RECYCLED CONCRETE

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A discarded concrete driveway that contained siliceous aggregates and a laboratory concrete beam that contained limestone as coarse aggregate and natural siliceous sand as fine aggregate were selected. Portions of each kind of concrete were processed into aggregate sizes. Three test mixtures and two control mixtures were made. Specimens from each round of each mixture were tested for compressive strength at different ages up to 6 months, for resistance to accelerated freezing and thawing, and for volume changes due to temperature changes or to moisture effects at a constant temperature. The aggregate particles produced by crushing concrete had good particle shape, high absorption, and low specific gravity by comparison with conventional natural mineral aggregates. It is concluded that the present results are promising for the use of recycled pavements or similar concretes as concrete coarse aggregate and perhaps as fine aggregate. If additional work tends to support this tentative conclusion, then existing specifications should be revised to permit and encourage the use of this material as concrete aggregate so that existing supplies of natural aggregates are conserved and the amounts of solid wastes are reduced. The results in this work pertain only to waste concrete that is free of contamination by other materials such as sulfates.

•EXISTING supplies of natural aggregates are being depleted even as the demand for aggregates continues to rise. Because the remaining aggregate supplies are less and less accessible for convenient and economical use, the supply problem is compounded. There is a need now to develop replacements for conventional aggregates. If any of the materials that are now treated as solid wastes can be effectively utilized as aggregates, then the amount of waste that must be disposed of will be reduced, and aggregate resources will be conserved at the same time.

This report covers tests and evaluation of waste concrete of two types for use as concrete aggregate. Waste concretes from pavements and from buildings should be considered separately as raw material for concrete aggregate because concrete from buildings is likely to contain calcium sulfates from plastering or gypsum wallboard, which could raise the problem of sulfate attack if the recycled concrete is used in concrete accessible to moisture. Enough concrete of both kinds is demolished and wasted each year to make the reuse of either kind as aggregate of real benefit. The two concretes evaluated as aggregates in this investigation did not contain contaminating sulfates. One came from a driveway and the other from a test beam containing 3-in. maximum-sized aggregate.

LITERATURE REVIEW

A search of literature on the use of solid wastes as aggregate of any kind is continuing. Because the present interest was in the use of waste concrete as aggregate, special efforts were made to include work done in European countries during the late 1940s and early 1950s. This selection was made because it is known that considerable amounts of debris produced by bombing and shelling were used in rebuilding in urban areas in European countries after World War II.

The majority of the foreign work that was found described the use of bricks and of material identified as rubble for aggregates during the rebuilding process. Because rubble is a general term, references made to it were of no direct value, nor are those made to bricks valuable at this time. The results of some Russian work (1) with waste concrete will be discussed later.

Some references to the use of waste concrete as aggregate for asphaltic mixtures and as base course material in this country (2, 3) were found. However, no references to the use in the United States of waste concrete as concrete aggregates were found.

TEST PROCEDURE

Materials

Several tons of large pieces were obtained from a 6-in. thick concrete driveway that was being removed. This air-entrained concrete was about 8 years old when it was removed; it had been made by a local ready-mix concrete plant, using natural chert gravel and natural sand as the coarse and fine aggregates, to a specified strength of 3,000 psi at 28 days of age. Some of this material was processed into $\frac{3}{4}$-in. maximum-sized aggregate. All of the fines produced by this crushing and sizing operation were caught, combined, and saved.

A large unreinforced concrete beam that had been tested in flexure in the laboratory was processed into the same sizes by the same methods that were used for the waste driveway concrete. The concrete in the beam contained aggregate of 3-in. maximum size and had been wet-screened from a mixture containing aggregate of 6-in. maximum size. The beam was $9\frac{1}{2}$ months old when it was made into aggregate.

Because many concrete aggregates are predominantly siliceous or calcareous, the use of one waste concrete containing the siliceous aggregate (chert gravel and natural sand) and of another containing the calcareous coarse aggregate (limestone) and a siliceous natural sand represented two aggregates that are frequently used.

The chert gravel and the natural sand that were used as coarse and as fine aggregate were intended to be similar to the aggregates that had been used in the driveway concrete; sand from the same lot was used in making the concrete beam.

The limestone coarse aggregate used was from the same lot that was used in the concrete beam.

Portland cement meeting the requirements of Federal Specification SS-C-192g for low-alkali Type II was used. Cement from the same lot was used in the beam.

After selected physical tests of the aggregates, the materials that have been described were used in different combinations to make five concrete mixtures.

Mixtures

Three rounds of three concrete mixtures were made to evaluate the recycled concrete from the driveway as aggregate. The designations of the mixtures and aggregate combinations are as follows:

Mixture Number	Coarse Aggregate	Fine Aggregate
1	Chert gravel	Natural sand
2	Crushed concrete	Natural sand
3	Crushed concrete	Crushed concrete fines

Mixture 1 was the control mixture for this series. All mixtures were proportioned as directed in CRD-C 114 (4), which specifies the aggregate gradings, a water-cement ratio of 0.49, an air content of $6 \pm \frac{1}{2}$ percent, and a slump of $2\frac{1}{2} \pm \frac{1}{2}$ in. Although neither fine aggregate completely met the grading requirements of the test method, they were used without modification of grading for reasons described later.

One round of two other concrete mixtures was made to evalute the recycled concrete that contained limestone coarse aggregate. The designations of the mixtures and aggregate combinations are as follows:

Mixture Number	Coarse Aggregate	Fine Aggregate
4	Limestone	Natural sand
5	Crushed concrete	Natural sand

Mixture 4 was the control mixture for this pair. These mixtures were also proportioned to conform with CRD-C 114(4) except for the sand grading as already mentioned.

The specimens made from each round of each mixture were as follows:

Specimen Number	Size and Type
20	3- by 6-in. cylinders
3	$3\frac{1}{2}$- by $4\frac{1}{2}$- by 16-in. beams
4	3- by 3- by 11-in. prisms with gauge studs

Tests

The compressive strength of three 3- by 6-in. cores, which had been drilled from representative portions of the old driveway concrete, was determined according to ASTM Designation C 42. The approximate compressive strength of the concrete beam was already known.

Specimens from each mixture were tested for compressive strength, frost resistance, linear coefficient of thermal expansion, and length changes due to changes in moisture content.

The compressive strength of three cylinders from each round of each mixture was determined at ages of 7, 28, 56, 90, and 180 days according to ASTM Designation C 39.

Three beams from each round of each mixture were tested in accelerated freezing and thawing in conformance with CRD-C 114(4).

Three prisms from each mixture were tested to determine their linear coefficient of thermal expansion at 28 days according to CRD-C 39 (4). The test plan required testing only one round of specimens from each mixture, but the test was repeated for the third round of mixture 3 because of difficulties with loose inserts in the specimens from the first round.

One prism from each round of each mixture was stored in the moist room at relative humidity above 90 percent and temperature of 73 ± 2 F. The lengths were measured at 1, 28, and 90 days.

TEST RESULTS

Both of the coarse aggregates and the sand made from waste concrete had good particle shape as judged by visual inspection.

Most of the particles in the coarse aggregate sizes of crushed driveway concrete were individual chert particles or crushed portions of them with partial coatings of mortar adhering to the chert. Small proportions of chert particles and of mortar particles were also present. The same types of particles were present in the fine aggregate sizes, with the amounts of mortar and rock particles increasing at the expense of mortar-coated rock with decreasing particle size.

About 75 percent of the $\frac{1}{2}$- and $\frac{3}{8}$-in. sizes of the crushed-beam concrete are particles composed of rock with partial coatings of mortar, with the other 25 percent consisting of individual particles of limestone.

The compressive strength of the beam was about 8,000 psi before it was crushed. The compressive strengths of three 3- by 6-in. cores drilled from different portions of the driveway concrete and broken in the laboratory at about 9 years of age are as follows:

Core Number	Compressive Strength (psi)
1	6,510
2	5,500
3	5,960
Average	5,990

The absorption and specific gravity of the aggregates that were used are given in Table 1. The gradings of the natural sand and of the fines from the crushed driveway concrete are given in Table 2 with the fine aggregate grading prescribed in CRD-C 114(4). The absorptions and specific gravities of the natural sand, the chert gravel, and the crushed carbonate rock are within the usual range for these materials. The two crushed concrete coarse aggregates had high absorptions and rather low specific gravities. The crushed concrete fines used as fine aggregate had absorptions of 7.6 and 9.0 (8.3 ± 0.7) in repeat determinations and low specific gravity. The relatively high absorptions and low specific gravities are to be expected in aggregates produced by recycling concrete.

The data given in Table 2 show that neither of the fine aggregates meets the grading requirements of CRD-C 114 (4) and that the concrete fines depart more widely from the limits than the natural sand. The concrete fines were used in the grading in which they were produced to see what effect this might have on the test results; it was not considered worthwhile to alter the grading of the natural sand.

Properties of the freshly mixed concrete are given in Table 3. Mixture 3, which contained only crushed concrete as aggregate, had lower slump and higher cement content than the other siliceous mixtures. This mixture appeared wet even though it was stiffer than its companion mixtures 1 and 2. When natural sand was used as fine aggregate, there was little difference in slump, air content, or cement content between the control mixtures and their companions, mixtures 2 and 5 respectively.

Compressive strengths of all mixtures are given in Table 4, through 180-day tests. Mixtures 2 and 5, containing waste concrete as coarse aggregate, ranged from about 300 to 1,300 psi lower than the control mixtures at corresponding ages. Mixture 3, with crushed concrete coarse and fine aggregates, is intermediate in strength between mixtures 1 and 2. Mixture 3 may have had higher strength than mixture 2 because the water-cement ratio of mixture 3 was actually lower than that of mixture 2. The lower strengths of mixtures 2, 3, and 5 will be discussed later.

The results of the freezing-thawing tests are given in Table 5. Although the average DFE_{300} values (durability factor based on modulus of elasticity after 300 cycles of freezing and thawing) of 3, 23, and 28 for mixtures 1, 2, and 3 are low, the increased resistance to freezing and thawing indicated by the mixtures containing crushed chert-gravel concrete (2, 3) as aggregate is striking. Probable reasons for this will be discussed later. A reversed trend is shown by the average DFE_{300} values for mixtures 4 and 5, with the control mixture showing slightly higher DFE.

The linear coefficients of thermal expansion are given in Table 6. The value for control mixture 1 is as expected for concrete containing chert gravel and siliceous sand, and the coefficients of mixtures 2 and 3 are similar. The coefficient of mixture 4 is as expected for a limestone coarse aggregate with siliceous natural sand. The coefficient of mixture 5 is higher; the difference is probably significant, but the value is still lower than the coefficients of the first three mixtures.

Length change of prisms stored in the moist room at high humidity and constant temperature is given in Table 7. The test mixtures have about the same amount of change as the corresponding control mixtures.

DISCUSSION

The intent in this work was to evaluate crushed waste concretes similar to concrete used in pavements for use as concrete aggregates. Pavement and building concrete should be considered separately because sulfate from plaster or wallboard may be associated with building concrete and may create the problem of sulfate attack. The chert-gravel concrete from the driveway and the crushed limestone concrete from the laboratory beam used in this work are believed to be fairly similar to pavement concrete, except that the beam contained aggregate of 3-in. maximum size. One concrete contained chert gravel and natural sand, and the other contained limestone and natural sand; both had compressive strengths of about 6,000 and 8,000 psi. Because the beam was not reinforced and the concrete from the driveway contained wire mesh, there are no results from this work on possible problems in processing concrete that contains

Table 1. Specific gravities and absorptions of aggregates.

Aggregate	Bulk Specific Gravity Saturated Surface-Dry[a]	Absorption[a] (percent)
Crushed siliceous concrete		
Coarse	2.43	4.0
	2.44	4.3
Fine	2.34	7.6
	—	9.0
Crushed calcareous concrete (coarse)	2.52	3.9
Chert gravel	2.52	2.6
Limestone	2.67	0.8
Natural sand	2.63	0.4

[a]Tested in accordance with ASTM Designations C 127 and C 128.

Table 2. Gradings of fine aggregates.

	Percent Passing U. S. Standard Sieve						
Aggregate	No. 4 (100)[a]	No. 8 (85 ± 3)	No. 16 (65 ± 5)	No. 30 (45 ± 5)	No. 50 (21 ± 5)	No. 100 (7 ± 2)	No. 200
Crushed siliceous concrete (fine)	100.0	77.1	58.7	42.6	23.5	12.4	6.6
Natural sand	98.1	87.6	74.4	52.6	25.6	7.0	1.2

[a]Figures in parentheses are fine aggregate gradings prescribed in CRD-C 114.

Table 3. Selected physical properties of the five concrete mixtures tested.

Mixture Number[a]	Round	Slump[b] (in.)	Air[c] (percent)	Cement Content (lb/yd^3)
1	1	2¼	6.0	461
	2	2½	6.3	461
	3	2½	6.3	461
2	1	2½	5.7	461
	2	2½	5.8	461
	3	2½	6.0	461
3	1	2	6.3	498
	2	2	6.0	508
	3	2	5.9	508
4	—	2¾	6.0	508
5	—	2½	6.1	489

[a]Tested in accordance with CRD-C 114 using the slump and air content as controls. All mixtures had 0.49 water-cement ratio.
[b]The specified slump is 2½ ± ½ in.
[c]The specified air content is 6 ± ½ percent.

Table 4. Average compressive strengths of the five concrete mixtures tested.

		Compressive Strength (psi)				
Mixture Number	Round[a]	7 Days	28 Days	56 Days	90 Days	180 Days
1	1	2,880	4,420	5,160	5,230	5,660
	2	2,360	3,840	4,400	4,890	5,120
	3	2,520	4,160	4,530	5,070	5,050
	Combined	2,590	4,140	4,700	5,060	5,280
2	1	1,910	2,880	3,480	3,900	3,850
	2	1,990	3,210	3,620	3,840	4,090
	3	2,030	3,050	3,650	3,900	4,140
	Combined	1,980	3,050	3,580	3,880	4,030
3	1	2,440	3,210	3,790	4,270	4,570
	2	2,210	3,570	3,930	4,440	4,640
	3	2,240	3,430	3,700	4,120	4,340
	Combined	2,300	3,400	3,810	4,280	4,520
4	—	3,180	4,510	4,790	5,320	5,530
5	—	2,580	4,150	4,000	4,660	4,840

Note: Tested in accordance with CRD-C 114.
[a]The individual round values are for three 3- by 6-in. cylinders; the combined values are for nine 3- by 6-in. cylinders.

steel bars. However, two literature sources (2, 3) and a personal communication on the use of recycled highway concrete as aggregate for asphaltic mixtures and as a base course material indicate that processing of waste concrete that contains steel reinforcing bars is practical.

Strength, durability, and volume-change tests were made to see if there were substantial differences between test mixtures that contained crushed concrete as aggregates and control mixtures. A comparison between some 1946 test results (1) on waste concrete from the U.S.S.R. and results of tests made at the waterways experiment station is given in Table 8. Where comparisons are possible, the agreement between the Russian results (1) and the present work is excellent.

The mixtures containing crushed concrete as fine aggregate required more cement and were slightly stiffer; however, the increased cost for additional cement should be partly or wholly compensated by the advantage to be gained by using the crushed concrete fine aggregate instead of having to dispose of it. Blending with natural sand, modification of mixture proportions, or use of water-reducing admixtures might permit lowering the cement content and improve the workability when using crushed concrete as sand. None of the test information in this work rules out its use. Its use in an unusual grading did not seem to have any appreciable effect on the test results.

The reasons for the lower compressive strengths of mixtures containing crushed concrete as coarse aggregate (as compared to mixtures containing only natural aggregates) are not known at this time. Several explanations have been considered and rejected or cannot be proved at present. It should be recalled that, although the strengths were lower, they were satisfactory for many uses. It is hoped that slight adjustments of such mixtures will improve their strengths.

The improved frost resistance of mixtures 2 and 3, containing concrete as aggregate, compared to control mixture 1 from a DFE_{300} of 3 to 23 and 28 was substantial. It is thought that this improvement may have occurred because the old mortar, which coats many of the crushed concrete particles, effectively seals off the voids in the frost-susceptible porous chert particles and prevents them from taking up enough moisture to be damaged by freezing.

Comparison of data for test mixtures containing recycled waste concrete as coarse aggregate with data for control mixtures shows the following:

1. There were no unusual problems in mixing or working with the test mixtures,
2. The test mixtures have compressive strengths that are about 300 to 1,300 psi lower than the corresponding control mixtures at all ages tested through 180 days,
3. The resistance to accelerated freezing and thawing is greatly improved when the waste concrete originally contained chert-gravel coarse aggregate,
4. The resistance to freezing and thawing is a little lower but essentially comparable when the waste concrete originally contained limestone coarse aggregate, and
5. Volume changes in response to temperature changes or to continued exposure to moisture at a constant temperature were similar and normal.

The findings for mixture 3, which contained waste chert-gravel concrete as coarse and fine aggregate, were generally like the control mixtures except that cement demand was somewhat higher and workability slightly lower than with the control mixture.

CONCLUSIONS AND RECOMMENDATIONS

The results indicate many reasons in favor of the use of crushed discarded concrete pavements as concrete aggregates. If additional work indicates that the lower concrete strengths obtained with waste concrete as coarse aggregate are not a serious problem, then all existing specifications should be revised to permit and encourage the use of crushed pavement or similar concrete as concrete coarse aggregate.

If, in addition, the mild undesirable effects of waste concrete fine aggregate on workability and cement content of concrete mixtures can be eliminated or reduced or tolerated, then the use of this material should also be encouraged by specification revisions.

Table 5. Durability factor for concrete beams in accelerated freezing and thawing.

Mixture	Round (DFE$_{300}$)[a] 1	2	3	Combined
1	4	4	2	3
2	28	22	19	23
3	30	28	25	28
4	62	—	—	—
5	45	—	—	—

Note: Tested in accordance with CRD-C 114.

[a]The values by round are for three beams; the combined values are the average of nine values.

Table 6. Linear coefficient of thermal expansion of the five concrete mixtures tested.

Mixture Number[a]	Round (coefficient value)[b] 1	2[c]	Combined
1	6.3	—	—
2	6.1	—	—
3	5.6	5.7	5.6
4	3.6[d]	—	—
5	4.7[d]	—	—

[a]Tested in accordance with CRD-C 39.
[b]Round value is for 3 specimens; combined value is for 6 specimens.
[c]Test repeated with different specimens to verify low value; gauge studs were recemented.
[d]A few obviously faulty values were discarded. This lowered the average coefficient values by only 0.2 and 0.3.

Table 7. Length changes of concrete specimens stored at constant moisture and temperature.

Mixture Number	Round	Specimen[a]	Length Increase[b] (percent) 28 Days	90 Days
1	1	1	0.013	0.019
	2	5	0.016	0.018
	3	9	0.010	0.008
		Average	0.013	0.015
2	1	1	0.014	0.023[c]
	2	5	0.010	0.011
	3	9	0.012	0.014
		Average	0.012	0.016
3	1	1	0.017[c]	0.036[c]
	2	5	0.007	0.009
	3	9	0.007	0.011
		Average	0.010	0.019
4	1	1	0.003	0.001
	2	5	—	—
	3	9	—	—
		Average	0.003	0.001
5	1	1	0.003	0.002
	2	5	—	—
	3	9	—	—
		Average	0.003	0.002

[a]Specimens were stored in a moist room at more than 90 percent relative humidity and a temperature of 73 ± 2 F.
[b]The initial reference length was measured at 1 day for mixtures 1 through 3 and at 2 days for mixtures 4 and 5.
[c]Loose inserts.

Table 8. Comparison of test results.

U. S. S. R.	Waterways Experiment Station
New concrete will be no better than the waste concrete that is used as aggregate.	No comparison possible. Waste concrete used was of good quality.
The use of concrete fines as sand requires an undue increase in the cement content of a mixture.	Mixture 3 was the only one that contained concrete fines as sand. It required 47 lb/yd^3 more cement than mixtures 1 or 2 with natural sand. This is not regarded as excessive.
Compressive strengths are lower when concrete is used as aggregate.	Concretes containing waste concrete as coarse aggregate range from 300 to 1,100 psi lower in compressive strength than corresponding control mixtures.
The specific gravity of crushed concrete aggregate tends to be lower than that of natural aggregates.	Work at waterways experiment station confirms this; in addition, the absorption tends to be high.
The cement factor can be lowered if the crushed concrete aggregate is moistened, not saturated, before use.	The coarse aggregates were inundated; the fine aggregates had moisture added 24 hours before mixing the concrete to satisfy their absorption.
For equal compressive strengths, the flexural strength of mixtures with crushed concrete aggregate is higher than for control mixtures.	No flexural tests were made.
Mixtures with crushed concrete aggregate stiffen rapidly but consolidate well with vibration.	No such difference noted with crushed concrete as coarse aggregate only, but mixture 3 with all aggregate crushed concrete was stiffer than the control even though it appeared wet.

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