fly ash fractions in the order mentioned is expected, given the stiffening effect of each one as was shown in the discussion of resilient modulus results.

The rut depth results for the three fly ash fractions are generally the same in the case of Gradation A but not B. This could be attributed to differences in residual asphalt, unit weight, and air voids between mixes made with Gradation A and those made with B.

When mixes are compared at the same aggregate gradation, the results indicate, although not very obviously, that increasing asphalt equivalent from 4 to 6 percent increases rut depth for control mixes (no fly ash added) and steepens slopes for curves representing the rut depth versus percentage of replacement. The first observation could be explained as follows: for control mixes, the residual asphalt is more at high than that at low asphalt equivalent. Consequently, the strength of high asphalt equivalent depends more on viscosity (resistance to flow) of the asphalt film than on particle-to-particle contact. This results in weaker mixes and, consequently, higher rut values in case of mixes made with high asphalt equivalent. The association of steeper slopes with higher asphalt equivalent could be attributed to the fact that, at a certain percentage of replacement, the higher the asphalt equivalent, the higher the amount of fly ash that should be added to the mix to replace asphalt at a given percentage of replacement. This, in turn, produces mixes with lower asphalt/aggregate ratios, resulting in stiffer mixes as the percentage of replacement increases in case of high asphalt equivalent.

TABLE 6 ESTIMATED MAIN EFFECTS FOR SOAKED RESILIENT MODULUS × 10^6 (kPa)

Parameter	Estimated Main Effects	Standard Deviation
Constant	1.24	0.03
Asphalt Equivalent		
6 Percent	0.17	0.03
5 Percent	0.01	0.03
4 Percent	-0.16	0.03
Aggregate Gradation		
A	0.17	0.03
B	0.13	0.03
C	-0.30	0.03
Percent of Asphalt Replaced		
10 Percent	-0.17	0.05
20 Percent	-0.05	0.05
30 Percent	0.17	0.05
40 Percent	-0.04	0.05
Fly Ash Size		
Fine	0.26	0.03
Medium	0.10	0.03
Coarse	-0.36	0.03

TABLE 7 ESTIMATED MAIN EFFECTS FOR INDEX OF RETAINED STIFFNESS

Parameter	Estimated Main Effects	Standard Deviation
Constant	0.69	0.008
Asphalt Equivalent		
6 Percent	0.08	0.01
5 Percent	-0.03	0.01
4 Percent	-0.05	0.01
Aggregate Gradation		
A	-0.03	0.01
B	0.02	0.01
C	0.01	0.01
Percent of Asphalt Replaced		
10 Percent	0.08	0.01
20 Percent	0.06	0.01
30 Percent	0.02	0.01
40 Percent	-0.16	0.01
Fly Ash Size		
Fine	-0.02	0.01
Medium	0.001	0.01
Coarse	0.02	0.01

TABLE 8 CONDITIONS FOR CALCULATING EXPECTED RUT DEPTH (*23*)

Condition	Measurement
Asphalt-fly ash concrete layer thickness	180 mm
Sublayer-1 thickness	40 mm
Sublayer-2 thickness	40 mm
Sublayer-3 thickness	100 mm
Unbound base course thickness	300 mm
Subgrade modulus	10^8 N/m^2
Axle loads/lane/day	2,000
Design period	15 years
Traffic growth/year	2 percent
Ann Arbor weather data for 1984	

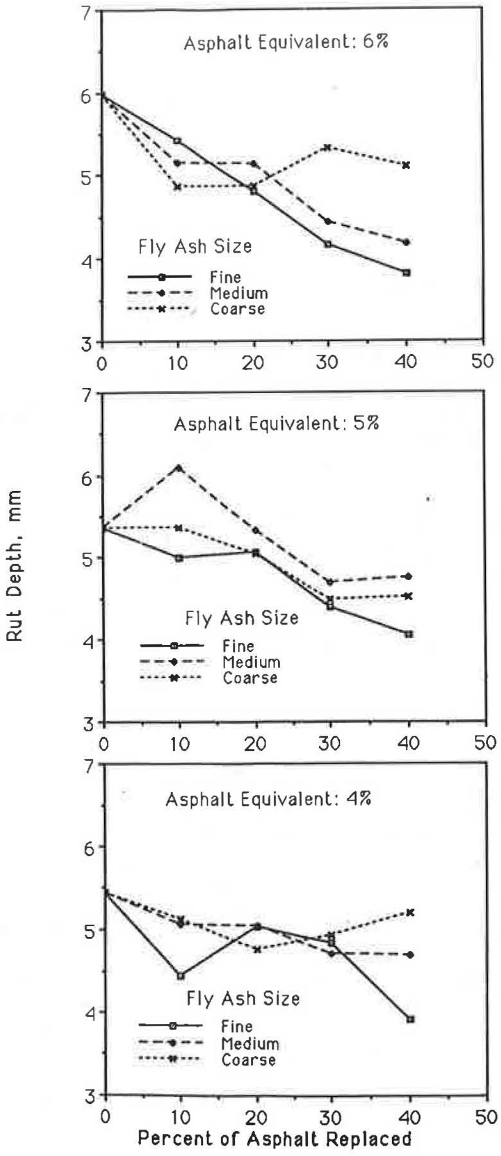

FIGURE 5 Estimated rut depth versus percentage of asphalt replaced for Aggregate A.

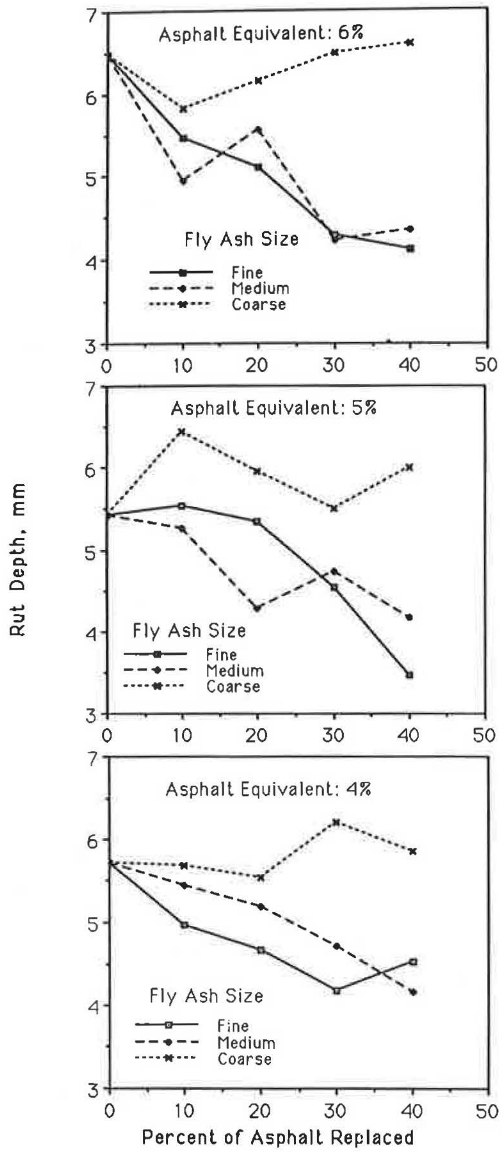

FIGURE 6 Estimated rut depth versus percentage of asphalt replaced for Aggregate B.

For 4 and 6 percent asphalt equivalents, the use of Gradation B resulted in a higher rut depth for control mixes than those produced by Gradation A. However, for 5 percent asphalt equivalent, the rut depth is about the same for both gradations. It was expected that control mixes made with Gradation B should give higher rut depth than those made with A (as is the case with 4 and 6 percent asphalt equivalent), because A produced mixes having higher unit weight and lower air voids than those made with B. So, the behavior of mixes made with 5 percent asphalt equivalent could only be attributed to experimental error.

For a given asphalt equivalent, changing aggregate gradation from A to B resulted in an increase in rut depth for mixes containing coarse fly ash. This could be explained by both unit weight and air voids, because mixes containing Gradation A possess both lower air voids and higher unit weight than those containing Gradation B (*19*).

TABLE 9 ESTIMATED MAIN EFFECTS FOR ESTIMATED RUT DEPTH (mm)

Parameter	Estimated Main Effects	Standard Deviation
Constant	5.32	0.07
Asphalt Equivalent		
6 Percent	0.053	0.09
5 Percent	-0.046	0.09
4 Percent	-0.007	0.09
Aggregate Gradation		
A	-0.50	0.09
B	0.16	0.99
C	-0.66	0.99
Percent of Asphalt Replaced		
10 Percent	0.35	0.12
20 Percent	0.27	0.10
30 Percent	-0.20	0.10
40 Percent	-0.42	0.10
Fly Ash Size		
Fine	-0.53	0.09
Medium	0.15	0.09
Coarse	0.38	0.09

Table 9 shows the estimated main effects of various variables on the estimated rut depth. Also shown are the standard deviations of these effects. These effects are consistent with those mentioned earlier. A descriptive model of these effects was presented earlier.

CONCLUSIONS

It was the purpose of this study to investigate the feasibility of using fly ash as an asphalt extender and to study the effect of fly ash particle size and other variables on the replacement process. The following is a summary of the main conclusions:

1. Fly ash having particle sizes between 1 and 44 μ is the best as an asphalt extender, because coarser particles tend to create more voids among aggregate particles and finer ones tend to stiffen mixes. In the latter case, a mix with low workability is produced that also possesses large amount of voids after compaction.
2. It was strongly indicated that increasing sand content increases the sensitivity of rutting potential of different mixes to changes in sizes of fly ash particles.
3. For a given asphalt equivalent and aggregate gradation, the three fly ash fractions are very similar in their effectiveness against moisture damage except for mixes having 40 percent replacement.
4. At 40 percent replacement, the fine fraction caused the least resistance to moisture damage.
5. As far as this study shows, it is reasonable to replace up to 40 percent of asphalt volume with medium fly ash (1 through 44 μ in size) for dry climates; however, for moist climates, the replacement should not exceed 30 percent.

PRACTICAL APPLICATIONS

The results of various tests performed on different mixes clearly show that the replacement of up to 30 percent of the asphalt volume by medium-size fly ash (passing Sieve #325) proved to be not detrimental to the mixes' performance. Because 80 percent of most fly ash produced by power plants passes Sieve #325, fly ash should be quite satisfactory when used to replace up to 30 percent of the asphalt volume. It is also expected that these mixes should perform well if they are installed in the field. Furthermore, substituting fly ash for part of the asphalt can mean savings for the road builders, fewer disposal problems for the fly ash producers, and less damage to the environment.

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