Fired-Clay Aggregates for Use in Flexible Bases

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This is the second report issued under a research study dealing specifically with nonbloated synthetic aggregates produced from naturally occurring clays. The first report described the results of a laboratory investigation that indicated that most (if not all) highly plastic soils could be used to produce high-quality synthetic aggregates. The present report describes a later investigation directed toward the development of acceptance criteria that can be used to evaluate aggregates of this type. The investigation included the production of aggregates in the rotary kiln, the evaluation of these aggregates, and a study of several synthetic aggregate flexible bases that have been in service in the vicinity of Houston, Texas, for several years.

•THIS PROGRESS REPORT is the second part of a study entitled "Synthetic Aggregate Research" being conducted by the Texas Transportation Institute, sponsored by the Texas Highway Department and the U.S. Bureau of Public Roads. This phase deals specifically with synthetic aggregates for use in flexible bases, and its primary objective is to develop acceptance criteria for such aggregates. It was initiated in 1966 after nonbloated, fired-clay aggregates had been used experimentally in flexible bases on several Texas highways. To the author's knowledge, fired-clay aggregates are, at present, the only synthetic aggregates economically feasible for use in flexible bases. Therefore, all research efforts so far have been directed toward evaluating this type of aggregate.

The first study done under this phase of the research was an investigation into the chemical and physical stability of laboratory-produced aggregates. The results were reported in a paper by Moore et al. (1), which included the following tentative conclusions:

1. The clay minerals, montmorillonite, illite, and kaolinite, will not rehydrate under atmospheric conditions once they have been completely dehydrated (dehydroxylated); therefore, once they have been completely dehydrated, they become chemically stabilized for use as highway construction materials. Complete dehydration is accomplished by heating the clay and holding it at the elevated temperature for sufficient time to allow the dehydration to occur. A period of 15 minutes at 1400°F. was sufficient to completely dehydrate the clay present in the small, oven dry laboratory specimens made from the Texas soils investigated.
2. Incomplete dehydration of aggregates made by dehydrating clay-type soils can be detected by a relatively simple laboratory test.
3. Most (if not all) clay-type soils having a relatively high strength when air dried can be fired to produce hard, durable aggregates suitable for use in flexible base and asphaltic concrete.

The conclusions listed above were based almost entirely on an evaluation of cylindrical particles (½ in. in diameter by 1½ in. long) that had been fired in a laboratory muffle furnace (Figs. 1 and 2). Therefore, the next investigation initiated under this phase of the research was an evaluation of aggregates produced in a rotary kiln, and the development of acceptance criteria for such aggregates. The investigation included the production of aggregates in the Texas Transportation Institute rotary kiln, their

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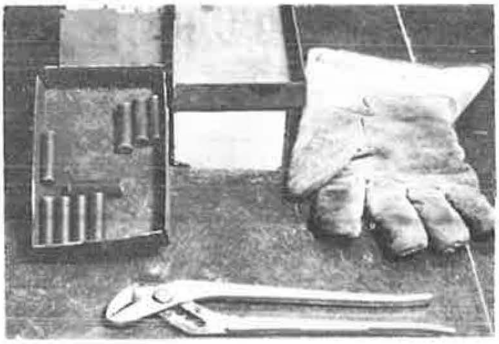

Figure 1. Molded specimens ready for firing in a laboratory muffle furnace.

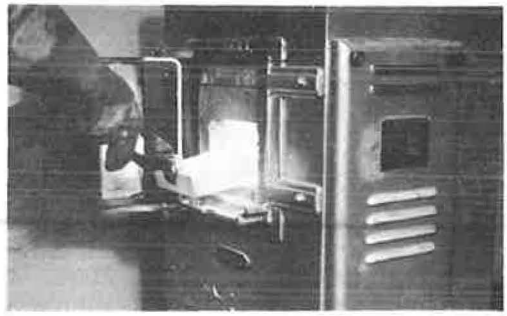

Figure 2. Specimens being removed from a laboratory muffle furnace after firing.

evaluation, and a study of several synthetic aggregate flexible bases that had been in service in the vicinity of Houston, Texas, for several years.

All research results to date are favorable to the use of fired-clay aggregates in flexible bases. The results indicate that these aggregates have great potential for use in highway construction in the many areas of the world where high-quality aggregates no longer exist, but where the clays required for the production of synthetic aggregates are plentiful.

MATERIALS

As a step in the development of a preliminary recommended criterion for the acceptance of flexible base aggregates, the Texas Transportation Institute's research rotary kiln (Fig. 3) was used to produce several samples of graded aggregates. The development of the research kiln and its capabilities are described elsewhere (2, 3).

Aggregate samples were produced from three plastic soils obtained from different sources in Brazos County, Texas. The Atterberg limits and gradations of the soils used are given in Table 1. Standard Texas Highway Department test procedures were followed in these determinations. Aggregates were made by firing each of the three soils at 8 different temperatures; thus, 24 aggregate samples were available for testing. Each sample consisted of about 250 lb of graded material, approximately 95 percent of which was sized between the 1-in. sieve and the No. 10 sieve.

In addition to aggregates made by the Texas Transportation Institute, 4 aggregate samples that had been produced in commercial rotary kilns for use in flexible bases were obtained. Two of the 4 aggregates have been successfully used in flexible bases by the Texas Highway Department. These are referred to as the Hopkins aggregate used by the Paris district and the Wharton aggregate used by the Houston district. Two other samples, designated as the Madison 1 and Madison 2 aggregates, were obtained. These aggregates had been investigated by the Bryan district for possible future use in flexible bases. The results of laboratory tests conducted by the Bryan district, which were

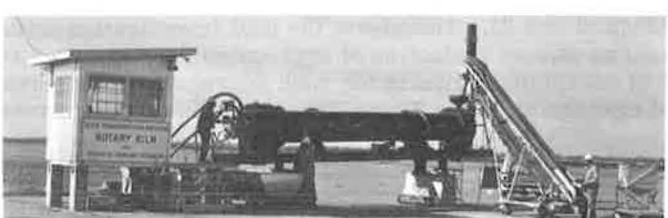

Figure 3. Texas Transportation Institute's research rotary kiln.

TABLE 1
MATERIALS USED FOR RESEARCH AGGREGATE PRODUCTION

Raw Material	Liquid Limit	Plastic Limit	Plasticity Index	Gradation[a] Percent Sand	Percent Silt	Percent Clay
Red clay	74	28	46	4	24	72
Gray clay	67	23	44	5	41	54
Black clay	53	19	34	13	34	53

[a]Determined by hydrometer analysis (MIT classification: sand, 2 to 0.06 mm; silt, 60 to 2 microns; and clay, smaller than 2 microns).

reported by Long (4), indicated that either of the two aggregates would be suitable for use in flexible bases.

None of the above aggregates can be classified as lightweight synthetic aggregates. However, 5 samples of lightweight aggregate—i.e., having a unit weight of less than 55 pounds per cubic foot (pcf)—produced commercially in Texas primarily for use in structural concrete were obtained. These aggregates are currently under investigation for portland cement concrete application in the first part of this study.

In summary, 33 aggregate samples were investigated; 24 of them were produced in the TTI research kiln, 2 have been used successfully in flexible bases on Texas highways, 2 have been investigated for possible similar future use, and the remaining 5 are lightweight aggregates that are available commercially in Texas.

EVALUATION OF AGGREGATES

The simple testing procedure developed during the initial laboratory studies is shown in Figures 4 and 5. Basically it consists of the cooking of specimens under water in a common kitchen-type pressure cooker, and then observing the effect of such treatment on the particles. This procedure works quite well for laboratory-produced cylindrical specimens because deterioration caused by the treatment is readily apparent on the smooth surface of the particles. It was initially thought that the same procedure would yield significant changes in the gradation of kiln-produced aggregates if they were not sufficiently dehydroxylated; however, this was found not to be the case. Only minor changes in gradation were observed after the cooking treatment for many aggregates obviously unsuitable for use in flexible bases. After the cooking treatment, these aggregate samples could be easily crumbled with the fingers.

Several variations of the initial test were tried. A procedure found to be adequate is given in Appendix A. It is called the pressure-slaking test to distinguish it from the slaking test (now considered obsolete) described elsewhere (1) and from the slaking procedures often used in the preparation of soil samples for laboratory testing. Basically the pressure-slaking test consists of the same underwater pressure-cooking (Fig. 6), but an additional treatment of severe agitation in water is inserted between the cooking and the gradation-change measurement. The agitation is accomplished using

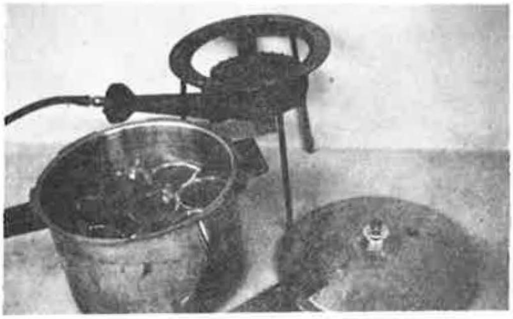

Figure 4. Specimens prepared for cooking in a pressure cooker.

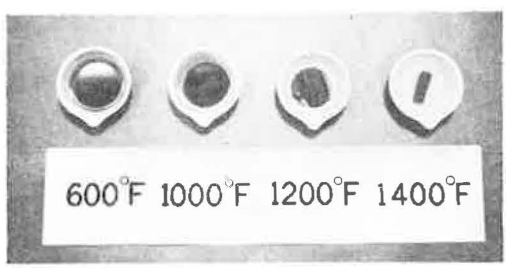

Figure 5. Specimens after cooking in pressure cooker.

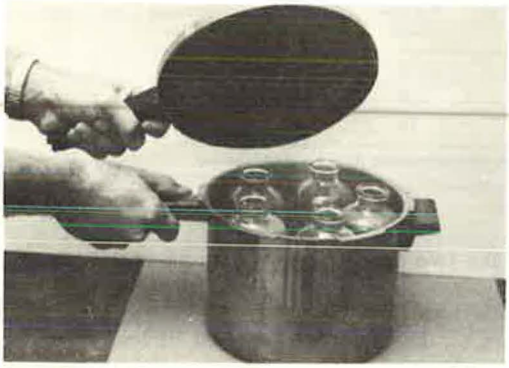

Figure 6. Bottles containing kiln-produced aggregates after cooking in pressure cooker.

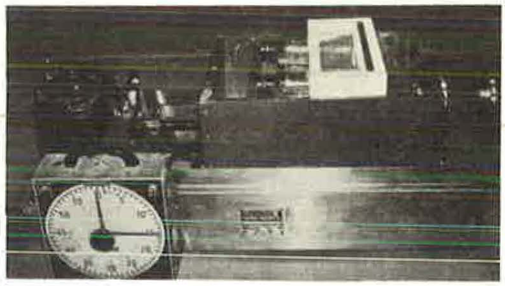

Figure 7. Kiln-produced aggregates subjected to severe agitation in water by a heavy-duty shaker.

Figure 8. Complete samples immediately after cooking and subsequent agitation in water (numbers refer to approximate firing temperature, hundreds of degrees F).

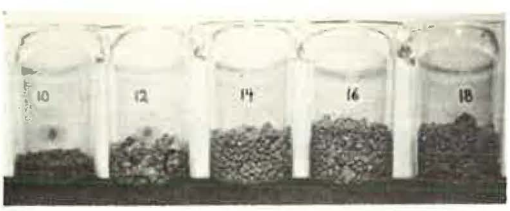

Figure 9. Fractions of samples retained on the No. 40 sieve.

TABLE 2

TEST RESULTS FOR RESEARCH AGGREGATES AND AGGREGATES PRODUCED IN COMMERCIAL KILNS

Aggregate Type	Sample Designation[a]	Pressure Slaking[b] (percent loss)	Los Angeles Abrasion[c] (percent wear)
Red clay, nonbloated, produced by TTI	RC-1000	66.6	64.2
	RC-1100	38.9	61.3
	RC-1205	20.5	56.6
	RC-1295	6.2	50.2
	RC-1390	4.5	42.8
	RC-1585	2.2	36.1
	RC-1800	2.5	36.8
	RC-1910	2.8	33.9
Gray clay, nonbloated, produced by TTI	GC-1030	66.4	62.2
	GC-1095	61.7	66.6
	GC-1200	25.6	55.2
	GC-1305	13.8	61.5
	GC-1400	9.8	62.8
	GC-1600	6.1	49.4
	GC-1800	5.8	52.7
	GC-1930	4.0	39.6
Black clay, nonbloated, produced by TTI	BC-1010	55.9	71.3
	BC-1100	37.4	67.0
	BC-1205	16.8	64.9
	BC-1310	9.3	60.1
	BC-1395	6.7	56.8
	BC-1610	6.5	51.7
	BC-1800	4.2	37.4
	BC-1940	4.2	37.0
Nonbloated, produced commercially	Hopkins	8.3	35.0
	Wharton	9.7	43.6
	Madison 1	6.9	33.3
	Madison 2	7.7	38.3
Bloated, lightweight, produced commercially	R	2.7	27.5
	S	4.9	22.5
	C	5.7	40.4
	E	2.5	25.2
	D	5.0	23.1

[a]The 4-digit numbers shown in some sample designations refer to the maximum kiln temperature measured during sample production.

[b]Each pressure-slaking loss value is the average of three tests performed in accordance with Appendix A.

[c]Each Los Angeles abrasion value is the result of a single test (ASTM Method C 131).

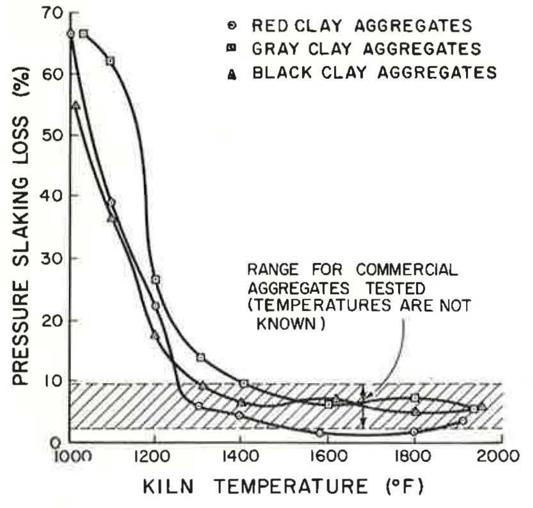

Figure 10. Pressure-slaking loss versus maximum kiln temperature for research aggregates made from three clays.

a standard laboratory heavy-duty shaker (Fig. 7). Typical results of cooking and gradation are shown in Figures 8 and 9. One can observe in these figures the relative amounts of disintegration resulting from the test.

Results of the pressure-slaking test and the Los Angeles abrasion test for the 24 aggregates produced by TTI as well as the 9 aggregates produced commercially are given in Table 2 and shown in Figure 10. From the figure it is clear that the research aggregates made at about 1,000 F would not be suitable for use in a flexible base, whereas all those made at firing temperatures of 1,400 F and higher compare favorably with the synthetic aggregates produced commercially.

EVALUATION OF FIELD SAMPLES

During 1963 and 1964, the Houston district of the Texas Highway Department constructed several projects totaling about 15 miles in length utilizing synthetic aggregate flexible base. The base material consisted of a mixture of approximately 70 percent aggregate produced from clay in a rotary kiln and 30 percent field sand. The Wharton aggregate (given in Table 2 for comparison with the research aggregates) was used in at least one of these projects. The field sand, taken from several sources, was required to have a liquid limit of less than 35 and a plasticity index of less than 10. In one of the projects, the base material was stabilized with lime. According to local engineers, all of the projects are still in good shape. One short section has been reworked (necessitated by a bridge grade change) and the synthetic aggregate flexible base in this section was salvaged and reused.

In the summer of 1968, at 6 different locations several miles apart, sections of these synthetic aggregate flexible bases were sampled and field-tested (Fig. 11). Samples from 5 of these locations were prepared for laboratory testing in accordance with standard Texas Highway Department testing procedures.

As may be seen from the gradations given in Table 3, the amount of soil binder (fraction finer than No. 40 sieve) in the 5 samples prepared for laboratory testing varied from 22 to 34 percent and averaged 28 percent. When one considers that the kiln-produced aggregates had from 2 to 5 percent soil binder, and that the construction specifications required that they be mixed with 30 percent of a field sand with 99 percent soil binder, it appears that there has been no significant disintegration of synthetic aggregates during the 5 to 6 years they have been in service.

The pressure-slaking tests (Table 3) were made on aggregate samples separated from the base samples by washing over the No. 10 sieve. The loss values obtained varied from 8.3 to 15.5 percent and averaged 11.0 percent, as compared to a range of 6.9 to 9.7 percent and an average of 8.2 percent for the 4 commercial flexible base aggregates sampled from stockpiles

Figure 11. Synthetic flexible bases sampled for laboratory testing after several years of service in the Houston area.

TABLE 3

TEST RESULTS OBTAINED ON SAMPLES FROM HIGHWAYS NEAR HOUSTON

Section No.	Moisture (percent)	Dry Density (pcf)	Percent Retained by Sieves				Pressure-Slaking Test
			¾ in.	No. 4	No. 10	No. 40	
2	13.5	111.2	0	29	50	66	12.6
7	15.8	105.9	1	32	60	78	10.0
8	15.9	90.6	0	28	54	71	8.7
9	15.8	90.8	2	34	58	73	15.5
14	15.7	111.4	1	24	49	72	8.3
15[a]	16.4	107.0	—	—	—	—	—

[a]Base material was stabilized with lime and could not be tested.

(Table 2). Thus, the material samples from the roadway had a somewhat greater range and a higher average loss than was the case for the materials sampled from stockpiles. According to the general trend shown in Figure 10, it appears that the synthetic aggregates taken from the roadway probably were produced at temperatures slightly lower than those taken from stockpiles.

In summary it can be said that all of the synthetic aggregate bases appear to have performed satisfactorily to date. The laboratory tests made on the samples that had been in service for several years indicate that these aggregates had not undergone any significant disintegration. Thus, it can be concluded—at least for the Houston environment—that synthetic aggregates suitable for use in flexible base can be produced by firing highly plastic clays. Such aggregates may or may not be suitable for use in more severe environments.

In the opinion of the author, 10 percent loss determined by the pressure-slaking test (Appendix A) is a safe and reasonable upper limit for an acceptance criterion for flexible base synthetic aggregates in Texas to ensure that the aggregates have been fired sufficiently to remain stable in their intended use.

PRESSURE-SLAKING TEST, MOD. 1

In order to utilize existing equipment in Texas Highway Department district laboratories, a modification of the pressure-slaking procedure described in Appendix A was undertaken. The modified procedure is called the "Pressure-Slaking Test (Mod. 1)" and is described in Appendix B. Basically it consists of the same procedure used in the pressure-slaking test except that it uses a Tyler sieve shaker (Figs. 12 and 13) for accomplishing the agitation in water instead of the heavy-duty shaker (Fig. 7). Comparative

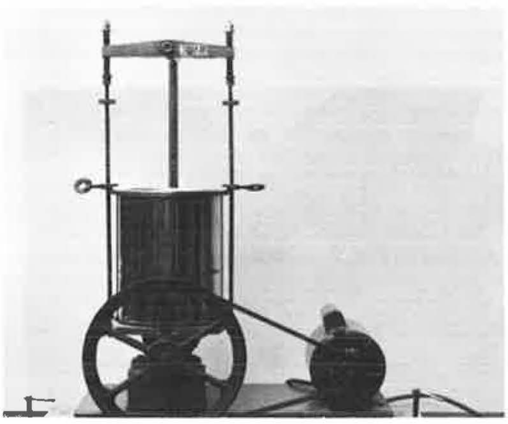

Figure 12. A Tyler sieve shaker used in the modified pressure-slaking test instead of heavy-duty shaker shown in Figure 7.

Figure 13. Container designed to fit shaker for agitating 5 samples simultaneously.

TABLE 4

COMPARATIVE RESULTS OF PRESSURE-SLAKING TEST VERSUS PRESSURE-SLAKING TEST (MOD. 1)

Aggregate Designation	Pressure-Slaking Test, Percent Loss[a]				Pressure-Slaking Test (Mod. 1), Percent Loss[b]			
	Test 1	Test 2	Test 3	Average	Test 1	Test 2	Test 3	Average
RC-1000	60.3	60.4	79.0	66.6	53.6	47.3	43.3	48.1
RC-1100	37.4	33.2	46.0	38.9	21.9	26.7	23.1	23.7
RC-1205	22.9	18.7	20.0	20.5	9.4	7.6	9.8	8.9
RC-1295	5.9	5.6	7.0	6.2	2.1	2.2	2.5	2.3
RC-1390	4.0	4.4	5.0	4.5	1.5	1.6	1.3	1.5
RC-1585	1.8	1.9	3.0	2.2	1.3	1.0	0.8	1.0
RC-1800	2.4	2.1	3.0	2.5	1.2	0.8	1.0	1.0
RC-1910	2.3	2.1	4.0	2.8	0.9	1.2	0.6	0.9
GC-1030	66.6	65.5	67.2	66.4	54.3	60.3	52.6	55.7
GC-1095	62.7	60.7	—	61.7	51.6	46.0	44.6	47.4
GC-1200	27.5	26.2	23.1	25.6	13.0	12.8	14.1	13.3
GC-1305	12.7	14.9	—	13.8	5.8	4.8	5.6	5.4
GC-1400	10.2	9.2	10.0	9.8	3.9	3.7	4.5	4.0
GC-1600	6.9	5.5	6.0	6.1	1.9	1.9	2.5	2.1
GC-1800	6.4	5.1	6.0	5.8	2.0	2.1	2.1	2.1
GC-1930	4.0	3.1	5.0	4.0	1.9	1.4	1.0	1.4
BC-1010	51.6	52.2	64.0	55.9	35.2	36.1	32.4	34.6
BC-1100	36.0	36.3	40.0	37.4	23.9	22.7	19.5	22.0
BC-1205	17.4	16.1	17.0	16.8	7.0	7.4	9.0	7.8
BC-1310	8.9	10.0	9.0	9.3	4.1	3.6	3.2	3.6
BC-1395	6.5	7.0	6.5	6.7	2.2	2.2	2.8	2.4
BC-1610	6.1	6.4	7.0	6.5	2.5	2.7	2.6	2.6
BC-1800	3.3	4.3	5.0	4.2	1.4	1.6	1.8	1.6
BC-1940	4.1	4.6	4.0	4.2	0.9	1.1	1.4	1.1

[a]Analysis of variance: within sample standard deviation, 3.1; within sample CV, 16.0 percent.
[b]Analysis of variance: within sample standard deviation, 1.8; within sample CV, 14.5 percent.

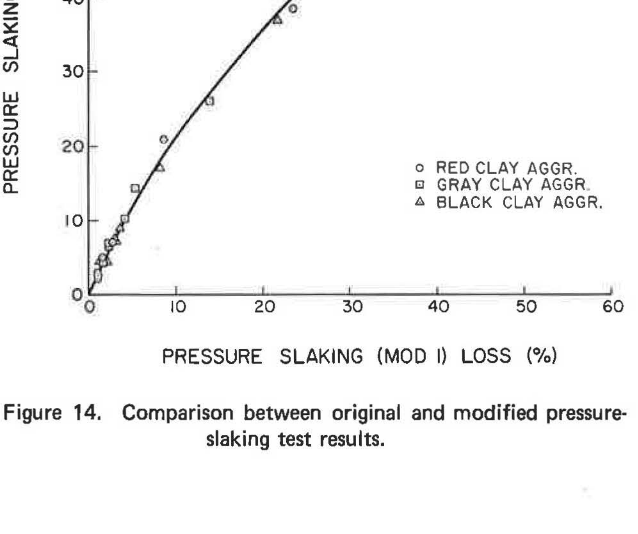

Figure 14. Comparison between original and modified pressure-slaking test results.

test results obtained using the two different procedures on the 24 aggregate samples produced by TTI are given in Table 4. It can be seen from these data that results obtained using the modified test are always lower than those obtained using the original procedure.

Comparative analyses of variance for the data obtained from the two test procedures indicate that the repeatability of the two is about the same. A plot of comparative values is shown in Figure 14. From this it is clear that there is a strong correlation between the tests; thus, the two are essentially measuring the same property. Specifically, it can be said that the recommended acceptance criterion of 10 percent loss based on the pressure-slaking test is equivalent to a loss of 4 percent based on the modified test.

CONCLUSION AND RECOMMENDATIONS

The following findings were reached as a result of the investigation described in this report:

1. Synthetic aggregates suitable for use in flexible bases in Texas can be produced in rotary kilns from highly plastic clays. These aggregates may or may not be suitable for use in locations having a more severe environment than Texas, such as locations subjected to deep frost penetration.
2. Incomplete dehydration of synthetic aggregates made by firing clays can be detected by two relatively simple tests. The procedures for these tests are given in Appendixes A and B.
3. Test results and service records to date indicate that these aggregates have great potential for use in highway construction in the many areas of the world where high-quality aggregates no longer exist but where the clays required for the production of synthetic aggregates are plentiful.

Based on the results of this investigation, it is recommended that synthetic aggregates for use in Texas flexible bases have a loss measured by the pressure-slaking test (Appendix A) of less than 10 percent or a loss measured by the modified pressure-slaking test (Appendix B) of less than 4 percent.

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The opinions, findings, and conclusions expressed in this paper are those of the author and not necessarily those of the Bureau of Public Roads.

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Appendix A

PRESSURE-SLAKING TEST

Scope

The test method described here is intended to be used to evaluate the amount of dehydration that has occurred in the production of synthetic aggregates fired in a rotary kiln. This procedure is a modification of the procedure previously reported elsewhere (1).

Apparatus

The apparatus shall consist of the following: (a) pressure cooker (common kitchen-type with 6-quart capacity and 15-psi pressure regulator); (b) centrifuge bottles, 500 ml Pyrex; (c) balance with 3,000 gram capacity having a sensitivity of 0.1 gram; (d) heavy-duty reciprocating laboratory shaker (Precision Scientific Cat. No. 5855 or equivalent); (e) sieves (¾-in., No. 10, and No. 40 sieves that meet the requirements of ASTM Specification E 11); and (f) drying oven capable of heating to 105 C (220 F).

Sample

An unwashed representative sample of sufficient volume to half fill the centrifuge bottle should be chosen. The sample material is that which passes a ¾-in. sieve and is caught on a No. 10 sieve. Any material retained on the ¾-in. sieve should be crushed to pass this sieve using a minimum amount of crushing. Because synthetic aggregates vary widely as to specific gravity, a volumetric measure of the sample is used rather than weight.

Procedure

1. Place the sample into the centrifuge bottle, and add 200 ml of distilled water. It is not necessary to determine the initial weight of the sample. (Repeat for any number of samples up to as many as can be conveniently placed in the pressure cooker.)
2. Place the centrifuge bottles containing the aggregates in the pressure cooker, add approximately ½ in. of distilled water to the pressure cooker, and seal the lid tightly.
3. Heat the pressure cooker with a large Bunsen burner until full pressure is indicated by the pressure regulator.
4. Adjust flame to allow only a slight escape of steam and maintain pressure for 15 minutes. Remove the Bunsen burner, release the pressure, and remove the centrifuge bottles.
5. After cooling to approximately 100 F, place corks in the centrifuge bottles and place the bottles in the laboratory shaker. Shake the aggregates for 15 minutes.
6. After removing the bottles from the shaker, wash the sample over a No. 40 sieve, taking care not to lose any of either -40 or +40 material.
7. Dry both -40 and +40 material to a constant weight at 105 C (220 F). Because of rehydration, the final total weight of the sample may be greater than the initial weight.

Calculations

The pressure-slaking loss is expressed as the percent passing the No. 40 sieve and is calculated by the following equation:

$$\text{Percent Loss} = \frac{\text{Weight of minus-40 mesh material}}{\text{Total weight of material}} \times 100$$

Appendix B

PRESSURE-SLAKING TEST (MOD. 1)

Scope

This procedure is a modification of the pressure-slaking test procedure given in Appendix A. The modification was made to better utilize existing equipment in the Texas Highway Department district laboratories.

Apparatus

The apparatus shall consist of the following: (a) pressure cooker (common kitchen-type with 6-quart capacity and 15-psi pressure regulator); (b) centrifuge bottles, 500 ml Pyrex; (c) Tyler sieve shaker (Soiltest Model No. C1-305A or equivalent, cpm = 285 ± 10, throw = $1\frac{3}{4} \pm \frac{1}{4}$ in.); (d) balance with 3,000 gram capacity having a sensitivity of 0.1 gram; (e) stainless steel bucket (fits Tyler sieve shaker) consisting of Bain Marie pot with cover and beaker without a pouring lip ($8\frac{1}{4}$ quart, 8-in. body diameter, $9\frac{3}{4}$-in. depth, $8\frac{3}{4}$-in. over bead diameter, available from Texas Highway Department D-4 stock; (f) spacer ($7\frac{3}{4}$-in. diameter by 2 in. thick), rubber cushion ($7\frac{3}{4}$-in. diameter by $\frac{1}{8}$ in. thick), and miscellaneous rubber sheeting or rags; (g) sieves ($\frac{3}{4}$-in., No. 10, and No. 40 sieves that meet the requirements of ASTM Specification E 11); and (h) drying oven capable of heating to 105 C (220 F).

Sample

An unwashed representative sample of sufficient volume to half fill the centrifuge bottle should be chosen. The sample material is that which passes a $\frac{3}{4}$-in. sieve and is caught on a No. 10 sieve. Any material retained on the $\frac{3}{4}$-in. sieve should be crushed to pass this sieve using a minimum amount of crushing. Because synthetic aggregates vary widely as to specific gravity, a volumetric measure of the sample is used rather than weight.

Procedure

1. Place the sample into the centrifuge bottle, and add 200 ml of distilled water. It is not necessary to determine the initial weight of the sample. (Repeat for any number of samples up to as many as can be conveniently placed in the pressure cooker.)
2. Place the centrifuge bottles containing the aggregates into the pressure cooker, add approximately $\frac{1}{2}$ in. of distilled water to the pressure cooker, and seal the lid tightly.
3. Heat the pressure cooker with a large Bunsen burner until full pressure is indicated by the pressure regulator.
4. Adjust flame to allow only a slight escape of steam and maintain pressure for 15 minutes. Remove the Bunsen burner, release the pressure, and remove the centrifuge bottles.
5. After cooling to approximately 100 F, place corks in the centrifuge bottles and place the bottles vertically in the stainless steel bucket. (The rubber cushion should be

placed beneath the bottles and the rubber sheeting or rags inserted between the bottles to press them firmly against the side of the bucket.)

6. Place the spacer over the rubber corks in the bottles and fasten the cover to press the bottles against the bottom of the bucket.

7. Lock the stainless steel bucket in the Tyler sieve shaker and shake the aggregates for 15 minutes.

8. After removing the bottles from the shaker, wash the sample over a No. 40 sieve, taking care not to lose any of either -40 or +40 material.

9. Dry both -40 and +40 material to a constant weight at 105 C (220 F). Because of rehydration, the final total weight of the sample may be greater than the initial weight.

Calculations

The pressure-slaking (Mod. 1) loss is expressed as the percent passing the No. 40 sieve and is calculated by the following equation:

$$\text{Percent Loss} = \frac{\text{Weight of minus-40 mesh material}}{\text{Total weight of material}} \times 100$$