Investigation of Segregation of Asphalt Mixtures in the State of Georgia

E. R. BROWN, RONALD COLLINS, AND J. R. BROWNFIELD

Using large maximum-size aggregates produced segregation of aggregate in asphalt mixtures in the state of Georgia. This report summarizes a study of the problem by Auburn University for the Georgia Department of Transportation. Researchers observed the extent of segregation on a number of construction projects and developed a test plan to quantify the problem. The results of this study suggest that most segregation can be prevented by following good construction practices and paying close attention to quality control. An associated laboratory study shows that the properties of an asphalt mixture can be significantly changed when segregation occurs.

The Georgia Department of Transportation (GDOT) typically uses relatively large maximum-size aggregates to ensure that base and binder course mixtures are resistant to rutting. Although such mixtures do minimize rutting, they tend to segregate during the production, hauling, and/or laydown operation. Previous GDOT-funded projects have examined procedures for minimizing aggregate segregation and recommended specific steps to alleviate the problem. Because these steps have not completely solved the problem, however, this project was undertaken to evaluate the aggregate segregation problem in Georgia and to recommend further steps to minimize the problem.

The proposed work began with a review of literature on aggregate segregation. Next, several ongoing construction projects were observed to identify any aggregate segregation problems and to evaluate existing construction procedures in the state of Georgia. In addition, a sampling and testing plan was developed to evaluate pavements with segregation problems and to compare samples of the segregated mixture with random samples. The GDOT Materials Laboratory and various division laboratories tested all the samples to determine gradation, asphalt content, and voids in total mix; the resulting data were analyzed to compare the gradation and asphalt content of mix from segregated areas to that of material from other areas. Finally, a series of laboratory tests conducted at Auburn University measured properties of asphalt mixture representing the segregated and nonsegregated areas.

PREVIOUS RESEARCH

Aggregate segregation in asphalt pavements occurs when coarse aggregate congregates at one spot in the pavement. The coarse spots exhibit open textures and low densities, which often result in areas of high permeability susceptible to raveling, cracking, and moisture damage (*1*). Previous research on aggregate segregation can be divided into three parts: sources of segregation, diagnosis of segregation, and prevention of segregation.

E. R. Brown, Department of Civil Engineering, Auburn University, Auburn, Ala. 31849-5337. R. Collins, Georgia Department of Transportation, 15 Kennedy Drive, Forest Park, Ga. 30050. J. R. Brownfield, CH_2M Hill, 2567 Fairlane Drive, Montgomery, Ala. 36116.

Sources of Segregation

The National Asphalt Paving Association (NAPA) suggested in 1987 (*2,3*) that stockpiling "single-sized" aggregate minimizes segregation in the stockpiles. Also, stockpiling in horizontal layers reduces segregation because the aggregate cannot roll down long slopes. In addition, NAPA recommended improved cold bin openings that allow unrestricted flow. Conventional bin openings may become partially plugged by bridging aggregate, but a trapezoidal bin opening, with the calibration belt flowing away from the wider end of the opening, allows more uniform flow out of the bin.

Kennedy et al. (*1*) state that a segregated stockpile creates special problems in a drum mix plant because there is no internal gradation check. They recommend using at least three stockpiles—more if there is a large variation in aggregate size—and up to five or six stockpiles to effectively minimize segregation. They state that loaders should not scoop from the side of a stockpile, but should instead ram the side of the stockpile and rotate the bucket after coming to a stop. The material should then be dumped directly into the center of the cold bins; if the aggregates in the cold bins intermingle, bulkheads should be used (*1*).

Conveyor Belts and Drums

The gradation of the aggregate is not usually altered on the conveyor belt that leads from the cold feeds to the drum. Segregation may occur in the drum mixer, however. NAPA (*3*) states that good asphalt coating of large particles will reduce this segregation, and recommends that the mixing dwell time be increased or the asphalt cement (AC) be introduced earlier in the drum. To achieve increased dwell time, NAPA suggests that donuts be welded to the inside of the drum or that the slope of the drum be decreased; either method would let the aggregate be coated with asphalt longer. NAPA also found that a mix can become segregated when it is deposited on the belt from drums that allow fines to fall on one side of the belt and coarse particles on the other.

Kennedy et al. (*1*) consider conveyor belt speed to be a possible reason for segregation: if the belt is run too fast, large particles will be thrown to the far side of the silo, eventually creating a coarse strip on one side of the mat.

Batchers, Rotating Chutes, and Silos

In their 1967 study on the effects of hot storage on an asphalt concrete mix (*4*), Middleton et al. concluded that storage silos had little or no effect on aggregate gradation. Their study concerned asphalt concrete mixtures with fine aggregate gradations (½-in. maximum size), which are not very susceptible to segregation.

In 1970, Foster (*5*), using a gradation with a maximum size of 1½ in., noted that considerable segregation can take place in the silo. He showed the segregation pattern to be large aggregates around the edge of the silo with finer aggregates in the center. He also established that the gradation of unloaded material differed from the gradation of the material that was being loaded into the silo.

Foster suggests keeping the material one silo diameter above the top of the cone to force the material to recombine as it is loaded into the trucks. He mentions the use of gob hoppers (batchers) at the top of the silo, but there are no data to show how much the hoppers could reduce segregation.

Dan Houston (*6*) in the same year reported that certain bin geometry combinations yield less segregation. The combination that made for the least segregation was a circular silo with a 1-ft by 4-ft opening at the bottom of the silo and a rotating spout at the top of the silo. The second least segregated mix came from a circular bin with a 1-ft by 4-ft opening at the bottom of the silo and a batcher at the top of the silo.

In 1974, Zdeb and Brown (*7*) reported that gradation variability increased with storage, as indicated by a more than twofold increase in standard deviation of percent passing most sieves.

In 1987, NAPA (*3*) considered storage silos the most sensitive place for segregation to occur. The report stated that batchers and rotating chutes are effective only as long as they are operated properly. Rotating chutes must rotate, and batchers must be filled sufficiently before dumping and never emptied until the end of the daily operation. NAPA says that emptying the silo below the cone, or operating the silo at maximum capacity, will also result in segregation. The report suggests that trucks be loaded in three separate drops instead of one large one. The first drop should be behind the cab, the second in front of the tailgate, and the third between the first two.

Kennedy et al. (*1*) also considered improper use of storage silos to be the most important cause of segregation. They stated, as did NAPA, that operating a silo at 25 to 75 percent capacity would produce the most consistent mix.

Pavers

Until recently, pavers have not been considered serious areas of segregation. However, NAPA now recognizes that poor paver operation can cause segregation (*3*). NAPA recommendations for paver operators are as follows:

- Do not empty hopper.
- Do not dump wings unless absolutely necessary.
- Flood the hopper.
- Adjust gates so that augers run continuously.
- Adjust paver speed to match the rate of production of the hot mix asphalt (HMA) plant.

Kennedy et al. (*1*) suggested modifications to the paver itself. They recommend welding a beveled bottom on the wings to promote a more continuous flow of HMA from the wings to the drag slats and placing fillets in the corners of the wings to hinder the collection of coarse material on the outside of the wings.

Diagnosis of Segregation

Nady, in a paper published in 1984 (*8*), reported that eight cores within a 20-ft section of roadway could not be removed intact due to a lack of fines in the mixture. He noted that there was no visible segregation in this area.

Two years later, Lackey, in a study directed toward segregation in Kansas (*9*), stated that a big problem with segregation is that it is often unnoticeable when the pavement is placed, but, after a year of traffic, segregated spots appear. The problem is, as Lackey says, "You can't cure them if you can't see them."

Lackey's concern about nonvisibility was shared by Kennedy et al., who suggested that wet pavements and a low angle of sunlight would make segregation more visible (*1*). Lackey approached the problem by measuring density profiles with nuclear density meters. As stated earlier, segregated areas of pavements have open textures and low densities; hence, low-density spots on profiles may well be the result of segregation. These profiles can indicate segregated spots shortly after the pavement is placed.

Plentiful information exists to help diagnose the cause of segregation that is visible behind the paver. Acott and Dunmire prepared a paper on hot mix construction (*2*) in which field and laboratory experience was rendered in a format that could readily assist field diagnosis of mat deficiencies, one of which was segregation. Their table points to possible causes of segregation and helps identify what may appear to be segregation but is in fact not detrimental to the performance of the HMA pavement. In another paper (*3*), NAPA presented much of the same data in a flowchart. Kennedy et al. (*1*) also prepared a checklist that can help pinpoint the source of a segregation problem.

Prevention of Segregation

In his 1984 paper, Nady (*8*) referred to a case study of several paving jobs in which all variables (e.g., aggregate blend, asphalt course, HMA facility, paver crew, and so on) were held constant except asphalt content. From this study, he concluded that segregation could be reduced by increasing the asphalt content.

Kennedy et al. (*1*) reported that a 0.2 percent increase in asphalt content often would eliminate segregation problems. They stated that a mix with an asphalt content significantly less than the one that produced the minimum voids in mineral aggregate (VMA) tended to have more segregation problems than the mix whose asphalt content was near the one that produced the minimum VMA. They also recognized that mixes with large or coarse-graded aggregate are more prone to segregate than fine-graded mixes; likewise, gap-graded mixes tend to segregate more than well-graded mixes.

NAPA (*3*) said that proper mix design could eliminate segregation without changing the asphalt content. NAPA cautioned, however, that segregation in the stockpiles had to be eliminated to produce a mix near the design gradation.

TEST PLAN FOR CURRENT RESEARCH

The first step in developing a test plan to collect data was inspecting ongoing projects to identify what problems needed to be studied. Completed pavements were also inspected to evaluate the extent of segregation.

Next, the causes of segregation on a number of projects were evaluated. Three types of GDOT mixes were evaluated, B, base, and E mixtures. Because the base mix was coarser than the other mixes, it tended to segregate more. Mixes produced with various types of plant and equipment were evaluated, as shown in Table 1. Projects under way did not encompass all of the combinations shown in Table 1, but as many combinations as possible were evaluated.

A sampling plan and series of tests were specified for each block evaluated. The sampling plan shown in Figure 1 was followed at each location. Additional samples were taken within each test area at observed segregated areas. Data were also obtained from quality control tests during construction. By using this approach, the aggregate gradation and variability could be followed from start to finish. Tests for gradation, asphalt content, density, and theoretical maximum density were run on all of the samples.

After data were obtained and analyzed, laboratory evaluation of material representative of that in the field began. One aggregate type was selected and mixes were prepared with gradation varying from slightly finer than the job mix formula to a gradation representative of a badly segregated mix. (When a mixture segregates, the asphalt content is normally higher for the finer material and lower for the coarser material, a fact taken into account when the laboratory samples were prepared.) The mixes were prepared in a Gyratory Testing Machine (GTM) using 120 psi pressure, 30 revolutions, and 1-degree angle. These samples were tested after being compacted to determine density, voids in total mix, stability, flow, indirect tensile strength, and permeability.

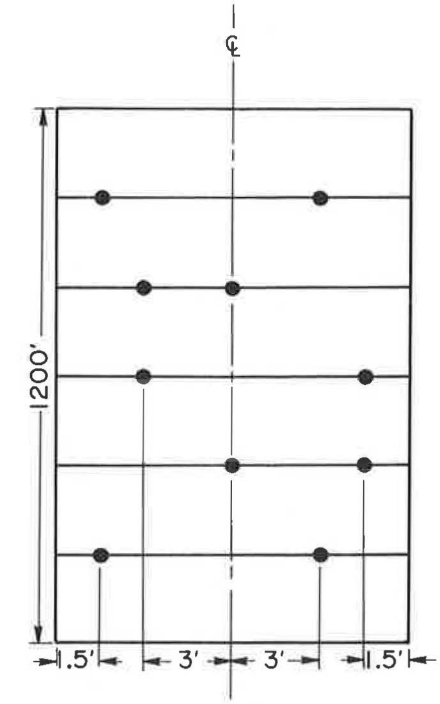

FIGURE 1 Layout of random sampling plan.

ANALYSIS OF TEST RESULTS TO EVALUATE AGGREGATE SEGREGATION

A test plan was developed to evaluate segregation of asphalt mixtures being produced and placed in the summer of 1987. The plan involved sampling a number of projects immediately after construction (see Figure 1) to evaluate bulk density, theoretical maximum density, gradation, asphalt content, and voids in total mixture. Cores were also taken in noticeably segregated areas within the 1,200-ft test layout and subjected to the same tests as the random cores. Data on mix design and testing during plant production were also obtained for comparison with the in-place properties.

The test results for the 19 projects evaluated for the random

TABLE 1 TYPES OF MIXES AND EQUIPMENT EVALUATED FOR SEGREGATION

	Batch Plant				Drum Mix Plant			
	Silo Used		Silo Not Used		Coater		No Coater	
	Separate Stockpiles[a]	Combined Stockpiles[b]	Separate Stockpiles	Combined Stockpiles	Separate Stockpiles	Combined Stockpiles	Separate Stockpiles	Combined Stockpiles
B mix	—	—	—	4[c]	—	2	—	3
Base mix	1	1	—	—	—	2	1	2
E mix	—	—	—	—	—	—	1	2

[a]Coarse aggregate stockpiles separated into individual sizes.
[b]Coarse aggregate stockpiles containing combined stockpiles.
[c]Number of projects evaluated.

TABLE 2 SUMMARY OF DATA FOR THE 19 PROJECTS EVALUATED

		Plant Mixes				Random Samples						Segregated Samples					
		Passing No. 8		Asphalt Content		Passing No. 8		Asphalt Content		Voids		Passing No. 8		Asphalt Content		Voids	
Project Number	Mix* Type	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ
1	1	36	2.3	4.4	0.26	34	1.2	4.3	0.20	3.0	1.2	-	-	-	-	-	-
2	2	38	3.1	4.6	0.13	37	3.1	4.6	0.27	3.5	0.5	35	5.4	4.5	0.24	4.1	1.5
3	10	37	0.0	4.9	0.01	42	2.1	5.3	0.40	3.7	0.8	39	2.4	5.0	0.23	5.0	0.9
4	10	36	1.2	4.9	0.09	34	1.9	4.8	0.25	6.3	3.6	-	-	-	-	-	-
5	10	36	1.4	5.2	0.12	37	2.7	5.4	0.30	-	-	35	4.2	5.4	0.71	-	-
6	10	38	1.5	5.0	0.01	38	1.3	5.0	0.20	6.4	2.1	31	5.3	4.4	0.57	10.5	1.1
7	14	-	-	-	-	37	2.2	4.5	0.24	3.6	0.6	30	2.4	4.4	0.49	5.8	1.0
8	14	33	2.5	4.8	0.29	34	3.2	4.0	0.46	7.5	1.8	32	3.6	4.0	0.42	7.8	1.3
9	16	37	1.2	4.5	0.20	35	2.2	4.0	0.58	4.1	1.8	28	1.8	3.6	0.10	4.4	1.9
10	16	37	2.7	4.5	0.22	39	1.5	4.6	0.14	6.1	0.9	36	1.3	4.5	0.30	7.1	0.3
11	19	36	2.1	4.2	0.23	34	4.1	4.1	0.84	7.3	1.7	30	2.0	4.6	1.21	2.6	-
12	20	36	2.5	4.4	0.21	38	3.4	4.4	0.57	7.1	1.8	26	3.3	3.2	0.42	9.6	2.5
13	20	34	1.7	4.0	0.20	37	3.0	4.1	0.16	5.5	3.8	28	0.7	3.2	0.35	2.8	1.3
14	22	40	1.0	5.1	0.09	42	4.8	4.8	0.37	7.3	1.5	28	7.3	3.6	0.63	9.5	1.1
15	22	39	2.0	5.0	0.16	40	2.0	5.0	0.19	4.4	1.2	30	1.1	4.3	0.23	6.4	1.9
16	22	28	7.7	3.7	0.65	36	2.9	4.4	0.29	4.5	1.1	28	2.5	3.6	0.33	8.8	0.8
17	23	48	2.0	5.5	0.22	48	0.8	5.6	0.2	5.5	0.7	-	-	-	-	-	-
18	24	43	2.7	5.4	0.16	42	1.6	5.4	0.16	5.2	0.9	42	2.5	5.7	0.18	4.2	1.0
19	24	47	4.7	5.3	0.10	50	3.3	5.8	0.51	8.6	1.2	48	5.6	5.9	0.52	8.6	0.7

* Mix Type 1 - Batch Plant with Silo, Base mix, Single Size Coarse Aggregate
2 - Batch Plant with Silo, Base mix, Combined Size Coarse Aggregate
10 - Batch Plant without Silo, B Mix, Combined Size Coarse Aggregate
14 - Drum Mix with Coater, Base Mix, Combined Size Coarse Aggregate
16 - Drum Mix with Coater, B Mix, Combined Size Coarse Aggregate
19 - Drum Mix without Coater, Base Mix, Single Size Coarse Aggregate
20 - Drum Mix without Coater, Base Mix, Combined Size Coarse Aggregate
22 - Drum Mix without Coater, B Mix, Combined Size Coarse Aggregate
23 - Drum Mix without Coater, E Mix, Single Size Coarse Aggregate
24 - Drum Mix without Coater, E Mix, Combined Size Coarse Aggregate

samples, segregated samples, and plant samples are shown in Table 2. The results cover percent passing the No. 8 sieve, asphalt content, and voids in total mix. These data were analyzed to evaluate the extent of segregation in the paving projects and to identify sources of segregation.

In many cases the plant mix tests were made over several days of operation, on material placed in the test area and on other material as well. Using plant mix samples beyond the test area was necessary to obtain sufficient plant samples for analysis. Also, although the random samples taken in the field were truly random, the plant samples were not. The plant samples did come from material taken from the back of trucks, however, and truck samples are normally representative of the batch being sampled.

After the random samples were obtained, the test area was inspected to locate any segregated areas. Of the 19 sections sampled, 16 contained segregated areas, which were tested for comparison with the random samples. The No. 8 sieve, common to all of the projects, was used to compare the various mixtures.

The test results were evaluated to better understand the difference between random and segregated samples. Test results indicate that the difference in the percent passing the No. 8 sieve for the random and segregated samples measures the degree of segregation. Figure 2 shows significant correlation between percent passing the No. 8 sieve and asphalt content, which suggests that high variability in asphalt content may be caused not by high variations in asphalt being added to the mixture nor by the variability of the extraction test, but by segregation of the mixture before sampling.

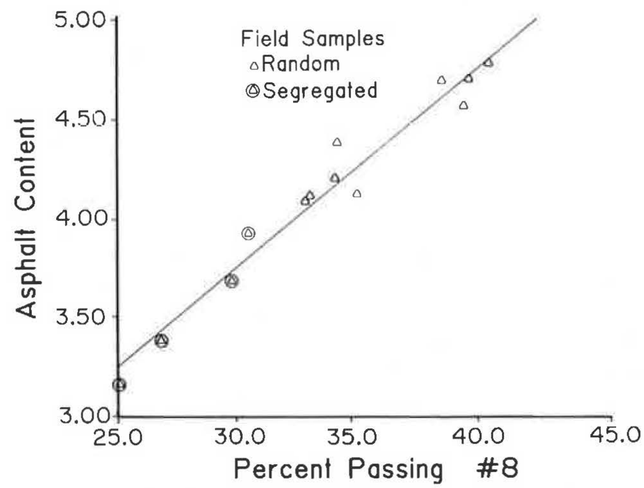

FIGURE 2 Typical relationship between asphalt content in field samples and percent passing no. 8 sieve (project 16).

The diversity of project sample origin precluded a statistical evaluation of the effects of plant type, silo, and mix type on segregation, but analysis of test results at least suggests trends. Three independent measurements of gradation and asphalt content could, however, be used to compare the various projects. These measurements are variability of random samples,

TABLE 3 NUMERICAL COMPARISON OF VARIOUS PROJECTS

Project	Mix Type	Rating for Random Samples	Rating for Plant Samples	Rating for Random Minus Segregated Samples	Overall Score	Overall Rating
1	1	2	9	1	4	2
2	2	13	13	2	9.3	12
3	10	8	1	3	4	2
4	10	6	2	1	3	1
5	10	10	3	2	5	3
6	10	3	4	5	4	2
7	14	9	-	5	7	7
8	14	14	10	2	8.7	11
9	16	9	2	5	5.3	4
10	16	4	12	3	6.3	6
11	19	4	12	3	7.7	9
12	20	16	10	9	11.7	15
13	20	12	5	7	8	10
14	22	18	6	10	11.3	14
15	22	7	7	8	7.3	8
16	22	11	11	6	9.3	12
17	23	1	7	1	3	1
18	24	5	12	1	6	5
19	24	15	14	2	10.3	13

TABLE 4 COMPARISON OF AVERAGE RESULTS FOR BATCH AND DRUM MIX PLANTS

Plant Type	Standard Deviation Plant Mixes: Percent Passing No. 8 Sieve	Standard Deviation Plant Mixes: Asphalt Content	Standard Deviation of Random Samples: Percent Passing No. 8 Sieve	Standard Deviation of Random Samples: Asphalt Content	Differences in Percent Passing No. 8 Sieve for Random and Segregated Samples
Batch	1.7	0.10	2.0	0.27	3.5
Drum Mix	2.7	0.25	2.8	0.38	7.6

variability of plant samples, and difference between random samples and segregated samples. A comparison of the various projects is shown in Table 3. The higher the variability of the project, the higher its numerical rating. The overall rating of a particular project was determined by averaging the three individual ratings. Table 3 clearly shows that the overall rating of the batch plant projects exceeds that of the drum mix projects. It also demonstrates that the overall best five projects (excepting E mixes, which tend not to segregate) from the standpoint of variability were constructed with batch plants. The worst performing projects were those with mix types 20 and 22, which included drum mix plants without coaters using combined-size coarse aggregate. Table 4 compares differences in random and segregated samples from drum mix and batch plants. On the average, control of mixes produced with a batch plant was much better than for those produced with drum mix plants.

LABORATORY INVESTIGATION OF PROPERTIES OF SEGREGATED MIXES

Shortly after placement of the binder layers of four different asphalt pavements in Georgia, ten 6-in. cores were drilled according to the pattern shown in Figure 1. Cores were also drilled at any apparent segregated spots in the 1,200-ft test section. Extraction tests were performed on all cores to reveal aggregate gradation and AC content. The results of these gradation tests were used to design a laboratory study to evaluate the effect of segregation on properties of asphalt mixtures.

Two facts emerged from the gradation test results. First, the severity of segregation varies widely from one project to another. Second, gradation curves apparently run approximately parallel for the random and segregated samples of the mixes investigated.

Six different gradations were used in the laboratory investigation (Table 5). These gradations ranged from the fine side of the mix design to the coarse side. The field data were also used to establish AC contents for the laboratory-prepared samples. The average asphalt content along with the average percent passing each sieve (for the random samples only) were used to determine the mix design film thickness. Working backwards from film thickness, the AC content was calculated for each aggregate gradation evaluated in the laboratory. These calculated AC contents compared favorably with those measured during extraction tests.

Each sample was compacted with a GTM set at 30 revo-

TABLE 5 RANGE OF AGGREGATE GRADATION FOR MIXTURES EVALUATED IN THE LABORATORY

Sieve Size	Mix 1	Mix Design Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1"	100	100	100	100	100	100
3/4"	100	98.1	96.6	95.0	93.4	91.9
1/2"	88.2	80.6	73.6	66.7	59.8	52.8
3/8"	77.6	67.0	59.6	52.3	44.9	37.6
4	60.1	51.5	44.0	36.6	29.2	21.8
8	45.8	39.8	34.3	28.8	23.3	17.8
16	31.4	27.8	24.5	21.2	17.9	14.6
30	24.0	21.2	18.8	16.5	14.2	12.1
50	16.7	14.7	13.3	11.9	10.5	9.1
100	10.7	9.1	8.2	7.4	6.6	5.7
200	6.4	5.4	4.8	4.3	3.8	3.2
% AC	5.75	5.04	4.57	4.09	3.61	3.13

lutions, 120 psi, and 1-degree angle. After the sample was compacted, it was removed from the mold and allowed to cool for at least 2 hr before handling.

Information on the voids in total mix for each of the six mixes is presented in Figure 3. The total voids increased dramatically as the degree of segregation increased. Since segregation leads to high voids, even the smallest amount of segregation is unacceptable.

A falling head permeability test was set up to more directly approach the problem presented by high voids. Tests were performed only after 30 mm of water had drained through the sample. If there was no noticeable drop (1 mm) in the water level in 5 min, the sample was considered impermeable.

The permeability data are plotted in Figure 4. Note that the samples are impermeable for gradations 1, 2, and 3, and that permeability increases dramatically from gradation 4 to gradation 6. Most AC pavement layers are designed and constructed to be impermeable. If segregation results in a permeable layer, then the AC will allow water to seep through, potentially causing weakening of the subgrade or stripping.

Samples of asphalt mixture with each aggregate gradation were used to determine how tensile strength changed with an increasing degree of segregation. The samples were tested in indirect tension using a constant deformation rate of 2 in. per minute. The data from the indirect tensile test are shown in Figure 5. The graph indicates that tensile strength decreased rapidly with an increase in degree of segregation. Decreased tensile strength may lead to excessive cracking in the pavement or to raveling of the mixture. Inspection of pavements that had segregation problems verified that raveling was a problem if the segregated areas had not been overlaid.

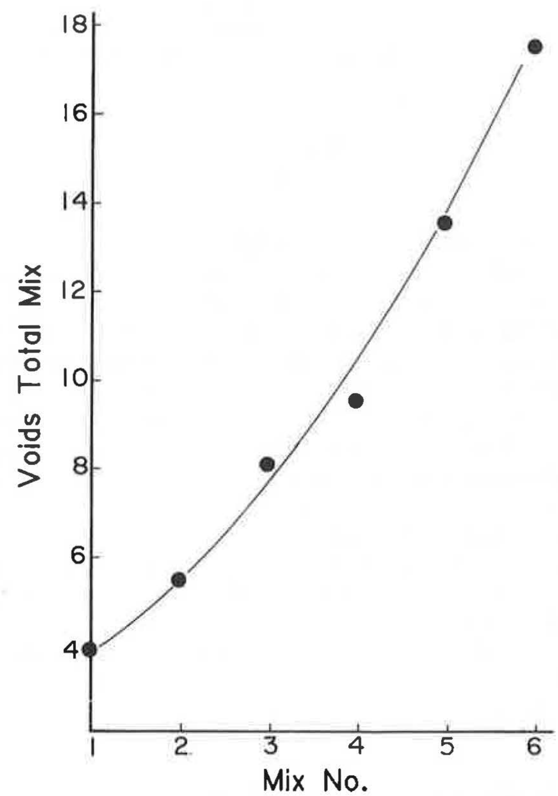

FIGURE 3 Voids in total mix versus degree of segregation.

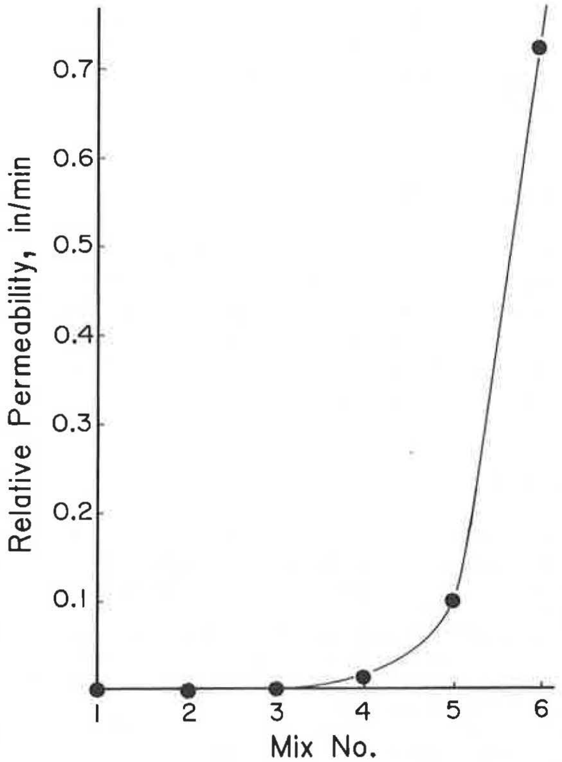

FIGURE 4 Permeability versus degree of segregation.

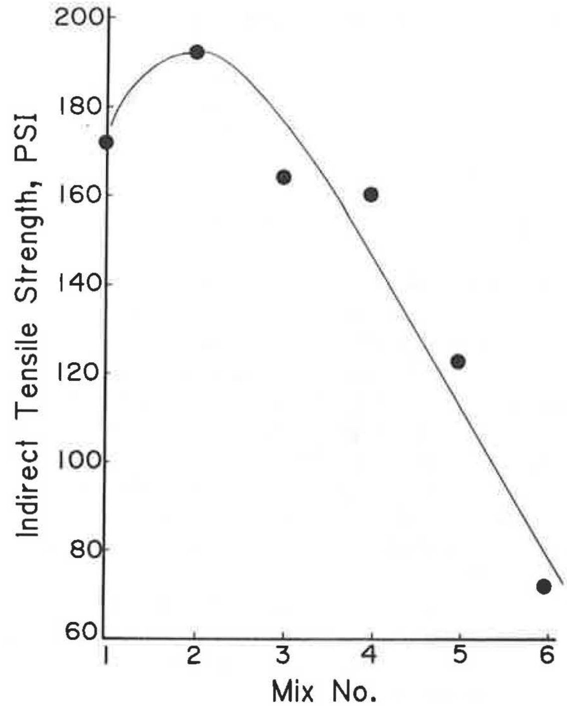

FIGURE 5 Indirect tensile strength versus degree of segregation.

REVIEW OF CONSTRUCTION PROCEDURES

Several site visits were made during construction of projects to observe construction procedures. Construction operations were observed at both the asphalt plants and laydown sites.

Most of the asphalt plants visited were drum mix plants, which were then becoming popular because of their portability, low initial cost, and production capacity. The stockpiling operations in some locations were satisfactory but less than desirable at other locations. In many instances, the contractor did not follow GDOT guidelines. For example, the contractor did not maintain separate stockpiles for different sizes of aggregate, especially for drum mix plants. The contractor often used one coarse aggregate containing several aggregate sizes, making it difficult to control aggregate gradation and minimize aggregate segregation. In a few cases, the contractor used crusher-run material graded from coarse to fine, yet segregation undoubtedly occurs when crusher-run material is used with a drum mix plant.

Many segregation problems in the field seemed to stem from the storage silo. All drum mix plants have some sort of storage silo and most batch plants do, as well. Segregation in some cases was caused by nonsymmetrically loading the conveyor belt carrying material to the silo. In at least one case, the batcher at the top of the silo was not functioning correctly, resulting in segregation. Again, following the comprehensive GDOT guidelines would have deflected these problems. However, on many projects segregation problems are either not seen as they occur or nothing is done to correct them during construction. Many contractors will not correct a problem if they are allowed to operate with the problem; it is the state that usually has to take the initiative to get a problem solved.

In some cases, the asphalt mixture segregated as it was loaded from the storage silo onto the truck. One reason for this segregation is the length of time the gate at the bottom of the silo remained open. Ideally, the material should be dropped in batches to minimize segregation caused by the large aggregate rolling down the side of the asphalt mixture to the edge of the truck bed. Most contractors used the suggested method of loading trucks (front first, back second, and middle last), but some did not.

Regardless of its source, segregation was most apparent when material was unloaded from trucks. If segregation could be eliminated at this juncture, segregation would no longer be a major concern. However, end-of-load segregation has many causes. On one project, the contractor used dump trucks with long bodies, which seemed to exacerbate segregation. On another, the asphalt paver was traveling too fast, allowing the material being fed to the screed to run low. The auger was turning rapidly to feed the two ends of the screed, consequently throwing coarse aggregate to the outside plate. Several steps have been taken to reduce end-of-load segregation. One method that has been partially successful is the use of Flo-Boys to haul asphalt mixtures; the mixture is extruded from the Flo-Boys and hence separation of materials is minimized.

In general, field observations validate that the contractor and GDOT personnel were paying close attention to segregation problems. Nonetheless, segregation is difficult to spot during construction and it is not always a simple matter to correct even when it is seen.

CONCLUSIONS AND RECOMMENDATIONS

Based on observation of paving projects during construction and on analyses of tests conducted by GDOT and further tests conducted at Auburn University, the following conclusions are warranted.

- Segregated areas that are not overlaid tend to ravel under traffic.
- The loss of desirable mixture properties is significant when the gradation of the segregated mixture is approximately 10 percent coarser than the job mix formula on the No. 8 sieve.
- Quality control is very important in reducing segregation. Either type of asphalt plant can be controlled to produce a good product; uncontrolled, either can produce a bad product. Generally, the batch plant produces a more consistent product (one with less segregation) than the drum mix plant. Data show that a drum mix plant with a coater produces a more consistent mixture with less segregation than a drum mix plant without a coater.
- Segregated areas are generally 8 to 15 percent coarser than nonsegregated areas on the No. 8 sieve; the voids are typically 3 to 5 percent higher; and the asphalt content is often 1 to 2 percent lower.
- There is no correlation between the variability of plant sample gradations and the amount of segregation. There is a general correlation for random in-place gradation and segregation.

Recommendations concerning segregation are as follows.

- The best approach for minimizing segregation is to use a batch plant without silo and to use good stockpiling techniques (separate horizontally layered stockpiles for different aggregate sizes). If a drum mix plant is used, a coater is preferred; good stockpiling techniques are a necessity. (Even a well-controlled mixture can segregate if it is improperly placed in the storage silo or when it is removed from the silo.)
- Since normal quality control tests cannot be used to predict segregation, some other method must be. Test results from this study show that visually locating segregated areas is difficult. Therefore, a nuclear gauge might be considered for use in identifying segregated areas since one will likely already be on the project for density measurement. Based on the results of this study, any segregated area with a density 4–5 pcf lower than the adjacent nonsegregated material will have a significant reduction in mix properties and should therefore be removed and replaced.

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REFERENCES

1. T. W. Kennedy, R. B. McGennis, and R. J. Holmgreen. Asphalt Mixture Segregation: Diagnostics and Remedies. Presented at the Annual Meeting of Association of Asphalt Paving Technologists, Reno, Nev., 1987.
2. M. Acott and R. Dunmire. Hot Mix Asphalt Construction—Field Diagnosis and Troubleshooting Guide. Presented at the Technical Session of the Annual Meeting of Association of Asphalt Paving Technologists, Reno, Nev., 1987.
3. *Hot Mix Asphalt Segregation: Causes and Cures*. QIP 110. National Asphalt Pavement Association, Riverdale, Md., 1987.
4. S. C. Middleton, J. C. Goodknight, and J. S. Eaton. The Effects of Hot Storage on an Asphaltic Concrete Mix. In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 36, 1967.
5. C. R. Foster. Hot Mix Storage Bins. In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 39, 1970.
6. D. X. Houston. *A Model Study of Segregation in Hot-Mix Asphalt Storage Bins II*. Department of Mechanical Engineering, University of Texas at Austin, May 1972. Photocopy.
7. M. S. Zdeb and R. A. Brown. Storage of Asphalt Concrete. In *Transportation Research Record 515*, TRB, National Research Council, Washington, D.C., 1974.
8. R. M. Nady. Resurfacing: Construction Problems. Solutions? In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 53, 1984.
9. W. M. Lackey. Segregation—A Mutual Problem. Presented at 31st Annual Convention of the National Asphalt Pavement Association, Honolulu, Hawaii, 1986.

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