Evaluation of Fine Aggregate Angularity Using National Aggregate Association Flow Test

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The state of Kansas currently requires a minimum percentage of crushed aggregate in their high-stability hot-mix asphalt mixtures. The current test methods rely on visual and microscopic examination of aggregate samples to determine percent crushed material. The test method for fine aggregates requires the use of a microscope and is time consuming, subjective in nature, and operator dependent. Therefore, it was desirable to develop a simple test that could be utilized in the field to determine aggregate acceptability. The National Aggregate Association (NAA) flow test was modified to replace the use of microscopic evaluation of fine aggregate to determine percent crushed material. The results of the modified flow test were compared with those of the NAA flow test, and the effects of natural sands on the void content were determined. The results from the modified flow test were related to the gyratory elastoplastic index, a measurement of mixture performance. As a result of this study, a new specification was developed utilizing the modified flow test to replace microscopic examination in the determination of percent crushed material. A void content of 46 percent or greater was found to provide satisfactory performance.

The Kansas Department of Transportation (KDOT) currently requires a minimum percentage of crushed aggregate in their high-stability hot-mix asphalt mixtures. The percentage crushed material varies from a high of 85 percent to a low of 50 percent, allowing the use of between 15 and 50 percent natural sands and uncrushed gravel. The eastern one-third of the state of Kansas has abundant deposits of stone that produce adequate amounts of high-quality crushed coarse aggregates and manufactured sands. The western two-thirds of the state relies mainly on deposits of sands and gravels for construction aggregates. Crushed gravels are generally utilized to meet the specification requirements for crushed material. Current KDOT specifications (*1*) for crushed gravel limit the minimum size before crushing, to ensure that all material is crushed, and the amount of material passing the No. 200 sieve after crushing. Historically, the major problem in meeting the specification requirements for crushed gravel occurs from contamination of the material with silts, clays, limestone fragments, and friable materials.

The current test methods employed by KDOT to determine whether aggregates meet the requirements for crushed gravel rely on visual and microscopic examination of aggregate samples submitted by contractors. The aggregates are tested to determine whether the material is crushed or uncrushed, not to determine the extent of crushing or the number of crushed faces. The current test method is easy to perform for coarse aggregates, requiring a visual check; however, for fine aggregates the test requires the use of a microscope. The test for fine aggregate is time consuming and subjective in nature, and has proved to be very operator dependent. Therefore, it was desirable to develop a simple test that could be utilized in the field to determine aggregate acceptability. Ideally, the test developed would relate to mixture performance.

A review of the literature indicated that the National Aggregate Association (NAA) flow test (*2*) might meet the requirements of the department. Several recent studies (*3–5*) indicate that the NAA flow test, a measure of aggregate angularity and surface texture, is related to flexible pavement performance. In addition, the use of the NAA flow test would allow the measurement of the angularity and texture of the aggregate, which is related to performance rather than percent crushed material.

OBJECTIVES

The objectives of this study were threefold: first, to develop a test method to replace the use of microscopic evaluation of fine aggregate in determining percent crushed material; second, to differentiate between blends of crushed and uncrushed samples and samples of crushed material with slight contamination; and third, to develop justifiable specification limits that are related to performance.

SCOPE

Samples of crushed gravel from four pits that supply aggregates to western Kansas were selected for testing. The aggregates from these four pits are typical of the aggregates utilized in western Kansas for production of crushed gravel. The aggregates were tested for percent crushed material using the current KDOT test method (microscopic examination), and the uncompacted void content was determined utilizing the NAA flow test and a proposed modification to the NAA flow test. Samples of the aggregates were combined, and the effects of differing amounts of natural sand in the blend on uncompacted void content were investigated. Aggregate blends were mixed with asphalt cement and compacted on the U.S. Army Corps of Engineers gyratory testing machine (GTM) and the gyratory elastoplastic index (GEPI) was determined.

TEST RESULTS AND DATA ANALYSIS

The entire project encompassed four phases. The original investigation was an exploratory process in which one phase of the plan was completed, and the following phases were determined on the basis of the results and findings from the previous phases.

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The experimental plan was developed and all testing was carried out by the Geology and Bituminous Sections of the Research Unit of the Bureau of Materials and Research, KDOT.

Phase 1

Phase 1 consisted of determining whether the NAA flow test could be utilized to determine the percent crushed material in a sample of fine aggregate, thereby replacing the current KDOT method of evaluating material under a microscope. In all, 54 samples from 4 different pits were evaluated.

The percent crushed material in each sample was determined utilizing microscopic examination, and the uncompacted void content was determined from NAA flow test Methods A, B, and C (*2*). Method A consists of testing 190 g of a standard sand grading.

TABLE 1 Results from Aggregate Testing: Phases 1 and 2

			UNCOMPACTED VOID CONTENT (%)						
LAB No.	SOURCE	PERCENT CRUSHED*	KDOT METHOD A	NAA METHOD A	NAA METHOD B	NAA METHOD C	BULK SPECIFIC GRAVITY	APPARENT SPECIFIC GRAVITY	PERCENT ABSORPTION
134	Fullmer Pit	99.6	50.2	49.1	53.5	39.1	2.62	2.67	0.7
247	Fullmer Pit	99.1	N/T	48.3	52.5	40.0	2.59	2.62	0.4
248	Fullmer Pit	98.8	47.7	48.5	52.6	40.4	2.61	2.65	0.6
249	Fullmer Pit	99.2	47.3	47.9	52.1	39.3	2.58	2.65	1.0
383	Fullmer Pit	98.8	46.9	48.1	52.3	37.9	2.57	2.63	0.9
384	Fullmer Pit	99.0	46.3	48.2	52.2	38.4	2.58	2.63	0.7
385	Fullmer Pit	99.5	47.9	48.9	52.6	39.3	2.60	2.65	0.7
386	Fullmer Pit	99.3	47.4	48.2	52.4	40.4	2.58	2.65	1.0
387	Fullmer Pit	99.2	47.0	49.4	53.0	39.7	2.61	2.66	0.7
413	Fullmer Pit	N/T	46.8	47.3	51.3	37.9	2.56	2.65	1.3
414	Fullmer Pit	99.2	47.5	47.9	51.7	38.3	2.58	2.65	1.0
415	Fullmer Pit	N/T	46.7	47.9	52.5	39.2	2.60	2.67	1.0
416	Fullmer Pit	99.5	47.6	47.6	51.5	37.3	2.57	2.65	1.2
417	Fullmer Pit	N/T	47.0	47.7	51.4	38.3	2.55	2.64	1.3
418	Fullmer Pit	99.1	46.9	41.2	50.4	38.7	2.56	2.65	1.3
419	Fullmer Pit	N/T	47.0	47.1	51.0	36.1	2.55	2.62	1.0
420	Fullmer Pit	99.6	46.9	46.9	51.0	36.8	2.55	2.59	0.6
421	Fullmer Pit	N/T	46.5	48.3	52.7	39.6	2.64	2.67	0.4
1242	TSG-Potter	99.4	47.4	48.5	53.2	42.1	2.61	2.68	1.0
497	JoDee Pit #1	98.8	48.5	48.6	52.4	39.3	2.62	2.65	0.4
3133	Trap Rock	N/T	N/T	50.1	54.5	N/T	2.66	2.77	1.5
388	TSG-Oldham	96.7	47.7	48.0	52.1	37.3	2.52	2.66	2.1
442	TSG-Oldham	97.0	48.3	47.8	52.2	37.8	2.49	2.62	2.0
443	TSG-Oldham	98.7	47.3	49.6	52.8	38.8	2.54	2.68	2.1
444	TSG-Oldham	98.6	48.4	49.2	53.2	39.5	2.57	2.67	1.5
445	TSG-Oldham	97.4	47.4	48.0	51.9	38.5	2.53	2.65	1.8
446	TSG-Oldham	98.6	47.4	48.7	52.8	41.0	2.58	2.66	1.2
447	TSG-Oldham	96.5	47.9	48.9	53.2	41.0	2.56	2.71	2.2
479	TSG-Oldham	97.3	48.2	47.8	52.2	39.0	2.55	2.67	1.8
480	TSG-Oldham	95.7	48.0	48.8	53.0	39.6	2.56	2.66	1.5
481	TSG-Oldham	97.6	48.0	46.4	52.4	39.2	2.53	2.63	1.5
482	TSG-Oldham	96.6	48.3	49.8	53.8	40.0	2.57	2.62	0.7
600	TSG-Oldham	96.1	47.6	48.6	52.9	39.7	2.56	2.71	2.2
601	TSG-Oldham	96.1	48.3	48.2	52.2	38.8	2.55	2.69	2.0
602	TSG-Oldham	97.9	47.5	52.6	53.3	39.7	2.60	2.68	1.1
603	TSG-Oldham	98.0	47.6	49.3	53.1	40.6	2.61	2.67	0.9
981	TSG-Oldham	97.2	41.4	46.9	N/T	N/T	2.59	2.69	1.4
982	TSG-Oldham	98.3	46.9	44.1	49.3	40.6	2.48	2.57	1.4
1055	TSG-Oldham	98.9	46.6	46.8	51.6	43.4	2.58	2.68	1.4
1056	TSG-Oldham	99.0	47.1	47.4	N/T	42.7	2.59	2.69	1.4
1057	TSG-Oldham	99.5	46.0	47.9	52.5	43.4	2.63	2.68	0.7
1137	TSG-Oldham	99.5	46.7	48.1	N/T	40.3	2.60	2.67	1.0
1138	TSG-Oldham	99.6	46.8	46.8	N/T	41.0	2.54	2.65	1.6
1191	TSG-Oldham	N/T	47.2	45.4	50.3	40.2	2.51	2.64	2.0
1192	TSG-Oldham	99.5	47.5	48.1	N/T	42.2	2.63	2.68	0.7
1193	TSG-Oldham	N/T	47.6	46.6	51.8	41.1	2.58	2.67	1.3
1282	TSG-Oldham	N/T	47.6	46.3	51.2	40.7	2.53	2.67	2.1
1356	TSG-Oldham	99.3	42.1	46.0	51.2	42.8	2.59	2.70	1.6
1357	TSG-Oldham	99.2	N/T	47.3	N/T	40.6	2.61	2.68	1.0
1358	TSG-Oldham	N/T	46.0	42.6	47.8	38.0	2.43	2.52	1.5
1447	TSG-Oldham	99.3	46.4	46.6	51.8	42.7	2.59	2.70	1.6
1448	TSG-Oldham	N/T	47.0	44.3	49.1	38.8	2.45	2.51	1.0
1449	TSG-Oldham	99.0	52.1	49.5	53.6	43.1	2.59	2.68	1.3
1450	TSG-Oldham	99.2	47.6	50.3	54.6	44.1	2.66	2.77	1.5

N/T = Not Tested
* Microscopically determined.

TABLE 2 Summary Statistics: Phases 1 and 2

SOURCE	TEST STATISTIC	PERCENT CRUSHED*	UNCOMPACTED VOID CONTENT (%) KDOT METHOD A	NAA METHOD A	NAA METHOD B	NAA METHOD C	BULK SPECIFIC GRAVITY	APPARENT SPECIFIC GRAVITY	PERCENT ABSORPTION
ALL	n	43	51	54	48	52	54	54	54
	Mean	98.47	47.25	47.74	52.13	39.89	2.58	2.67	1.26
	Std Dev	1.13	1.49	1.84	1.28	1.81	0.05	0.06	0.50
	Maximum	99.6	52.1	52.6	54.6	44.1	2.70	2.80	2.20
	Minimum	95.7	41.4	41.2	47.8	36.1	2.50	2.50	0.40
Fullmer	n	13	17	18	18	18	18	18	18
	Mean	99.22	47.27	47.69	52.03	38.71	2.60	2.66	0.88
	Std Dev	0.27	0.87	1.75	0.80	1.19	0.00	0.05	0.29
	Maximum	99.6	50.2	49.4	53.5	40.4	2.60	2.70	1.30
	Minimum	98.8	46.3	41.2	50.4	36.1	2.60	2.60	0.40
Oldham	n	28	32	33	27	32	33	33	33.0
	Mean	98.08	47.20	47.65	52.06	40.51	2.57	2.68	1.49
	Std Dev	1.22	1.77	1.93	1.51	1.79	0.06	0.06	0.45
	Maximum	99.6	52.1	52.6	54.6	44.1	2.70	2.80	2.20
	Minimum	95.7	41.4	42.6	47.8	37.3	2.40	2.50	0.70

* Microscopically determined.

Method B consists of testing three fine aggregate size fractions: the Nos. 8 to 16, Nos. 16 to 30, and Nos. 30 to 50. Method C consists of testing 190 g of the as-received gradation.

The bulk and apparent specific gravity and the percent absorption of the samples were determined in accordance with Kansas Test Method KT-6 (*3*). The results are shown in Table 1, and Table 2 shows the statistics of mean, range, and standard deviation. The bulk specific gravity, excluding the trap rock sample, ranged from a low of 2.50 to a high of 2.70 and the absorption from a low of 0.4 percent to a high of 2.2 percent. The range of specific gravities and absorptions of the materials tested are similar to those of the sands and gravel utilized in western Kansas.

The relationship between uncompacted void content and the percent crushed material is shown in Figure 1. The results show no correlation and indicate that the NAA flow test is not discrete enough to detect slight changes in percent crushed material for the samples evaluated. The results also indicate that the three methods, A,B, and C, give different results. The results of the correlation between percent crushed material and void content were as expected, because the NAA flow test is a measure of aggregate angularity and surface texture, not percent crushed material.

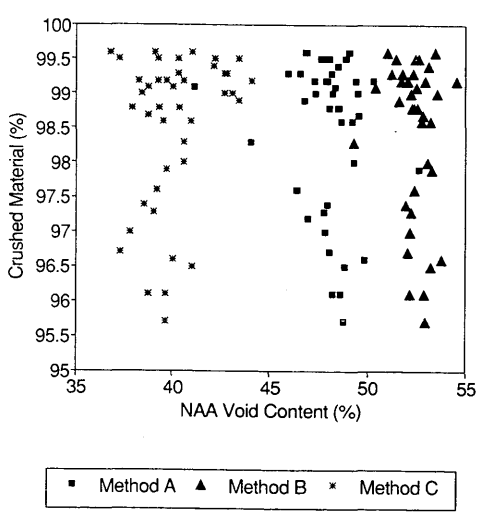

FIGURE 1 Percent crushed material versus NAA void content.

Phase 2

The NAA flow test requires the determination of the bulk specific gravity of the sample, which requires a 24-hr soak of the aggregate, making the test undesirable to KDOT for field testing for acceptance of material as crushed gravel. The aggregates typically utilized in western Kansas have low absorptions and similar specific gravities. Therefore, it was believed that apparent specific gravity could be determined instead of bulk specific gravity without significantly affecting the results. Eliminating the need to determine the bulk specific gravity of the aggregate would reduce the time required to complete the test, making it adaptable for field use. The proposed KDOT flow test involved a modification to the NAA test in which the aggregate in the calibrated cylinder is transferred to a volumetric flask and both are weighed. The volume of the sample is determined by adding water and reweighing. The substitution of the apparent specific gravity for the bulk specific gravity changed the original calculations and simplified the formula for void content to

$$\text{Percent void content} = \{[B - A - (200 - V)]/V\} * 100 \qquad (1)$$

where

A = weight of 200-ml flask and sample,
B = weight of 200-ml flask full of water and sample, and
V = volume of calibrated cylinder.

Each sample from Phase 1 was tested using the KDOT Method A flow test and the results are shown in Table 1. The statistics of mean, range, and standard deviation are shown in Table 2. The results indicate that the KDOT Method A flow test and the NAA Method A flow test have similar means, 47.2 percent and 47.7 percent, respectively. The standard deviations for the two Method A tests show less variation for the KDOT method, 1.49 percent compared with 1.84 percent, indicating better repeatability.

To determine whether the similarity in means was significant, a one-way analysis of variance (ANOVA) was performed on the uncompacted void contents. The analysis indicates a significant difference between the means at a confidence limit of 95 percent ($\alpha = 0.05$). Duncan's multiple range test was performed on the means to determine which were significantly different at a confidence limit of 95 percent. The results show that the NAA Method A and KDOT Method A tests give similar results but are significantly different from the NAA Methods B and C. Therefore, the KDOT Method A flow test could be used in lieu of the NAA Method A flow test and be expected to give the same results with less testing time for aggregates typically utilized in western Kansas for crushed gravel.

The above tests were performed on aggregates typical to western Kansas. The aggregates are silicious, with less than 15 percent carbonates, and have similar specific gravities and low absorptions. Differing results would probably be obtained for materials with greatly differing specific gravities and absorptions.

Phase 3

The results from Phase 2 showed that the KDOT Method A and NAA Method A flow tests gave similar results. The similarity of test results would allow the use of the KDOT flow test for evaluation of aggregates for acceptance as crushed gravel if an acceptance level for void content could be established and if undesirable amounts of contamination could be detected. The third phase of the study consisted of determining whether (*a*) the results from the KDOT flow test were related to percent angular and rounded material in a mixture; (*b*) the KDOT flow test could detect contamination of a sample with natural sands, silts, or clays; and (*c*) the KDOT flow test would relate to GEPI, a measure of a mixture performance. Adoption of the KDOT flow test would be a move away from a measure of crushed material toward a measure of aggregate angularity and surface texture, which was deemed desirable by KDOT.

Aggregate Angularity

The relationship between percent angular and rounded material in a mixture and the uncompacted void content from the KDOT flow test was determined by mixing samples of a very angular material, blast furnace slag, with differing amounts of very rounded material, Ottawa sand and glass beads, and determining the uncompacted void content. A series of samples were made to the Method A gradation (*2*) with various percentages of rounded material. Samples were prepared with 100 percent slag and with slag replaced by rounded material in 5 percent increments, keeping the gradation of the sample constant. The void content was determined using the KDOT flow test and the above experiment was repeated using crushed gravel as the angular material and Kansas River sand as the rounded material.

The results of the above testing are shown in Table 3 and presented in Figure 2. The relationships were found to be linear, with an R^2 of 0.98 for the slag and 0.99 for the gravel. However, the slopes of the regression lines appear to be dependent upon the material.

Effect of Contaminants

To determine the effect of sample contamination on uncompacted void content, a crushed gravel was mixed to the Method A gradation and material was substituted using the same procedure as that described earlier to replace a series of percentages of each sieve. Many different blends of crushed and rounded material and various sizes of contaminants were evaluated with similar results. Only three trials are reported here—No. 8 material, a 50/50 blend of plus and minus No. 200, and plus No. 200 as the contaminant. The uncompacted void content of the samples was determined using the KDOT flow test to determine the effect of contamination on uncompacted void content, and the results are shown in Table 4 and in Figures 3–5.

The results indicate that the uncompacted void content falls off from a high of approximately 45 percent for 100 percent crushed material to a point where the fines bulk the sample at approximately 50 to 75 percent contaminants. This corresponds to a void content of 38 to 42 percent. The void content either increased or stayed constant with a further increase in contamination. However, in only one instance, the 100 percent crushed sample, did the void content rise above the initial one. Therefore, if the void content is set at an appropriately high level, indicating 100 percent crushed material, the test could be used to differentiate between crushed material and crushed material with varying amounts of contamination.

GEPI Testing

There is no good, direct measure of aggregate performance in an asphalt mix; however, several researchers (*4–6*) have stated the importance of angular, rough-textured aggregates in asphalt mixtures. Samples of aggregates with known KDOT Method A flow test values were prepared and mixed with 5 percent asphalt cement by weight of the aggregate to give the mixtures cohesion. The samples were tested for GEPI in accordance with ASTM D3387 at 827.4 kPa (120 psi), 1 degree gyration angle, for 60 revolutions. The GEPI is a measure of the shear strain experienced by a sample and is an index of the angle of internal friction of the aggregate. Mixtures with low GEPI are typical of angular, rough-textured aggregates and high GEPI of rounded, smooth-textured aggregates.

Samples of 100 percent crushed limestone and 100 percent Kansas River sand and three samples of crushed gravel with the highest, mean, and lowest KDOT Method A void contents of the gravels tested in Phase 1 were tested for GEPI. In addition, samples of the highest void content crushed gravel were blended with 25, 50, and 75 percent river sand were also tested. The results are shown in Table 5 and Figure 6. For the 100 percent crushed gravels, the GEPI was constant at a level of 1.48, with uncompacted void contents ranging from 44.4 to 51.5 percent. For the remaining

TABLE 3 Results of Angular and Rounded Uncompacted Void Testing

PERCENT ANGULAR MATERIAL	KDOT METHOD A VOID CONTENT (%) SLAG	CRUSHED GRAVEL
100	54.0	43.61
95	54.5	
90	52.4	42.5
85	52.4	
80	50.6	42.52
75	47.2	
70	49.0	41.59
65	48.3	
60	47.3	41.39
55	46.3	
50	45.4	40.56
45	44.3	
40	43.9	39.87
35	42.3	
30	41.1	39.36
25	39.5	
20	N/T	38.48
15	N/T	
10	N/T	37.65
5	N/T	
0	35.1	37.07

N/T = Not Tested.

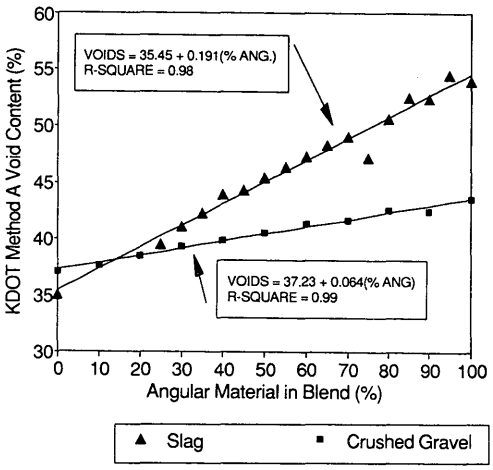

FIGURE 2 KDOT modified flow test versus aggregate angularity.

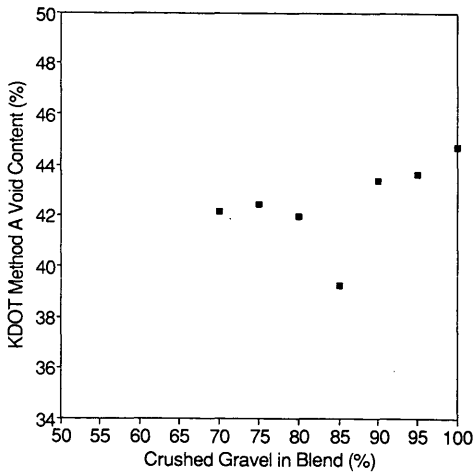

FIGURE 4 KDOT modified flow test versus plus No. 200 contamination.

TABLE 4 Results of Contamination on KDOT Method A Voids

PERCENT CRUSHED GRAVEL	KDOT METHOD A VOID CONTENT (%) PLUS No. 8	PLUS No. 200	50/50 BLEND +No. 200 -No. 200
100	43.66	44.73	44.51
95	N/T	43.67	43.39
90	42.68	43.39	42.6
85	N/T	39.26	41.44
80	40.83	41.96	40.75
75	N/T	42.46	40.21
70	39.88	42.16	40.89
65	N/T	N/T	40.53
60	38.32	N/T	40.69
55	N/T	N/T	40.68
50	37.9	N/T	40.76
45	N/T	N/T	42.75
40	40.18	N/T	N/T
30	40.93	N/T	N/T
20	42.98	N/T	N/T
25	N/T	N/T	47.72

N/T = Not Tested.

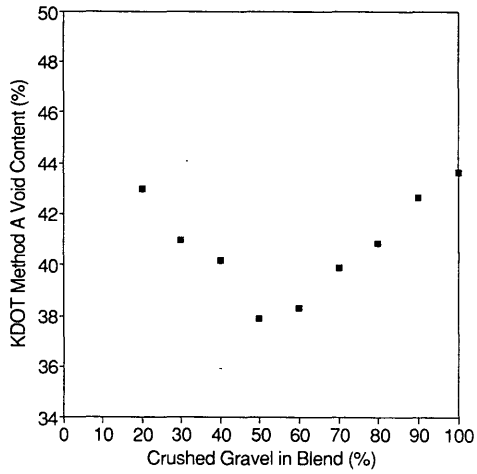

FIGURE 3 KDOT modified flow test versus plus No. 8 contamination.

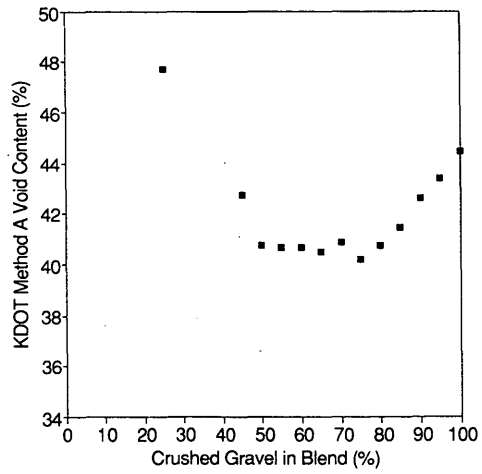

FIGURE 5 KDOT modified flow test versus 50/50 blend of plus and minus No. 200 contamination.

TABLE 5 Results of GEPI Testing

SAMPLE	KDOT METHOD A VOIDS (%)	GEPI
100% Crushed Limestone	49.0	1.4
100% Crushed Gravel High Quality	51.5	1.5
100% Crushed Gravel Medium Quality	47.0	1.5
100% Crushed Gravel Low Quality	44.5	1.5
75% Crushed Gravel 25% Natural Sand	45.0	1.6
50% Crushed Gravel 50% Natural Sand	42.5	1.7
25% Crushed Gravel 75% Natural Sand	39.5	1.7
100 % Natural Sand	37.0	1.9

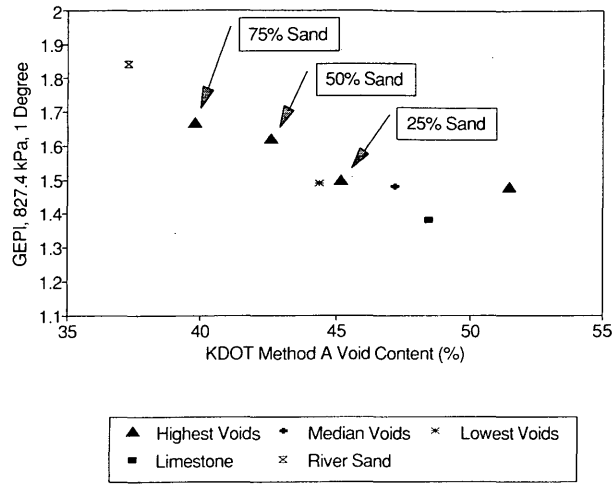

FIGURE 6 GEPI versus KDOT modified flow test.

crushed gravel and 100 percent natural sand mixtures, the GEPI increased with an increase in natural sand, indicating a less stable, more rounded, smooth-textured mixture. The results show that mixtures with an uncompacted void content of 46 percent or higher would have a GEPI, or an index of internal friction, as low as a sample of 100 percent crushed gravel.

From the results of the above testing it was believed that for the aggregates utilized in this study, a void content of 46 percent or higher would be indicative of a fine aggregate with a rough angular surface texture, which would give the same performance as a mixture utilizing 100 percent crushed gravel. The uncompacted void content of 46 percent is slightly higher than the value of 44.5 percent reported by Kandhal et al. (7) as separating natural from manufactured sands. The void content reported by Kandhal et al. (7) is based on the bulk specific gravity, and this study utilized the apparent specific gravity, which would give a higher void content.

TABLE 6 Results of KDOT Flow Tests for Phase 4

LAB #	SOURCE	% GRAVEL	KDOT METHOD A	KDOT METHOD C WITH - No. 100 MATERIAL REMOVED	KDOT METHOD C WITH - No. 200 MATERIAL REMOVED	KDOT METHOD C
A1	A	100	48.1	45.3	43.9	42.7
A3	A	100	48.6	46.3	44.6	42.7
A5	A	100	48.3	45.7	43.9	43.1
A7	A	100	48.4	45.1	43.9	42.2
A9	A	100	48.4	43.3	44.1	42.5
A11	A	100	48.1	45.8	44.5	42.6
A13	A	100	48.1	45.8	44.4	42.9
A15	A	100	48.5	43.9	44.7	38.2
B1	B	100	45.8	43.3	43.0	40.4
B3	B	100	46.1	43.3	43.3	40.4
B5	B	100	47.0	43.9	43.0	40.9
B7	B	100	46.6	43.9	42.2	40.8
B9	B	100	46.0	43.6	42.0	40.6
B11	B	100	46.0	45.6	41.9	41.4
B13	B	100	46.2	45.0	41.7	40.5
B15	B	100	46.4	43.7	42.7	41.5
A31	A	95	48.0	45.4	44.0	42.4
A32	A	95	47.3	45.5	44.1	42.0
A33	A	95	47.1	45.6	44.3	42.4
A34	A	95	47.6	46.0	44.5	42.4
A35	A	95	47.3	45.0	43.9	42.0
A36	A	95	48.0	45.7	44.5	41.9
A37	A	95	47.5	45.3	44.3	42.3
B31	B	95	45.7	43.4	41.9	40.3
B32	B	95	45.9	43.3	42.0	41.2
B33	B	95	N/T	43.0	41.9	39.6
B34	B	95	N/T	43.5	41.8	40.4
B35	B	95	N/T	43.8	41.6	40.8
B36	B	95	N/T	43.9	41.8	41.3
B37	B	95	N/T	43.3	42.6	41.2
B38	B	95	N/T	43.0	41.7	40.3

N/T = Not Tested.

Phase 4

The fourth phase of the study consisted of (*a*) verifying the proposed specification limit of 46 percent KDOT Method A void content, (*b*) determining the repeatability of the test method, and (*c*) determining whether Method C (*2*), the as-received aggregate gradation, could be utilized, thereby saving test preparation time. Two new aggregate sources were selected for Phase 4, one a high-quality crushed gravel (Source A) and the other a crushed gravel with a prior history of failing to pass the current KDOT crushed gravel specification (Source B).

Samples were prepared with 100 and 95 percent crushed gravel and 0 and 5 percent Kansas River sand. The samples were prepared to the Method A gradation, the as-received gradation (Method C), and to Method C with the percent passing the No. 100 and the No. 200 sieves removed. The results from the previous phases indicated that the variability occurring in Method C might be caused by the addition of the No. 8 and No. 200 material. By removing the percent passing the No. 100 and No. 200 sieves, it was thought that the variability might be reduced to an acceptable level.

The uncompacted void contents for Phase 4 are shown in Table 6. An ANOVA was performed on the data to determine whether there was a statistically significant difference between the means of the treatments. The analysis confirms that each flow test was statistically significantly different from the other and could differentiate between sources at a confidence limit of 95 percent ($\alpha = 0.05$). The means and standard deviations from Phase 4 are shown in Table 7. Duncan's multiple range test showed that none of the test methods could consistently differentiate between the samples with and without natural sand by source. This indicates that none of the test methods are discrete enough to detect slight amounts of natural sand. The means of the void contents shown in Table 7 indicate that Source B, a marginal gravel, would fail the proposed specification limit of 46 percent voids at 95 percent crushed gravel but not at 100 percent gravel. Source A, a high-quality gravel, has enough angularity and surface texture to pass the test with 5 percent natural sand.

The results indicate that either Method A or C could be utilized to replace the current specification for crushed gravel. However, the proposed specification limit of 46 percent would need to be lowered approximately 5.5 to 6.0 percent if Method C were utilized. The standard deviation for Method A was less than that for Method C, 1.00 percent to 1.12 percent, indicating that Method A would be more repeatable and therefore more desirable to use.

TABLE 7 Simple Statistics from Phase 4 Flow Test

TEST STATISTIC	KDOT FLOW TEST	SOURCE A 95% GRAVEL	SOURCE A 100% GRAVEL	SOURCE B 95% GRAVEL	SOURCE B 100% GRAVEL
MEAN	Method A	47.55	48.31	45.78	46.26
STD DEV	Method A	0.351	0.201	0.191	0.400
MEAN	- No. 100	45.50	45.14	43.39	44.02
STD DEV	- No. 100	0.307	1.022	0.320	0.823
MEAN	- No. 200	44.22	44.24	41.90	42.45
STD DEV	- No. 200	0.234	0.334	0.287	0.610
MEAN	Method C	42.19	42.11	40.64	40.80
STD DEV	Method C	0.209	1.608	0.568	0.440

CONCLUSIONS

On the basis of the data obtained in this study and for the materials investigated, the following conclusions are warranted:

1. The NAA flow test, Methods A, B, or C, did not correlate with percent crushed material, determined by microscopic evaluation, for the gravel mixtures evaluated.
2. The KDOT Method A flow test and the NAA Method A flow test gave statistically similar results at a confidence limit of 95 percent for the samples utilized.
3. The relationship between the KDOT Method A void content and sample angularity and surface texture was found to be linear.
4. A GEPI of 1.48 was found to differentiate between 100 percent crushed gravel and natural sand and crushed gravel samples. This corresponded to a minimum KDOT Method A flow test void content of 46 percent.

RECOMMENDATIONS

On the basis of the results of this study, KDOT developed a special provision to the standard specifications for crushed gravel. The requirements for determining the percent crushed material on that portion of the material passing the No. 4 sieve was changed from a microscopic evaluation to a minimum uncompacted void content of 46 percent as measured by the KDOT Method A flow test. The requirements for initial gradation before crushing and percent passing the No. 200 sieve after crushing were left unchanged.

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The opinions, findings, and conclusions are those of the authors and not necessarily those of the University of Kansas or KDOT.