Effect of Segregation on Performance of Hot-Mix Asphalt

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Segregation of hot-mix asphalt has resulted in poor performance in many pavements. There is no procedure currently available for quantifying how much segregation is required to cause a reduction in pavement performance. Five pavements from Alabama were selected for a study to determine how much segregation can be tolerated before premature raveling is likely. Visual estimations of the severity of raveling and segregation were made and cores from the pavement were obtained. The density of the pavement was measured with a thin-lift nuclear gauge, and the macrotexture of the pavement surface in the segregated areas and the gradation of the cores were determined. The results showed that a variation in the percent passing the No. 4 sieve of greater than 8 to 10 percent can lead to raveling. A model was developed to predict raveling from the macrotexture and expected traffic.

Segregation of hot-mix asphalt (HMA) pavements has resulted in poor performance in many pavements (*1–4*). Currently there is no procedure available for quantifying segregation to determine how much segregation is too much, or, in other words, how much coarser the gradation must be before a reduction in performance is expected. Quantifying segregation will result in data necessary to determine the quality of segregated areas and thus what action should be taken.

OBJECTIVE

The main objective of this study was to determine how much segregation can be tolerated before premature raveling is the likely result. A second objective was to determine whether an indicator test, such as the pavement macrotexture or thin-lift nuclear gauge, could be used to quantify segregation and raveling.

SCOPE

Five pavements from Alabama Highway Department (AHD) Divisions 4 and 6 were selected for inclusion in the study. The pavements consisted of similar surface mixes; therefore, this is a preliminary study of limited scope. Visual estimations of the severity of segregation and raveling were made and cores from the pavements obtained. The unit weight was measured with a thin-lift nuclear gauge, and the macrotexture of the pavement surface was determined. A detailed laboratory testing program was performed on the cores obtained from the pavement and evaluated to characterize the mixture properties and their effect on segregation and raveling. Traffic data, mix design information, and construction information were obtained for each pavement.

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PLAN OF STUDY

Field Testing

Five pavements showing signs of segregation were selected for sampling and evaluation. The pavements selected varied in age and amount of segregation and raveling. A visual ranking of the pavements was made on the basis of the overall amount of segregation and raveling. The pavements were ranked from 1 to 5, with 5 being the best pavement, with little or no segregation and no raveling, and 1 representing severe segregation with raveling.

Field testing consisted of obtaining three sets of cores 10.2 cm (4 in.) in diameter at each site. One set of cores was taken from segregated areas and one set was taken adjacent to the segregated cores (within 0.5 m of the area of open texture). The segregated areas within a test site varied in the amount and severity of segregation and raveling. A third set of five to eight cores was obtained, with each core obtained at a random location within the test section. The cores from the segregated areas were obtained to measure the amount of segregation, and those adjacent to the segregated areas were obtained to determine whether visual means could be used to determine the extent of segregation. The random cores were selected to determine the average aggregate gradation, asphalt content, and unit weight. The macrotexture was determined in the segregated area to measure the amount of segregation and raveling and at the random areas to determine the average macrotexture of the test section.

The unit weight of the surface mix was determined at the location of each segregated core and random core using a thin-lift nuclear gauge. Sand was not used to fill surface voids for thin-lift nuclear gauge testing; hence the unit weight measured with the nuclear gauge in segregated areas was likely to be lower than the actual unit weight.

The macrotexture of the pavement at segregated, adjacent-to-segregated, and random core locations was determined in general accordance with ASTM E965. The deviations from the standard test method consisted of using natural sand passing the No. 30 sieve and retained on the No. 50 sieve instead of using Ottawa sand or glass spheres as specified. The sand was a commercially available 50-grit blasting sand. Fifty g of sand was used in the test. The difference in macrotexture between the average of the random locations and the macrotexture of a segregated area was determined to indirectly quantify the amount of segregation and raveling. Without monitoring new construction it would be difficult to separate the macrotexture due to segregation and that due to raveling. A higher difference in macrotexture between random and segregated areas indicated that more segregation or raveling, or both, had occurred.

Laboratory Testing

All the cores were measured to determine the thickness of the surface layer. Next, the surface layer was separated from the remainder of the core with a water-cooled rock saw. After sawing, the surface layer was air dried to a constant weight, and the bulk specific gravity was determined in accordance with ASTM D2726. Two random cores were selected for determining the theoretical maximum specific gravity in accordance with ASTM D2041. All the cores were then heated, broken apart, and dried to a constant weight. After drying to a constant weight, all the mix from each core was extracted to determine the asphalt content (ASTM D2172) and the gradation of the mineral aggregate (ASTM C117 and C136). No attempt was made to remove sawed pieces of coarse aggregate from the core before extraction.

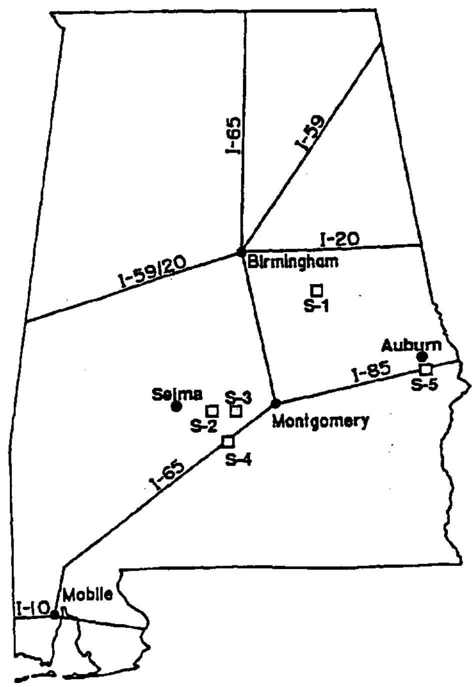

FIGURE 1 Test site location diagram.

State-Supplied Data

The average annual daily traffic (AADT), date of construction, and mix design information, if available, were supplied by AHD for each site.

SUMMARY OF TEST RESULTS

Visual Observations

The test sites were located in Alabama Divisions 4 and 6 (Figure 1) on level tangents of four-lane divided highways. The pavements were ranked from 1 to 5 on the basis of the amount of segregation and raveling as described earlier. The pavement ranking, condition, age, traffic, and location of each test site are shown in Table 1. All of the surface courses tested consisted of an Alabama 416 B mix, a dense-graded, high-stability mix with 100 percent passing the 25.4-mm (1-in.) sieve. A brief description of each site is provided.

Site 1

Site 1 was located in the northbound travel lane of US-280/231 at Milepost 41 in Talledega County. The surface mix was placed in 1988, and the segregation at this site appeared to be end-of-load segregation typical of many segregation projects. Part of the coarse aggregate used for the surface mix was a steel slag with a higher bulk specific gravity (3.138) than the remainder of the coarse aggregate (2.588). AHD personnel stated that the use of the slag as part of the coarse aggregate aggravated the segregation problem.

The segregation at Site 1 had led to raveling throughout the test section. The open texture at this site had allowed moisture to be absorbed, causing stripping and raveling of the surface aggregates. This site was given a visual rank of 1 as the test site with the most segregation and severe raveling.

Site 2

Site 2 was located in the eastbound travel lane of US-80 at Milepost 99 in Dallas County. The surface mix was placed in 1989, and the segregation at this site appeared to be end-of-load segregation. The segregation at Site 2 had not led to any raveling at the time of this investigation. The segregated areas were absorbing slight amounts of moisture, but stripping and raveling of the surface aggregates had not occurred. This site was given a visual rank of 4, the second best pavement, and described as having some segregation but no raveling.

Site 3

Site 3 was located in the eastbound travel lane of US-80 at Milepost 103 in Lowndes County. Site 3 was the newest construction of the five sites, placed in 1990. Much of the apparent segregation and raveling occurring at this site appeared to be associated with pulling of coarse aggregate by the screed, tearing the fresh mat. A slight amount of end-of-load segregation was also apparent. The segregation at Site 3 had not led to any apparent raveling at the time of this investigation. The segregated areas were absorbing slight amounts of mois-

TABLE 1 Traffic, Age, Rank, and Visual Condition Rating

SITE	ROUTE	COUNTY	AADT	AGE (years)	TRAFFIC x 10^6	RANK*	VISUAL CONDITION RATING
1	US-280/231	TALLEDEGA	11,710	2.83	12.1	1	SEVERE SEGREGATION & RAVELING
2	US-80	DALLAS	5,970	1.83	4.0	4	SEGREGATION
3	US-80	LOWNDES	5,970	0.92	2.0	5	SLIGHT SEGREGATION
4	I-65	LOWNDES	15,970	2.25	13.1	2	SEGREGATION & RAVELING
5	I-85	LEE	17,920	3.33	20.7	3	SEGREGATION & SLIGHT RAVELING

* 1 - Worst
5 - Best

ture, but stripping and raveling of the surface aggregates had not occurred. This site was given a visual rank of 5, the site with slight segregation and no raveling.

Site 4

Site 4 was located in the northbound travel lane of I-65 between Mileposts 143 and 144 in Lowndes County. The surface mix was placed in 1989, and the segregation at this site appeared to be end-of-load segregation. The segregation had led to spot raveling throughout the test section. The open texture at this site had led to absorption of moisture, causing stripping and raveling of the surface aggregates. The raveling at this site was not as severe as that at Site 1, so Site 4 was given a visual rank of 2, the second worst pavement, having segregation and raveling.

Site 5

Site 5 was located in the northbound travel lane of I-85 between Mileposts 56 and 57 in Lee County. The surface mix was placed in 1988, and the segregation at this site appeared to be end-of-load segregation. The segregation was beginning to lead to spot raveling throughout the test section, and the open texture had led to absorption of moisture. Stripping and raveling of the surface aggregates had begun. The raveling at this site was very similar to, but appeared to be slightly less than, raveling that was occurring at Site 4; therefore, Site 5 was given a visual rank of 3, indicating segregation with slight raveling.

Test Data

The results of the macrotexture test, thin-lift nuclear gauge unit weight, and bulk unit weight from the pavement cores are shown in Table 2. The results from the extraction and gradation analysis are shown in Table 3 along with the available job mix formulas.

ANALYSIS OF DATA

The data were analyzed to determine how much coarser the mix can get before segregation leads to raveling. Segregated areas of a pavement have more surface voids and, therefore, a larger macrotexture and lower thin-lift nuclear gauge unit weight than the average value of the pavement. Raveled areas should have even larger macrotexture and lower measured unit weights.

The amount of segregation and raveling at each segregated core was determined by subtracting the percent passing each sieve for each segregated core from the average percent passing that sieve from the random cores. Preliminary investigations of the visual pavement ranking and the measured change in gradation on each sieve indicated that the measured change in gradation on the No. 4 and No. 8 sieves agreed best with visual ranking. The measured change in gradation on the No. 4 sieve was therefore selected to quantify segregation and raveling. Regression analysis was performed to determine the relationship between test variables and the amount of segregation and raveling (measured change in gradation on the No. 4 sieve).

Visual Ranking

It is well known that segregation can lead to raveling and loss of pavement serviceability (*1–4*). To determine how much change in gradation on the No. 4 sieve is required before raveling is likely to occur, the visual ranking of the surface segregation and raveling was compared with the average measured difference between the percent passing the No. 4 sieve for each of the five segregated cores from each site and the average percent passing the No. 4 sieve for the random samples. The results are shown in Figure 2. From this figure it

TABLE 2 Sand Patch, Core, and Nuclear Gauge Data

SITE NUMBER	SAMPLE	SAMPLE LOCATION	SAND PATCH DIAMETER (cm)	SAND PATCH DEPTH (mm)	CORE BULK UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)
1	A	1	21.43	0.99	23.14	21.22
1	A	2	30.32	0.50	22.54	22.20
1	B	1	16.99	1.58	22.91	19.81
1	B	2	27.31	0.61	22.85	22.67
1	C	1	12.94	2.73	23.95	19.62
1	C	2	28.26	0.57	23.06	22.23
1	D	1	12.62	2.87	22.75	18.93
1	D	2	25.72	0.69	22.58	21.40
1	E	1	14.37	2.21	23.30	17.56
1	E	2	27.23	0.62	22.69	22.17
1	RANDOM	1	27.31	0.61	22.48	22.07
1	RANDOM	2	30.32	0.50	23.01	22.29
1	RANDOM	3	28.65	0.56	23.18	22.36
1	RANDOM	4	29.69	0.52	23.46	22.37
1	RANDOM	5	26.99	0.63	22.85	22.07
1	RANDOM	6	31.12	0.47	22.92	22.59
1	RANDOM	7	28.50	0.56	22.65	22.15
1	RANDOM	8	27.15	0.62	22.75	21.92
1	RANDOM	AVG.	28.71	0.56	22.91	22.23
2	A	1	22.23	0.93	23.46	21.33
2	A	2	25.56	0.70	22.93	21.52
2	B	1	25.88	0.68	23.32	21.10
2	B	2	27.94	0.59	22.40	21.95
2	C	1	25.24	0.72	23.63	21.68
2	C	2	26.67	0.64	22.64	21.98
2	D	1	24.13	0.78	23.44	21.59
2	D	2	26.67	0.64	22.57	21.66
2	E	1	24.29	0.77	23.41	21.77
2	E	2	25.40	0.71	22.81	21.74
2	RANDOM	1	N/T	N/T	22.98	22.54
2	RANDOM	2	28.26	0.57	22.99	22.72
2	RANDOM	3	27.94	0.59	23.09	22.70
2	RANDOM	4	N/T	N/T	23.07	22.83
2	RANDOM	5	N/T	N/T	23.12	22.80
2	RANDOM	AVG.	28.10	0.58	23.05	22.72
3	A	1	26.83	0.63	23.00	21.32
3	A	2	28.26	0.57	23.16	22.70
3	B	1	24.13	0.78	21.93	20.49
3	B	2	28.42	0.57	22.56	22.48
3	C	1	28.89	0.55	22.24	22.10
3	C	2	30.64	0.49	22.96	22.92
3	D	1	21.27	1.01	22.00	20.66
3	D	2	26.35	0.66	22.18	21.95
3	E	1	19.21	1.24	22.32	19.26
3	E	2	28.42	0.57	22.34	22.10
3	RANDOM	1	30.48	0.49	23.00	22.98
3	RANDOM	2	N/T	N/T	23.09	23.35
3	RANDOM	3	N/T	N/T	23.27	22.92
3	RANDOM	4	31.75	0.45	23.16	23.27
3	RANDOM	5	N/T	N/T	23.25	22.75
3	RANDOM	AVG.	31.12	0.47	23.15	23.05
4	A	1	20.48	1.09	22.41	20.78
4	A	2	25.24	0.72	22.74	20.63
4	B	1	23.65	0.82	23.02	20.66
4	B	2	24.92	0.74	22.39	20.93
4	C	1	21.43	0.99	22.58	19.87
4	C	2	27.46	0.61	22.49	20.83
4	D	1	17.78	1.45	22.79	20.01
4	D	2	29.85	0.51	22.99	22.20
4	E	1	20.48	1.09	23.06	20.47
4	E	2	27.46	0.61	22.88	21.51
4	RANDOM	1	N/T	N/T	22.86	21.90
4	RANDOM	2	28.73	0.55	22.91	21.55
4	RANDOM	3	27.94	0.59	22.99	21.87

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TABLE 2 *(continued)*

SITE NUMBER	SAMPLE	SAMPLE LOCATION	SAND PATCH DIAMETER (cm)	SAND PATCH DEPTH (mm)	CORE BULK UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)
4	RANDOM	4	N/T	N/T	22.80	21.59
4	RANDOM	5	N/T	N/T	22.91	21.65
4	RANDOM	AVG.	28.34	0.57	22.89	21.71
5	A	1	19.84	1.16	23.01	20.30
5	A	2	26.19	0.67	22.65	20.66
5	B	1	21.91	0.95	23.21	20.80
5	B	2	27.15	0.62	22.89	21.63
5	C	1	19.84	1.16	23.11	20.16
5	C	2	24.77	0.75	22.96	20.61
5	D	1	16.19	1.74	22.99	18.80
5	D	2	23.02	0.86	23.15	20.03
5	E	1	15.24	1.97	22.61	18.47
5	E	2	23.65	0.82	22.73	20.82
5	RANDOM	1	27.31	0.61	22.84	22.04
5	RANDOM	2	27.62	0.60	22.85	21.33
5	RANDOM	3	26.04	0.67	23.06	21.38
5	RANDOM	4	25.88	0.68	23.15	21.68
5	RANDOM	5	26.99	0.63	22.75	20.93
5	RANDOM	AVG.	26.77	0.64	22.93	21.48

Note: For samples A-E sample location 1 is segregated area and sample location 2 is adjacent to a segregated area.

N/T = Sample not tested.

TABLE 3 Extraction and Gradation Analysis

SITE NO.	SAMPLE	SAMPLE LOC.	AC (%)	PERCENT PASSING 19.05m (3/4")	12.7m (1/2")	9.5m (3/8")	#4	#8	#16	#30	#50	#100	#200
1	A	1	5.4	99	88	74	49	38	31	24	15	8	4.2
1	A	2	6.2	100	94	83	58	46	38	29	18	10	4.9
1	B	1	5.4	94	84	72	46	35	28	22	14	9	4.7
1	B	2	6.5	95	88	80	56	45	37	28	17	9	3.9
1	C	1	4.2	95	77	57	32	25	21	17	12	7	3.5
1	C	2	6.1	99	92	79	56	45	37	29	18	10	4.5
1	D	1	2.5	98	82	61	33	25	21	18	13	9	5.5
1	D	2	4.0	98	93	83	57	44	36	28	19	12	7.0
1	E	1	3.2	93	72	53	31	25	22	18	13	8	4.7
1	E	2	6.6	100	90	80	54	43	36	28	18	10	4.9
1	RANDOM	1	5.4	100	93	81	57	45	37	28	17	9	5.3
1	RANDOM	2	5.4	100	94	83	58	45	37	28	18	10	5.6
1	RANDOM	3	6.0	100	92	81	58	47	37	25	12	6	5.2
1	RANDOM	4	5.4	99	90	78	55	44	36	28	17	10	5.3
1	RANDOM	5	6.1	98	91	83	58	46	38	29	18	10	4.7
1	RANDOM	6	6.4	97	90	81	58	46	38	28	17	9	4.3
1	RANDOM	7	5.8	99	94	84	59	45	36	26	15	9	5.6
1	RANDOM	8	5.7	99	92	80	58	46	37	28	17	9	5.2
1	RANDOM	AVG.	5.8	99	92	81	58	45	37	27	16	9	5.1
1	JMF		5.4	99	90	76	56	46	N/A	27	16	10	4.2
2	A	1	4.4	95	77	68	53	40	33	25	15	11	9.4
2	A	2	4.7	99	87	77	59	45	37	28	16	12	10.5
2	B	1	5.5	99	83	74	55	39	30	21	10	6	4.6
2	B	2	4.1	98	76	66	50	38	30	20	7	3	3.0
2	C	1	7.4	95	69	61	44	31	23	15	6	4	2.8
2	C	2	6.3	99	81	73	57	42	33	24	11	7	5.4
2	D	1	4.5	97	76	67	51	37	30	22	10	6	4.7
2	D	2	5.1	97	87	80	63	46	36	25	11	7	4.8

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TABLE 3 *(continued)*

SITE NO.	SAMPLE	SAMPLE LOC.	AC (%)	PERCENT PASSING 19.05m (3/4")	12.7m (1/2")	9.5m (3/8")	#4	#8	#16	#30	#50	#100	#200
2	E	1	4.8	99	78	67	51	37	30	22	10	6	4.3
2	E	2	4.9	97	79	70	50	38	31	23	10	6	3.9
2	RANDOM	1	4.1	97	85	78	62	47	38	27	14	10	8.7
2	RANDOM	2	5.0	98	85	78	62	47	37	26	12	7	5.5
2	RANDOM	3	4.6	96	86	79	62	46	36	24	10	6	4.3
2	RANDOM	4	4.3	100	90	82	65	49	39	28	15	11	9.4
2	RANDOM	5	6.0	99	87	79	62	48	38	27	13	8	6.3
2	RANDOM	AVG.	4.8	98	87	79	63	47	37	26	13	9	6.8
2	JMF		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3	A	1	9.7	99	88	78	60	44	33	22	10	5	3.3
3	A	2	6.2	100	91	80	59	43	33	23	11	6	4.1
3	B	1	5.9	100	86	75	53	40	32	22	12	7	4.4
3	B	2	5.6	99	81	72	54	40	31	22	11	7	4.6
3	C	1	6.3	99	89	76	55	40	30	20	14	9	3.6
3	C	2	5.3	99	88	80	62	46	35	23	11	6	4.1
3	D	1	6.7	98	83	69	48	35	26	18	8	5	3.1
3	D	2	5.3	100	87	75	54	39	30	20	9	5	3.4
3	E	1	4.9	96	80	65	47	37	30	23	15	10	8.6
3	E	2	5.4	99	79	69	51	39	32	24	15	11	9.5
3	RANDOM	1	5.6	98	89	78	59	46	37	26	15	12	10.0
3	RANDOM	2	5.4	99	89	81	62	46	36	19	14	11	10.0
3	RANDOM	3	6.2	99	88	76	59	42	33	17	8	5	3.9
3	RANDOM	4	6.1	99	90	81	65	50	40	29	17	15	12.3
3	RANDOM	5	6.7	N/T	N/T	N/T	N/T	N/T	N/T	N/T	N/T	N/T	N/T
3	RANDOM	AVG.	6.0	99	89	79	61	46	37	23	13	11	9.0
3	JMF		5.0	98	93	81	56	45	36	28	15	9	5.7
4	A	1	4.1	99	80	64	45	38	33	26	13	9	5.2
4	A	2	4.5	97	78	63	42	35	29	23	10	6	3.5
4	B	1	5.2	100	88	76	55	45	38	29	13	8	4.7
4	B	2	5.2	100	85	73	54	45	39	30	13	8	4.7
4	C	1	4.8	100	86	75	54	45	39	30	14	9	5.5
4	C	2	4.9	99	84	73	53	44	38	29	14	9	4.8
4	D	1	4.4	100	82	65	43	35	30	23	11	7	4.0
4	D	2	6.1	99	89	78	58	47	40	30	13	8	4.1
4	E	1	4.5	99	85	66	41	33	28	22	11	7	4.2
4	E	2	5.5	99	86	73	54	44	37	28	12	7	4.3
4	RANDOM	1	5.6	99	87	74	51	41	35	26	11	6	3.4
4	RANDOM	2	5.7	100	88	77	55	44	37	28	12	7	4.4
4	RANDOM	3	5.4	99	85	73	51	41	34	26	12	7	4.3
4	RANDOM	4	5.9	100	89	77	56	46	38	29	13	8	5.0
4	RANDOM	5	6.2	100	87	76	57	46	39	29	12	8	4.6
4	RANDOM	AVG.	5.8	100	87	75	54	44	36	28	12	7	4.3
4	JMF		5.7	98	85	71	54	46	N/A	29	13	9	5.5
5	A	1	4.5	97	76	64	46	37	31	23	14	8	5.4
5	A	2	5.6	99	89	79	59	47	38	26	15	8	5.7
5	B	1	4.6	96	78	67	49	39	32	22	13	7	4.9
5	B	2	5.8	100	88	77	56	45	36	25	14	7	4.8
5	C	1	4.8	96	78	66	47	39	31	22	13	8	5.4
5	C	2	4.3	100	86	77	59	48	38	27	16	9	6.6
5	D	1	3.4	97	66	51	34	28	24	18	12	7	4.5
5	D	2	5.0	100	87	74	54	43	35	25	14	8	5.4
5	E	1	3.3	96	65	48	33	28	24	19	12	7	4.8
5	E	2	4.6	99	86	73	52	42	34	25	15	8	5.6
5	RANDOM	1	5.1	99	84	73	55	44	36	25	15	8	5.6
5	RANDOM	2	5.3	97	87	76	55	44	36	25	15	9	5.5
5	RANDOM	3	4.9	98	82	70	53	42	34	25	14	8	5.5
5	RANDOM	4	4.7	99	82	69	49	40	32	24	14	8	5.4
5	RANDOM	5	5.3	100	85	72	51	39	22	11	7	6	5.2
5	RANDOM	AVG.	5.1	98	84	72	53	42	32	22	13	8	5.5
5	JMF		5.0	98	85	76	57	45	N/A	28	16	10	6.5

Note: For samples A-E sample location 1 is segregated area and sample location 2 is adjacent to a segregated area.

N/A = Data not available. N/T = Not tested.

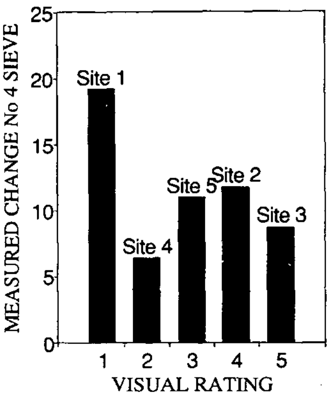

FIGURE 2 Visual ranking versus measured change in gradation on No. 4 sieve.

appears that most of the raveled areas have a change in measured gradation on the No. 4 sieve of greater than 8 to 10 percent.

Lateral Extent of Segregation

Cores were obtained in areas adjacent to (within 0.5 m of the area of open texture) each core from a segregated area to determine the lateral extent of segregation. From the data in Table 3 it can be seen that the gradation of the random cores is very similar to the gradation of the cores from the areas adjacent to the segregated cores and different from the segregated cores. A *t*-test was performed on the percent passing the No. 4 sieve between adjacent and random cores and on the difference in gradation on the No. 4 sieve for adjacent and segregated cores. The results show a significant difference between the measured change in gradation on the No. 4 sieve for the adjacent and segregated cores at a confidence level of 99 percent, but no significant difference in gradation at a confidence level of 95 percent for the adjacent and random cores, indicating no segregation in the adjacent cores. This indicates that segregation is confined to those areas noted visually and does not extend into the adjacent areas.

Asphalt Cement Content

Normally end-of-load segregation results in lower measured asphalt cement contents (*4*, Kandhal and Cross in a paper in this Record). The relationship between the change in gradation measured on the No. 4 sieve and the measured change in asphalt cement content from the random average asphalt cement content for all of the data is shown in Figure 3. The relationship has an R^2 value of 0.22. Two cores, Core A from Site 3 and Core C from Site 2, are outside the 95 percent confidence limits, two standard errors of the mean, and appear to be outliers. Treating these two cores as such, the relationship has an R^2-value of 0.42. Figure 3 shows that as the amount of segregation increases, the deficiency in asphalt cement content increases. The correlation is poor; however, the trend agrees with that in the work of others (*4*, Kandhal and Cross in a paper in this Record).

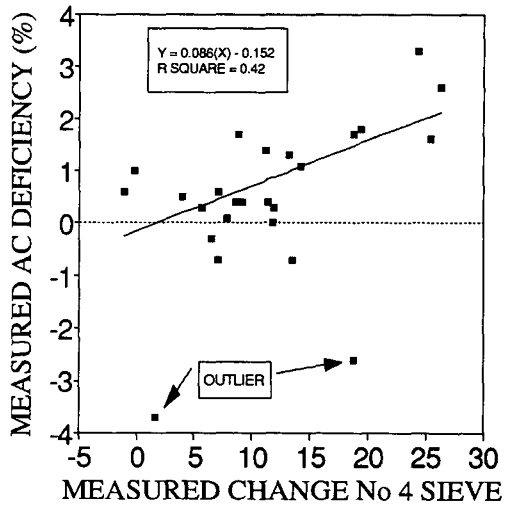

FIGURE 3 Asphalt cement deficiency versus measured change in gradation on No. 4 sieve.

HMA Unit Weight

The unit weight of the HMA at each core location was determined using a thin-lift nuclear gauge and from cores. As shown in Table 2, the nuclear gauge unit weight is lower than the unit weight obtained from the corresponding core. If the nuclear gauge is used to determine the unit weight of segregated areas of a pavement, low values will be determined that may be useful in verifying segregation during construction. The relative percent compaction of each core was determined by dividing the unit weight of the HMA, determined from the thin-lift nuclear gauge, by the average unit weight of the random samples from that site. The results were multiplied by 100 to get the percent relative compaction for comparison between sites. The results are shown in Table 4. The relationship between percent relative compaction and amount of segregation as measured on the No. 4 sieve for all of the data is shown in Figure 4. The relationship has an R^2 value of 0.43 and shows that as the amount of segregation and raveling increases the relative percent compaction, as measured by the thin-lift nuclear gauge, decreases.

Macrotexture Determination

The macrotexture at each core location and the average macrotexture of the random core locations for each site are shown in Table 2. The relationship between the difference in macrotexture for each segregated core and the random average cores (the amount of segregation and raveling) and the change in gradation on the No. 4 sieve, for all of the data, is shown in Figure 5. The figure shows that as the amount of segregation and raveling increases the difference in macrotexture increases, indicating more segregation and raveling. The relationship has an R^2 value of 0.73. Again Core C from Site 2 appears as an outlier, and Table 3 shows that Core C has a very high asphalt content, which probably explains why it is an outlier. Using Core 2C as an outlier, the relationship has an R^2 value of 0.83. The equation uses the square of the

TABLE 4 Summary of Test Results from Random and Segregated Cores

SITE NO.	SAMPLE	SAMPLE LOC.	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE PCT. OF RANDOM (%)	MACROTEXTURE DEPTH (mm)	MACROTEXTURE DIFF FROM RANDOM (mm)	AC CONTENT AC (%)	AC CONTENT DIFF. FROM RANDOM (%)	NO. 4 SIEVE PCT. PASS. (%)	NO. 4 SIEVE DIFF. FROM RANDOM (%)
1	A	1	21.22	95.48	0.99	0.43	5.40	0.40	49.10	8.50
1	B	1	19.81	89.12	1.58	1.02	5.40	0.40	46.20	11.40
1	C	1	19.62	88.27	2.73	2.17	4.20	1.60	32.20	25.40
1	D	1	18.93	85.16	2.87	2.31	2.50	3.30	33.30	24.30
1	E	1	17.56	79.01	2.21	1.65	3.20	2.60	31.20	26.40
1	RANDOM	AVG.	22.23	N/A	0.56	N/A	5.80	N/A	57.60	N/A
2	A	1	21.33	93.91	0.93	0.35	4.40	0.40	53.40	9.20
2	B	1	21.10	92.88	0.68	0.10	5.50	-0.70	55.50	7.10
2	C	1	21.68	95.44	0.72	0.14	7.40	-2.60	43.80	18.80
2	D	1	21.59	95.02	0.78	0.20	4.50	0.30	50.70	11.90
2	E	1	21.77	95.85	0.77	0.19	4.80	0.00	50.80	11.80
2	RANDOM	AVG.	22.72	N/A	0.58	N/A	4.80	N/A	62.60	N/A
3	A	1	21.32	92.50	0.63	0.16	9.70	-3.70	59.60	1.60
3	B	1	20.49	88.89	0.78	0.31	5.90	0.10	53.30	7.90
3	C	1	22.10	95.91	0.55	0.08	6.30	-0.30	54.80	6.40
3	D	1	20.67	89.69	1.01	0.54	6.70	-0.70	47.70	13.50
3	E	1	19.26	83.57	1.24	0.77	4.90	1.10	47.00	14.20
3	RANDOM	AVG.	23.05	N/A	0.47	N/A	6.00	N/A	61.20	N/A
4	A	1	20.78	95.65	1.09	0.52	4.10	1.70	45.00	8.90
4	B	1	20.66	95.07	0.82	0.25	5.20	0.60	55.00	-1.10
4	C	1	19.87	91.45	0.99	0.42	4.80	1.00	54.10	-0.20
4	D	1	20.01	92.11	1.45	0.88	4.40	1.40	42.70	11.20
4	E	1	20.47	94.20	1.09	0.52	4.50	1.30	40.70	13.20
4	RANDOM	AVG.	21.73	N/A	0.57	N/A	5.80	N/A	53.90	N/A
5	A	1	20.30	94.45	1.16	0.52	4.50	0.60	45.60	7.10
5	B	1	20.80	96.79	0.95	0.31	4.60	0.50	48.70	4.00
5	C	1	20.16	93.79	1.16	0.52	4.80	0.30	47.10	5.60
5	D	1	18.80	87.51	1.74	1.10	3.40	1.70	33.90	18.80
5	E	1	18.47	85.97	1.97	1.33	3.30	1.80	33.30	19.40
5	RANDOM	AVG.	21.49	N/A	0.64	N/A	5.10	N/A	52.70	N/A

Note: For samples A-E sample location 1 is a segregated area.
N/A = Not Applicable.

percent passing the No. 4 sieve (X^2) only, because adding a second term (X) did not improve the fit of the model. Figure 5 shows that a measured change in gradation of 8 to 10 percent on the No. 4 sieve—the threshold value for raveling—would cause a difference in macrotexture of 0.38 to 0.48 mm (0.015 to 0.019 in.).

Model To Predict Raveling

From these data it was shown that the amount of segregation and raveling can be related to the measured change in gradation on the No. 4 sieve. The thin-lift nuclear gauge and the difference in macrotexture were both shown to correlate with the measured change in gradation on the No. 4 sieve, with the difference in macrotexture having the strongest correlation.

The macrotexture is a measure of the amount of segregation and raveling. Without monitoring newly constructed segregated pavements, it is impossible to separate the contribution of segregation and that of raveling to the total measured macrotexture. The difference in macrotexture was compared with the visual rating to determine whether the macrotexture difference would predict the performance of the pavement on the basis of the visual rating. The results of the plot of the average difference in macrotexture for the segregated cores from each site and the visual rating are shown in Figure 6. Because Sites 2 and 3 had little to no raveling, a difference in macrotexture of less than 0.50 mm (0.020 in.) is indicative of no raveling; from Figure 5 this is equivalent to a change in percent passing the No. 4 sieve of 10.3 percent.

The pavements sampled in this study ranged in age at the time of sampling from less than 1 year to more than 3 years. Raveling is a function of traffic; therefore, the observed macrotexture would be caused by not only the amount of segregation but also the total applied traffic. Since the macrotexture is a measure of raveling as well as segregation, the addition of the variable total traffic should significantly improve the correlation. The relationship between the difference in macrotexture (raveling) and the measured change in gradation on the No. 4 sieve (segregation) and total traffic has an R^2 value of 0.88, (Figure 7) and has the following form:

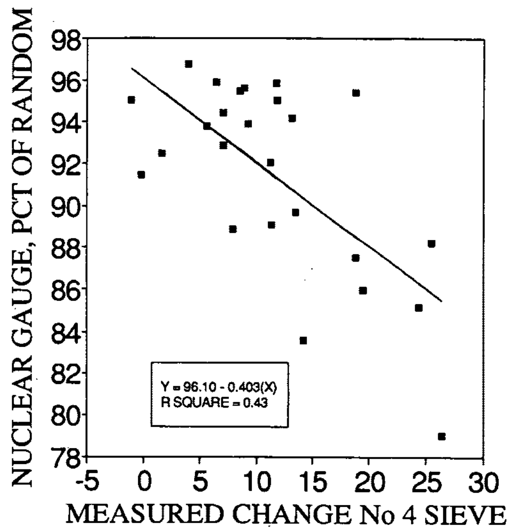

FIGURE 4 Percent of nuclear gauge random average density versus measured change in gradation on No. 4 sieve.

$$P = 0.0346 + 0.0178(T) + 0.00265(P4)^2 \tag{1}$$

where

P = measured difference in macrotexture (mm),
$P4$ = measured change for percent passing No. 4 sieve, and
T = total traffic (vehicles $\times 10^{-6}$).

Knowing that the difference in macrotexture should be less than 0.50 mm (0.020 in.), from Figure 6, one could use the model in Figure 7 to determine whether a given set of traffic and segregation conditions would result in raveling. Obviously, there are not many data to support this equation, and many other variables not investigated would influence the amount of raveling. However, this concept appears to be reasonable. More testing is needed to verify this relationship, including monitoring of new construction and investigating the effect of asphalt cement viscosity on raveling.

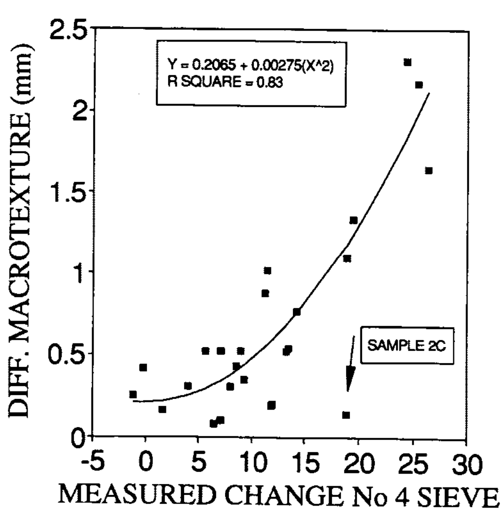

FIGURE 5 Difference in macrotexture versus measured change in gradation on No. 4 sieve.

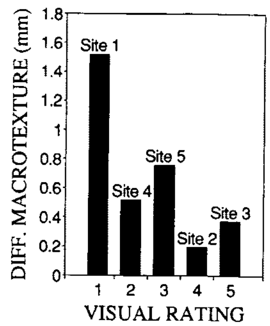

FIGURE 6 Visual rating versus difference in macrotexture for each site.

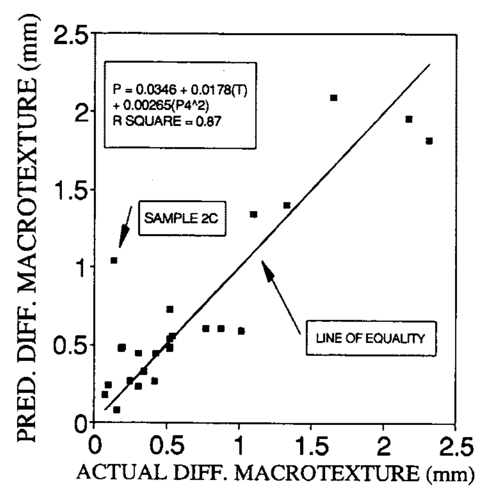

FIGURE 7 Relationship between difference in macrotexture (*P*) and measured change in gradation on No. 4 sieve (*P4*) and total traffic (*T*) in million vehicles.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the limited data obtained in this study and for the mixes investigated the following conclusions and recommendations are warranted.

1. A variation in the percent passing the No. 4 sieve greater than 8 to 10 percent can lead to raveling.
2. Segregated areas of a pavement have larger macrotextures than the average macrotexture of the pavement, indicating differences in surface texture. For the pavements in this study, a difference in macrotexture of 0.50 mm or greater was measured on the mixtures that had raveled.
3. Total traffic as measured by AADT has an effect on the macrotexture and hence on raveling.
4. The macrotexture that can be quantified correlates to the amount of raveling.

5. Visual means can identify the lateral extent of segregation.

6. When the mix becomes coarser because of segregation as measured by a change in percent passing the No. 4 sieve, the measured asphalt content decreases.

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