

RECYCLING PORTLAND CEMENT CONCRETE

William A. Yrjanson, Director of Engineering,
American Concrete Pavement Association

In a growing number of areas in the United States, it is becoming increasingly advantageous to recycle old portland cement concrete. The momentum for recycling has been primarily generated in areas where there is a shortage of, or a complete lack of, supplies of aggregates meeting present day quality standards. Another equally important factor is the problem of solid waste disposal, particularly in urban areas. A reduction in construction costs and conservation of energy have also sparked interest in recycling. Under the recycling concept, existing roadways, airport pavements or any suitable waste concrete becomes a readily available source for producing aggregates. Laboratory research and experience at several recent projects have proven that recycling concrete into aggregate for use in new concrete is feasible and should be considered whenever quality aggregates are not locally available or waste disposal of concrete rubble is costly.

Why Recycle

There is an ever increasing requirement for quality construction materials to meet the needs of our growing society in providing the necessary structures and transportation facilities.

Existing supplies of natural aggregates are being depleted in many areas of the country as the demand for aggregates continues to rise. In many areas there is a complete void of aggregates meeting present day specifications.

The reserves of commercially usable aggregate are vast, however, in some areas the remaining aggregate sources are becoming less and less accessible for convenient and economical use. Often it is buried deep in the earth or it is too distant from markets to offer a desirable return on investment.

There is a need to develop replacements for conventional aggregates in these aggregate short areas. In the past, concrete pavements have been built in many of the aggregate short areas because they required less granular materials than a flexible pavement. These pavements are good candidates for recycling when they have served their useful life.

With the growing concern about land pollution and its effect on the environment, disposal or rubble and other waste materials by dumping or burial is becoming increasingly less attractive and more difficult. As a consequence, serious consideration is now being given to recycling rubble and other wastes into usable construction aggregate. This is particularly true in urban areas. The disposal of the massive quantities of concrete waste generated in these areas poses a difficult problem. These wastes have for years been used in landfill, however, the need for fill today, especially in the highly developed metropolitan centers, can take only a small portion of the waste generated to make way for new construction. It has become increasingly difficult and expensive to dispose of construction debris in these areas due to the increasingly critical environmental requirements.

There is also the potential for a savings in the cost of aggregates in many areas where aggregate sources are distant. With the ever increasing haul costs for construction materials recycling will become attractive in more areas. Energy savings through a reduction in haul distance can be realized in many regions of the country.

For the reasons discussed above, State and Federal Agencies and others are actively encouraging recycling of portland cement concrete where it is economically feasible. The Federal Highway Administration is actively promoting demonstration projects on recycling of portland cement concrete pavements. These projects are intended to assist in developing the technology and to determine the feasibility of recycling old pcc pavements.

History of Recycling of P.C. Concrete

Whenever a new technology is introduced, it is invariably faced with some doubts and skepticism. Concrete recycling technology had to overcome some of these barriers.

In the materials research area, a number of studies have been constructed by such agencies as the Army Corps of Engineers, Waterways Experiment Station, the Iowa Department of Transportation, Massachusetts Institute of Technology, the Minnesota Department of Transportation and the Federal Highway

Administration. These studies were conducted to determine the suitability of recycled aggregates and the economic feasibility of recycling.

When an urgent rebuilding need was found in Europe after World War II, there was a massive job of recycling waste material, especially building rubble, into new concrete construction with generally good success. As soon as the need for this action was satisfied, such recycling was generally abandoned.

Laboratory Studies

Following is a resume of some of the laboratory studies that have been conducted in the United States:

U.S. Army Engineers, WES

The Concrete Laboratory, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, Mississippi, published a report on Recycled Concrete in 1972. (1) This investigation was made to evaluate the use of crushed waste concrete similar to pavement concrete as concrete aggregate. One concrete contained siliceous (chert) aggregates and the other limestone as coarse and natural siliceous sand as fine aggregate.

The aggregate particles produced by crushing concrete had good particle shape, high absorptions, and low specific gravities by comparison with conventional natural mineral aggregates. Other results included:

1. The use of crushed concrete as coarse aggregate had no significant effect on the mixture proportions or workability of the mixtures by comparison with the control mixtures.
2. When the crushed concrete was also used as fine aggregate, the mixture was slightly less workable and required more cement than the control mixture.
3. The use of waste concrete as coarse aggregate results in concrete compressive strengths that are lower than comparable strengths of control mixtures.
4. The use of chert gravel waste concrete in mixtures substantially improved frost resistance as indicated by an increase from $DFE_{300} = 3$ in control mixture to $DFE_{300} = 23$ and 28 in the test mixtures. It is thought that the improved frost resistance 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 from taking up enough moisture to be damaged by freezing.
5. A slightly lower frost resistance was noted for the other mixture from a $DFE_{300} = 62$ to $DFE_{300} = 45$ when compared to the control mixture.
6. The use of waste concrete as aggregate did not have any significant effect of the volume response of specimens to temperature or moisture effects.

Recycled Aggregate Characteristics

Inspection of the coarse aggregate fractions of both crushed concretes and of the sizes passing No. 4 sieve of the chert gravel concrete showed that the coarse and fine aggregates did not contain excessive amounts of flat or elongated particles. The most common particle shape was pyramidal, a desirable situation. The strengths of the concrete prior to processing was about 55.2 MPa (8,000 psi) for the

limestone concrete and about 41.4 MPa (6,000 psi) for the chert gravel concrete.

The absorption and specific gravity of the aggregates that were used are shown in table 1. The gradings of the natural sand and of the fines from the crushed chert gravel concrete are also shown with the fine aggregate grading prescribed in the Handbook for Concrete and Cement, WES Corps of Engineers CRD-C 114. 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, since the specific gravities of the original aggregates will be lowered by the specific gravity of the cement paste.

Additional research in 1976 on Recycled Concrete (2) by the Waterways Experiment Station was an extension of the work previously reported and was concerned with the following:

1. Does the use of low-compressive-strength concrete as aggregate mean that new concrete will also be of low strength?
2. Does recycling concrete containing chert gravel reduce the tendency of popouts to form in new concrete surfaces in addition to improving the frost resistance of the new concrete?
3. The use of building rubble containing calcium sulfate (plaster, wallboard) is likely to result in damage due to chemical activity of the sulfates in the concrete. Feasible contamination levels and possible control measures were to be investigated.
4. Previous work had shown that the compressive strength of concrete mixtures containing recycled concrete was lower than that of companion control mixtures. It was intended to investigate whether this lower strength could be increased by modification of the concrete mixtures.

Based on the work performed under this study and previous work, the following conclusions were reported:

1. The use of low-strength recycled concrete as aggregate need not be detrimental to the compressive strength of concrete mixtures that contain this aggregate. The low strength recycled concrete used as aggregate had a compressive strength of 12.8 MPa (1,860 psi).
2. The data indicates that recycling of concrete that originally contained chert gravel results in a substantial increase in resistance to freezing and thawing. The experiment to demonstrate a decrease in popout susceptibility of recycled concrete was inconclusive.
3. The use as concrete aggregate of building rubble that contained excessive amounts of contaminating sulfate resulted in deleterious sulfate reactions. Therefore, the amount of sulfate should be restricted to 1 percent or less of the total aggregate by weight to be safe. Other control measures are also possible.
4. The use of a water-reducing admixture to lower water content is effective in increasing the strengths of concrete mixtures that contain recycled concrete as aggregate.
5. The use of the fines of recycled concrete

Table 1. Specific gravities and absorptions of aggregates.

	Crushed Concrete Chert Gravel		Crushed Concrete Limestone Coarse	Chert Gravel	Limestone	Natural Sand
	Coarse	Fine				
Bulk Specific Gravity						
Saturated Surface-Dry	2.43	2.34	2.52	2.52	2.67	2.63
	2.44					
Absorption, %	4.0	7.6	3.9	2.6	0.8	.04
	4.3	9.0				

Table 2. Physical properties of selected concrete mixtures.

Material Mixture	Cement Content	28 Compressive Strength	365 Day Compressive Strength	DFE 300*
Low strength 12.8 MPa (1,860 psi) coarse & fine recycled aggregate	lb./yd. ³ (Kg/m ³) 583 (344)	psi (MPa) 3610 (24.9)	psi (MPa) 4710 (32.5)	81
Chert gravel & natural sand	461 (273)	4080 (28.1)	5760 (39.7)	15
Recycled Chert gravel coarse & fine aggregate	583 (344)	3470 (23.9)	5580 (38.5)	80

*Tested in accordance with CRD-C114 (3)

The gradation and specific gravity of the crushed product was as follows:

Table 3. Gradation of crushed product.

Sieve	Crushed Concrete Specific Gravity=2.457	Crushed Asphalt & Concrete Specific Gravity=2.445
	% Passing	% Passing
1" (25.4 mm)	89.9	85.0
3/4" (19 mm)	71.3	68.0
1/2" (12.7 mm)	47.9	46.3
3/8" (9.51 mm)	39.3	37.8
#4 (4.76 mm)	23.3	21.9
#8 (2.38 mm)	15.7	14.1
#16 (1.19 mm)	11.3	9.9
#30 (595 μm)	7.6	6.2
#50 (297 μm)	4.1	3.2
#100 (149 μm)	2.2	1.8
#200 (74 μm)	1.2	1.0

The specific gravity of the natural sand used in these mixtures was 2.68.

as fine aggregate may mean that the concrete mixture may require about 100 pounds of cement more per cubic yard than if conventional sand is used.

Table 2 gives some of the physical properties, strengths, and freeze-thaw durability of selected mixtures.

Here again the freeze-thaw tests of the chert gravel and aggregates made from recycled chert gravel concrete show a five fold increase in the freeze-thaw durability of these mixtures. The results would indicate that aggregates made from recycled concrete containing a frost susceptible aggregate are benefitted significantly by recycling.

Iowa Department of Transportation Research

U. S. 75 Lyon County, Iowa. Iowa conducted their initial recycling project in 1976 on U. S. 75 in Lyon County, Iowa. The existing roadway was a portland cement concrete pavement 178 mm (7 in.) thick and thickened to 254 mm (10 in.) at the edges. The pavement was 5.49 m (18 ft.) and 6.09 m (20 ft.) wide, paved in 1934 and 1936, using gravel as a coarse aggregate. It had been widened with 254 mm (10 in.) of portland cement concrete in 1958 and resurfaced with 76 mm (3 in.) of asphalt concrete in 1963.

Two objectives were involved in this recycling project:

1. To determine if: the asphalt concrete surfacing could be removed, the existing portland cement concrete pavement broken, removed, crushed to 38 mm (1½ in.) minus, proportioned through a conventional central mix proportioning plant with the addition of concrete sand, and placed with a conventional slipform paver.
2. To determine if a two course, composite pavement, each course of different mix proportions, could be placed monolithically with conventional slipform equipment after being proportioned and mixed in a conventional central mix plant.

The pavement removal began in March, 1976; the paving was completed in mid-October, 1976.

The project was completed with no major problem. The objectives were satisfactorily met. The project was a success to the degree that the Iowa Department of Transportation proceeded with two projects for the 1977 construction season that utilized the old recycled pavement as aggregate for the new pavement.

Aggregate materials used in this project were crushed portland cement concrete, crushed portland cement concrete and asphalt concrete combined, and natural sand. A Type I Cement was used and admixtures consisted of an air-entraining agent and a water reducer.

You will note that crushing this gravel aggregate concrete to 38 mm (1½ in.) top size resulted in only about 24% and 22% respectively passing the No. 4 screen for the recycled portland cement concrete and the portland cement concrete-asphalt combination.

The specific gravities again being lower than the parent aggregate materials.

The crushed material was not separated on this initial project and contained particles from 38.1 mm (1½ in.) top size to the -200 sieve material. Some segregation did occur in the stockpile which caused obvious mix problems and the crushed product was difficult to batch. The feed through the bin gates was inconsistent, causing abnormal difficulties in setting the automatic

gate closure operation.

To help remedy the segregation problem, future projects involving crushing the old pavement require splitting the crushed product at the 9.51 mm (3/8 in.) screen size. By providing the crushed aggregate in both coarse and fine fractions, the mixture proportions would be easier to control. Separating the crushed product would also facilitate mix design. An economical and workable mixture design can be readily attainable by using a three-aggregate mixture of uniform coarse and fine crushed product plus concrete sand.

The mixtures used on this project are shown in Table 4. The "A" and "B" mixtures were used on a 229 mm (9 in.) full depth section while the "C" and "C3" mixtures were used as a lower course of a composite pavement consisting of 178 mm (7 in.) of "C" or "C3" mixture with a 102 mm (4 in.) monolithically cast "A" mixture.

Concrete made from recycled portland cement concrete aggregate appears to have excellent flexural strength properties which are important in load carrying capacity of pavements.

Durability testing was performed using crushed material from the project in concrete specimens made in the laboratory. Under Iowa Standard Specifications for coarse aggregate durability, test specimens using the aggregate in question must exhibit a durability factor of at least 80 when tested according to ASTM C666, Procedure B, and moist-room cured for 90 days. Test results at 300 cycles are shown in Table 5.

I-680 Pottawattamie County, Iowa. Iowa recycled another portland cement concrete pavement in 1977 based upon the success of the 1976 Lyon County project. This project was 4.83 km (3 mi.) of I-680 in Pottawattamie County. The old pavement, constructed in 1952 with a good quality crushed limestone (Gilmore City) coarse aggregate, was in good condition exhibiting essentially no distress when it was recycled. The crushed portland cement concrete aggregate was used with natural sand in the 102 mm (4 in.) econocrete base and the 152 mm (6 in.) portland cement concrete shoulders on one lane of I-680.

Iowa Route 2-Taylor & Page County. Another recycling project in southwest Iowa was constructed in 1978 with completion in 1979. The materials for this project was crushed in 1977. The project was approximately 25.8 km (16 mi.) in length beginning near Clarinda and extending easterly to near Bedford, Iowa.

The old pavement was constructed in 1929 using Platte River sand-gravel aggregate from Oreapolis, Nebraska. The slab thickness varied from 178 mm (7 in.) in the middle to 254 mm (10 in.) at the outer edges. The pavement was 5.49 m (18 ft.) wide with 76 mm (3 in.) curb on all but about 4.84 km (3 mi.) of the 25.8 km (16 mi.). In 1964, all curbed sections were resurfaced with asphalt concrete for curb elimination.

The old pavement was in generally good condition. There was some surface check cracking that is typical, to varying degrees, of the Feldspathic Platte River material. This surface cracking had little adverse effect on the pavement except in a few localized areas. Twenty-three 102 mm (4 in.) diameter cores were taken from the old pavement. The average strength of those cores was 45.1 MPa (6,535 psi) (Corrected for height to diameter ratio). The reason for reconstruction of this roadway was

Table 4. Concrete Mixtures.

	Basic Abs. Vol.	Quantities lb./yd. ³ (kg/m ³)
<u>Mix "A": 35% C. A. - 65% F. A.</u>		
Cement	.106611	564 (335)
Water	.181030	305 (181)
Air	.060000	
Agg. (Crushed PCC)	.300429	1244 (738)
F. Agg. (Sand)	.351930	1589 (943)
w/c = 0.54 lb./lb.	Max. w/c = 0.613 lb./lb.	
<u>Mix "B": 50% F. A. - 50% C. A.</u>		
Cement	.106611	564 (335)
Water	.164411	277 (164)
Air	.060000	
Agg. (Crushed PCC)	.440117	1822 (1081)
Agg. (Sand)	.228861	1033 (613)
w/c = 0.49 lb./lb.	Max. w/c = 0.556 lb./lb.	
<u>Mix "C": Crushed A. C. & P. C. (Lower Course of Composite Section)</u>		
Cement	.088842	470 (279)
Water	.150760	254 (151)
Air	.060000	
Aggregate	.700398	2885 (1712)
w/c = 0.54 lb./lb.	Max. w/c = 0.613 lb./lb.	
<u>Mix "C3": 85% A. C. & P. C. - 15% Sand (Lower Course of Composite Section)</u>		
Cement	.088842	470 (279)
Water	.150760	254 (151)
Air	.060000	
Crushed A. C. & P. C.	.595338	2452 (1455)
Aggregate (Sand)	.105060	474 (281)
w/c = 0.54 lb./lb.	Max. w/c = 0.613 lb./lb.	

The above quantities are based on the following:

Specific gravity of cement	3.14
Specific gravity of fine aggr. (sand)	2.68
Specific gravity of crushed P. C. Conc.	2.457
Specific gravity of crushed A. C. & P. C. concrete	2.445

Approx. 24% of crushed P. C. conc. will pass No.4 (4.76 mm) screen.

Approx. 22% of crushed A. C. & P. C. conc. will pass No.4 (4.76 mm) screen

Concrete Compression - 28 day - Average Results

	psi	(MPa)
Mix A	4431	30.4
Mix B	4292	29.5
Mix C	2250	15.5
Mix C3	2290	15.8

Modulus of Rupture - 28 day - Average Results

	psi	(MPa)
Mix A	799	5.51
Mix B	811	5.59
Mix C	586	4.04
Mix C3	560	3.86

obsolescence of width and alignment.

Table 5. Durability tests.

Mix	Cement lb./yd. ³ (Kg/m ³)	Aggregate Type	Aggregate Proportion %	Sand Added	Durability Factor
1	564 (335)	Cr. PC	60 C. A.-40 F. A.	633	88
2	564 (335)	Cr. PC	50 C. A.-50 F. A.	1043	94
3	470 (279)	Cr. ACPC	66 C. A.-34 F. A.	486	79

There was substantial reinforcing steel with four longitudinal 15.9 mm (5/8 in.) smooth round bars along both edges and on either side of the centerline. The transverse steel consisted of 3.35 m (11 ft.) by 15.9 mm (5/8 in.) diameter plain bars at .91 m (3 ft.) centers. They were placed so that they extended within 152 mm (6 in.) of the edge of pavement and on alternate side of the centerline. There were dowels and additional 2.44 m (8 ft.) by 15.9 mm (5/8 in.) diameter bars at all transverse construction joints.

Primary crushing reduced the concrete to approximately 76 mm (3 in.) size material. The crushed product was further processed in the secondary crusher with a Universal 10-36 jaw and separated into 38.1 mm (1½ in.) to 9.52 mm (3/8 in.) and minus 9.52 mm (3/8 in.) material. At the start the fines were removed from the minus 9.52 mm (3/8 in.) material at the secondary crusher, but after the "grizzly" was opened for scalping off fines this was no longer necessary. The crushed products were stockpiled by a conveyor belt with radial movement capability. Washing of the aggregates was not required on any of the Iowa Recycling Projects.

The two earlier Iowa Department of Transportation recycling projects had demonstrated that some natural sand was necessary to produce a workable mixture. In this case, 553 kg (934 lbs.) of natural sand was added in addition to 377 kg (637 lbs.) of 9.52 mm (3/8 in.) screen material.

Durability of the concrete made with recycled aggregate was tested by ASTM C666 Method B (freezing in air, thawing in water). Concrete abrasion tests conducted on both recycled aggregate concrete and concrete made with virgin aggregate showed very similar wear characteristics.

The specific gravity of the crushed coarse and fine aggregate on this project was 2.35 or somewhat lower than reported on other projects and tests. This can be explained by the higher mortar content of concrete which contained the Platte River sand-gravel having essentially a 9.51 mm (3/8 in.) top size material.

Minnesota Department of Transportation Research

Construction of the first major concrete recycling project in the United States to utilize a "D" cracked concrete pavement as a source of aggregate for a new portland cement concrete pavement was accomplished in 1980. The project was developed through extensive research and testing by the Minnesota Department of Transportation. The project involves recycling of 25.8 km (16 mi.) of U. S. 59, from Worthington to Fulda in southern Minnesota.

The pavement was constructed in 1955 utilizing a gravel coarse aggregate with approximately 60%

soft limestone particles susceptible to "D" cracking. After about 25 years of service, the pavement exhibited a great deal of distress primarily in the form of "D" cracking.

The rehabilitation of this section of highway involved the recycling of the pavement into coarse aggregate for a new portland cement concrete pavement and the utilization of -4 screen (4.76 mm) materials for a granular base under the pavement and shoulders.

Laboratory research and field performance has shown that crushing a potential "D" cracking aggregate to a smaller size substantially reduces the "D" cracking potential of concrete made with the aggregates. With this in mind, Minnesota DOT specified crushing the concrete to 19 mm (3/4 in.) top size with 95 to 100% passing the 19 mm (3/4 in.) screen and 0 to 5% passing the No. 4 (4.76 mm) screen.

Although no intermediate gradation requirements were specified, gradation tests run during the aggregate processing operation indicate a very uniform and clean material was being produced. During the initial testing of the recycled aggregate it was found that the -200 sieve materials were not deleterious so washing was not required.

The core strength of the original pavement was in the range of 34.5 MPa (5,000 psi) to 37.9 MPa (5,500 psi) and the air content about 4.5%.

The material passing the No. 4 (4.76 mm) sieve was very angular and the trial mixture using this material increased water demand substantially to get workability. For this reason, Minnesota DOT engineers decided to use a natural sand with the recycled coarse aggregate.

During the trial mixture investigations, mix designs were developed using fly ash as a replacement for cement. Three mixtures were investigated with one containing no fly ash, a 10% fly ash replacement for cement and a 20% fly ash replacement for a 15% cement reduction. It was the intent to use the fly ash as a plasticizer, thereby reducing the water demand.

Freeze-thaw durability testing was performed on these concretes to note "D" crack activity. The fly ash concretes showed a reduced "D" crack potential with the concrete having the 20% fly ash replacement showing a greatly reduced potential for "D" cracking.

The paving operation proceeded without any problems with the materials or the mixture. The control of entrained air was not a problem. Flexural strength at 14 days averaged approximately 4.83 MPa (700 psi) by the mid-point loading method of test. Here again, excellent flexural strengths were developed with recycled materials. Smoothness as measured by the Roughometer averages about 70, indicating a very smooth pavement.

This project is a milestone in salvaging an old "D" cracked pavement by recycling. There are many

Table 6. Typical Gradation of Crushed Concrete

<u>Coarse Fraction</u>	
<u>Sieve Size</u>	<u>Percent Passing</u>
1½ in. (38.1 mm)	100
1 in. (25.4 mm)	72
¾ in. (19.0 mm)	39
½ in. (12.7 mm)	21
3/8 in. (9.51 mm)	9.3
No. 4 (4.76 mm)	2.9
No. 8 (2.38 mm)	2.0
No. 200 (74 µm)	0.7
Clay lumps	0.2%

<u>Fine Fraction</u>	
<u>Sieve Size</u>	<u>Percent Passing</u>
3/8 in (9.52 mm)	100
No. 4 (4.76 mm)	76
No. 8 (2.38 mm)	51
No.16 (1.19 mm)	30
No.30 (595 µm)	16
No.50 (297 µm)	8.0
No.100 (149 µm)	3.5
No.200 (74 µm)	2.0

The crushing operation produced approximately 65% coarse fraction and 35% fine fraction. The total estimated production was 54,000 tons from this section of roadway.

The mixture proportions used on this project were as follows:

Table 7. Mixture Proportions

	<u>Basic Abs. Volume</u>	<u>Approximate Dry Quantities/c.y.</u>
Cement	0.118330	626 lbs. (370 kg/m ³)
Water	0.178063	
Air	0.600000	
Crushed Concrete, Coarse	0.273533	1083 lbs. (640 kg/m ³)
Crushed Concrete, Fine	0.160902	637 lbs. (377 kg/m ³)
Concrete Sand	0.209172	934 lbs. (553 kg/m ³)

Design water - cement ratio 0.48

Maximum water - cement ratio 0.545

The quantities are based on the following assumptions:

Specific gravity of crushed concrete, coarse	2.35
Specific gravity of crushed concrete, fine	2.35
Specific gravity of crushed sand	2.65
Specific gravity of cement	3.14
Weight of water	62.4 lbs. per cu. ft.

An approved water reducing admixture was required.

Table 8. Flexural Strength, Air Content & Density of Concrete

Slump	Air	Modulus of Rupture		Density
		7 Day	14 Day	
1.65	6.8	718 (4.95 MPa)	778 (5.36 MPa)	135.8
1.46	6.9	745 (5.14 MPa)	809 (5.58 MPa)	
1.47	7.0	771 (5.32 MPa)	843 (5.81 MPa)	

The mixture used on the U. S. 59 project (in Southern Minnesota) follows:

Table 9. Concrete Mixture Proportions

Material	lbs./ cu. yd.
Cement	465 (270 kg/m ³)
Fly Ash	109 (64.5 kg/m ³)
Water	255 (150.5 kg/m ³)
Sand (Sp.G. 2.62)	1,198 (708.9 kg/m ³)
Recycled Coarse Agg. (Sp.G 2.38)	
Absorption - 4.5%	1.632 (965.7 kg/m ³)
Assumed % Air	5.5

miles of pavements showing distress from "D" cracking in aggregate short areas of where good quality aggregates are not available. These pavements would be prime targets for recycling when rehabilitation is needed. Proper sizing of aggregates made from these pavements along with the increased resistance to freezing and thawing as shown by tests will produce an aggregate that has a greatly reduced potential for "D" cracking.

Mixture Designs Using Recycled Aggregates

Recycling projects have demonstrated that some natural sand is necessary to provide a workable mixture. Iowa has utilized both the coarse +9.51 mm (3/8 in.) and fine aggregates produced by recycling in their mixtures and as shown earlier they also use about 30% of a natural sand to obtain the workability of the standard pavement mixture. Iowa does use a 50 - 50 mixture of coarse and fine aggregate in their standard mixture. This is somewhat higher on the sand percentage than many state agencies specify.

The mixture used on the Minnesota U. S. 59 project utilized about 40% natural sand and the crushed coarse aggregate with a 19 mm (3/4 in.) top size. This mixture was workable and no problems were encountered in finishing the pavement.

Concrete made from recycled aggregates in general has a higher flexural strength to compressive strength ratio than is normally found with many conventional aggregates. Since pavement thickness design is based on the flexural strength of concrete, the flexural properties of recycled concrete should be determined. If the compressive strength of cylinders is used for control purposes, a relationship should be established between the flexural strength of beams and the compressive

strength of cylinders using the recycled materials.

Removal and Crushing of PCC Pavements

U. S. Route 75 - Iowa

The first Iowa project on U. S. 75 in Lyon County utilized a pneumatic hammer mounted on the rear of a John Deere back hoe/loader to punch holes in the old pavement on approximately .61 m (2 ft.) to .91 m (3 ft.) centers. This caused weak points so that the old slab would more readily break. The existing 76.1 mm (3 in.) asphalt pavement was easily removed with a back hoe. It came off in large, .91 m (3 ft.) to 1.22 m (4 ft.) pieces. The surface was cleaned with a loader bucket and this essentially completely removed the asphalt.

After the asphalt was removed, the back hoe picked up the slab in approximately .61 m (2 ft.) to .91 m (3 ft.) square sections and loaded dump trucks for transport to the crushing site. A hydraulically operated shear cut the slabs free that were tied together by the reinforcing steel. Reinforcing steel consisted of four (4) longitudinal bars 228 mm (9 in.) on each side of the pavement centerline and along both edges. Transverse 15.9 mm (5/8 in.) bars 3.35 m (11 ft.) long at .91 m (3 ft.) centers placed alternately on either side of centerline were also present as were dowel bars at joints.

The old pavement was placed directly on the subgrade soil and only a very small amount of the subgrade soil stuck to the slabs in dry weather conditions. During wet weather the subgrade tended to adhere to the old pavement. The contractor limited his removal operations to dry weather conditions. By taking care, the back hoe operator was able to leave most of the fine material on the grade.

The contractor made no attempt to recover any of the broken concrete smaller than approximately 152 mm (6 in.) to 203 mm (8 in.) from the grade. By doing so, he was able to effectively eliminate the majority of fines at the crusher that could have otherwise been a problem. The contractor estimated that approximately 12 percent of the old pavement was left on the grade.

At the crushing site, the contractor charged a Pioneer 3042, 1066 mm (42 in.) jaw crusher with an end loader. This primary crushing operation reduced the material to a 152 mm (6 in.) maximum size.

The conveyor below the jaw crusher was positioned several feet below the jaws to prevent damage to the belt by pieces of the reinforcing steel. Two laborers, positioned on either side of the belt conveyor, removed the reinforcing steel from the stream of crushed material. Approximately 53 tons of steel were recovered at the crushing site, most of it during the primary crushing operation.

The minus 152 mm (6 in.) material was stockpiled, and after a considerable quantity was on hand, a Hewitt-Robins Apache Twin portable crushing and screening plant was brought to the crushing site. This plant, fed with a front-end loader, further crushed the product to 100 percent passing the 38.1 mm (1½ in.) screen. This plant had the prescreening capability to reject the minus No. 8 material, as required by the specification, but was not used.

The combined portland cement and asphalt concrete aggregate was produced by crushing the portland cement concrete and asphalt pavement together in approximately the same proportions the two materials existed in the old pavement. The blend was controlled by the feed to the secondary crusher from separate stockpiles.

Small pieces of reinforcing steel were removed, again by hand, from the feed point to the secondary crusher as well as from the resulting stockpile.

Iowa Route 2

Two contracts were let for this work. The first was for "grading" which included the "removal and crushing of old pavement." Following is a portion of the specifications for this project:

"183.01 REMOVAL. All mainline pavement on the project is to be removed and salvaged as described below, unless specifically excluded by the plans.

Where asphaltic concrete resurfacing is present, the asphaltic concrete shall be removed before the portland cement concrete pavement is removed. The asphaltic concrete that is removed is to be buried in the fill. It is intended that all of the asphaltic concrete be removed. Isolated areas of adhering asphaltic concrete up to one inch in thickness will be considered acceptable, including patches of asphaltic concrete.

The portland cement concrete pavement shall be removed in a manner that does not develop a large amount of fines in the salvaged concrete and which excludes subgrade and subbase material to the maximum extent practicable. It is intended that this operation will produce a maximum amount of salvaged portland cement concrete that is crushed and stockpiled, suitable for use in new portland cement concrete; the operation is to be conducted in such a manner as to salvage, in the stockpile, at least 80 percent of the portland cement concrete to be removed. The method of breaking and

removing shall be subject to approval of the engineer.

All reinforcing steel shall be removed from the salvaged pavement, either prior to or during the crushing operation.

183.02 CRUSHING AND STOCKPILING. The salvaged pavement shall be crushed and stockpiled at the site designated on the plans for stockpiling. Salvaged portland cement concrete shall be crushed to pass a 38.1 mm (1½ in.) sieve. A hammermill secondary crusher is prohibited. The crushed material shall be separated by screening on a 9.5 mm (3/8 in.) screen, and the two products shall be stockpiled separately. Processing equipment shall include a screen by which excessive fines in the minus 9.5 mm (3/8 in.) product can be controlled by removal of fines passing a No. 8 screen. Control will be as directed by the engineer, so that the maximum passing the No. 200 sieve in the minus 9.5 mm (3/8 in.) material is 5 percent. Washing will not be required. Fines removed from the minus 9.5 mm (3/8 in.) material shall be stockpiled separately.

The two main products of the operation, 38.1 mm (1½ in.) to 9.5 mm (3/8 in.) and minus 9.5 mm (3/8 in.) shall be stockpiled in accordance with 2301.16, in locations designated by the engineer at the designated site.

Reinforcement removed from the pavement shall become property of the contractor and shall be disposed of off the project."

Removal of the Asphalt Overlay. The first phase in the recycling project was the removal of the 50.8 mm (2 in.) to 76.1 (3 in.) of asphalt resurfacing. In planning for the project, the general consensus was that the asphalt removal would be relatively easy. Unfortunately, this was not true and it required substantial effort and a number of operations to remove the asphalt.

Shattering of the asphalt resurfacing was the first operation in the removal. This was accomplished with a special pavement breaker designed and manufactured by Reilly Construction. The pavement breaker was fabricated using a new diesel pile driving hammer mounted on the running gear of a motor grader and towed with an end loader.

The diesel hammer was adjusted to produce the right amount of energy when coordinated with the forward speed 1.61 km (1 mph) to 4.8 km (3 mph) to fracture the overlay with minimal damage to the underlying slab.

After the fracturing, a #16 motor patrol equipped with three ripper teeth tore the asphalt from the pcc slab. There were times when the asphalt adhered very tightly and the patrol could not pull three teeth. In some cases, the patrol could pull only two teeth, and in some cases, only one tooth.

A rubber tired front end loader was used to remove the loosened material and scrape free any adhering material. The final operation was brooming to remove the fine material.

Breaking, Removal and Crushing of the Pavement.

There is no standard method of breaking and removal. The procedure selected is dependent on the contractor's plans for steel removal and crushing. In the first Iowa DOT recycling project (Lyon County) the contractor used a pneumatic hammer mounted on the rear of a back hoe to punch holes in the old slab on .92 m (3 ft.) centers.

The concrete rubble was transported in larger chunks and most of the steel was removed at the crushing plant. On the second recycling project, a commercial pavement breaker was used.

This recycling project was much larger and, therefore, allowed the contractor more options and the consideration of more specialized equipment. The old slab of this project contained more steel than the first two Iowa projects. With this in mind, the contractor intended to extensively shatter the concrete, but because the concrete rubble was to be picked up, care was required not to punch the concrete into the grade. The special diesel pile driver breaker was designed to accomplish these tasks. For breaking of the old pcc slab, a large front end loader towed the special breaker at about 1.609 km/hr (1 mph) operating at 80 to 90 blows per minute. The breaking operation required 12 passes (6 per lane) to provide the desired shattering on the curbed sections. Another precaution, to avoid including subgrade material, was to blade away the shoulders and expose the edges of the slab.

A rubber tired hydraulic excavator equipped with a ripper tooth which was referred to as a "Rhino horn" was used to dislodge and remove part of the reinforcing steel. To avoid punching the concrete rubble into the base, the equipment was operated from the excavated shoulder area. The operator would reach across the slab and rip back to the center of the slab.

The steel was hooked and elevated to expose it for removal. This operation was conducted from each shoulder so the rubble was moved toward the center of the old slab. A cutting torch was used to cut the exposed steel free of the concrete rubble. A shear was used to cut the steel into .61 m (2 ft.) lengths to increase its value as scrap. The contractor salvaged 200 tons of scrap from the 25.7 m (16 mi.) of recycling.

The concrete rubble was then loaded with a track mounted front end loader for transport to the crushing site.

Loading of rubble was very important as special provision required recovery of at least 80% of the old concrete slab. It was necessary to avoid incorporating earth subgrade into the rubble that would cause problems in producing a crushed product with not more than 5% passing the 75 μ m (No. 200) sieve. The concrete was stockpiled for crushing at two sites that had been leased by the Iowa DOT. Crushing the concrete rubble presented some problems not encountered in quarrying operations. First, a scalper referred to as a "grizzly" was used ahead of the primary jaw (Universal 20-76) crusher to remove mud balls and other fines.

This was effective in alleviating the problem of meeting the No. 200 sieve specification.

There was still some reinforcing in the rubble. Sufficient clearance of the conveyor belt at the primary crusher was required to allow the metal pieces to leave the jaw. It was then necessary to remove this steel to avoid damage to the secondary crusher. This was accomplished by a large electromagnet. A laborer manually removed the steel from the magnet. The contractor indicated that on future recycling, he would use a self-cleaning magnet.

Primary crushing reduced the concrete to approximately 76.2 mm (3 in.) size material. The crushed product was further processed in the secondary crusher with a Universal 10-36 jaw and separated into 38.1 mm (1½ in.) to 9.5 mm (3/8 in.) and minus 9.5 mm (3/8 in.) size material. At the start, the fines were removed from the minus 9.5 mm (3/8 in.) material at the secondary crusher,

but after the "grizzly" was opened for scalping, this was no longer necessary. The crushed products were stockpiled by a conveyor belt with radial movement capability.

The typical gradations for the coarse and fine aggregates were shown earlier in this report. The crushing operations produced approximately 65% coarse and 35% fine fractions. Approximately 90% of the concrete was salvaged from the roadway.

Environmental and Conservation Benefits

Recycling provides a direct benefit in conservation of raw material and energy. On these Page-Taylor projects, 28,124 tons of coarse and 12,661 tons of fine crushed concrete aggregate were used. This eliminated the need of disposing of 40,785 tons or 20,602 cubic yards (Sp. Gr. = 2.65). Approximately 200 tons of steel were salvaged for recycling.

If the gasoline and diesel fuel used in reclaiming the old slab are considered similar to that used for removing the overburden and obtaining virgin aggregate, there is a substantial fuel savings in eliminating the aggregate transportation from the quarry to the project with a haul distance estimated at 121 km (75 mi.). It is further estimated that this prevented \$27,000 damage to haul roads in the vicinity of the project.

Removal and Crushing - U. S. Route 59, MN

The first operation on this project was the removal of limited areas which had an asphalt overlay. This was followed by removal of joint seal material and asphalt patches in the joints. The joint seal material was removed by a 975 Bobcat loader equipped with a cutting tooth.

The breaking of the pavement was accomplished by a 440 Link Belt diesel hammer mounted on a frame fabricated at the contractor's shop. This was similar to the breaker used on the Iowa Route 2 project. The breaker was operated at about 90 blows/minute. The operator controls the fuel flow to adjust to the conditions of the concrete. The more sound the concrete, the more fuel is used to break the concrete. The head of the breaker is 35.6 cm (14 in.) x 45.7 (18 in.). Four passes in a 11 m (12 ft.) lane produced optimum size material. This pavement did not contain any steel except centerline tie bars. The maximum size pieces were about 1.82 m (2 ft.).

The concrete was picked up with a 235 American back hoe equipped with a special oversize bucket to aid in rapid filling of the bucket. A 450 John Deere dozer equipped with long teeth pushed the concrete to the back hoe for pickup and the concrete pavement was removed at the rate of 1372 m (1500 ft.) to 2286 m (2500 ft.) per day. A 91.4 cm (36 in.) x 121.9 cm (48 in.) primary crusher was used with 137.1 cm (54 in.) cone crusher.

Recycled PCC for Econocrete (Lean Base) Hwys.

California has been recycling portland cement concrete pavements for a number of years. They were the first to use recycled concrete aggregates in the lean concrete (econocrete) base for new concrete pavement. The contractor used a mixture of recycled concrete and asphalt. Recycled concrete has also been used for cement treated subbase and as aggregates in bituminous pavements.

Cost ComparisonAverage Cost of Recycled Material

33,904 sq.yds. Removal and Crushing @ \$3.70	=	\$ 125,444.80
127,845 sq.yds. Removal and Crushing @ \$3.30	=	421,888.50
Minus normal removal cost		
1,61,749 sq. yds. @ \$1.00	-	- 161,749.00
Plus added cost for Class to material		
54,000 tons @ \$0.30	=	+ 16,300.00
TOTAL COST		\$ 401,784.30

Material Cost Using Recycled Concrete

Crushed coarse aggregate 0.542 tons @ \$7.44/ton	=	\$ 4.03
Crushed fine aggregate 0.319 ton @ 7.44/ton	=	2.37
pc sand 0.467 ton @ 5.60/ton	=	2.62
Cement 0.313 ton @ 48.00/ton	=	15.02
		\$ 24.04

8 " paving = \$5.34/sq/ yd.

Material Cost Using Locally Available Material for A-6 Mix

Coarse aggregate (Class 2) 0.582 tons @ \$10.50	=	\$ 6.11
pc sand 0.873 tons @ 5.60	=	4.89
Cement 610 lbs. @ 48.00	=	14.64
		\$ 25.64

8" paving = \$5.70/sq.yd.

Savings

243,356 sq. yd 8" paving @ \$0.36	=	\$ 87,608.16
2,765 sq.yd. 6" paving @ 0.27	=	746.55
Haul Road Savings		27,000.00
		\$115,354.71

1 sq. yd = .84 sq. meters

1 ton = 907 kilograms

Cost Savings of Recycling Concrete on U.S. 59, Minnesota

<u>Item</u>	<u>Quantity</u>	<u>Recycle Cost</u>	<u>Conventional Cost</u>
Remove Conc. Pavement	229,170 sq. yd.		\$ 401,047
Salvage Conc. Pavement, Crush and Stockpile	229,170 sq. yd.	\$ 595,842	
Stabilizing Aggregate	10,596 ton		26,490 (1)
Class 3 Shoulder	32,112 ton (2)		80,280 (1)
Structural Concrete	46,544 cu. yd.	1,140,328	1,791,944
Structural Concrete (High Early)	3,333 cu. yd.	99,990	146,652
		\$1,836,160	\$2,446,413
		-	1,836,160
	Savings	=	\$ 610,253

1 sq. yd. = .84 sq. meters

1 ton = 907 kilograms

(1) Differential cost between Recycled Material and Aggregate from Gravel Pit

(2) Portion of Class for which #4 - Recycle Material is available

Recycling of Urban Freeways

Paris, France

In the summer of 1976, and again in the summer of 1977, the two roadways of a freeway north of Paris, France, received extensive rehabilitation. The work involved complex traffic handling problems, removal of the existing outer two concrete lanes of the three-lane roadbeds, removal of the cement treated base, and stabilization of the underlying foundation soils. Reconstruction involved recycling of the old concrete pavement for use in the new lean concrete base layer and in the porous concrete shoulder. This entire 8.53 km (5.3 mi.) of reconstruction of the southbound lane was completed in seven weeks. This pavement carries the heaviest traffic in France - 150,000 vehicles per day with more than 20% trucks.

The pavement was broken up with two Wirtgen machines imported from Germany. This machine drops a 7 ton weight from a height of 2.14 m (7 ft.) hitting the slab every 406 mm (16 in.). Average production was 10,032 s.m. (12,000 s.y.) per day. The recycled concrete aggregate was mixed with 159.6 kg/m³ (269 lbs.) of cement and 70 kg/m³ (118 lbs.) of fly ash per cubic yard to make the lean concrete subbase. The subbase and pavement were placed with a slipform paver.

The northbound lane was similarly reconstructed in the summer of 1977. The experience from the 1976 project permitted modifications which accelerated the operations in 1977. In 1977, the shoulders were constructed of porous concrete composed of recycled concrete aggregate with nothing below a 5 mm size and 150 Kg/m³ (253 lbs.) of cement per cubic yard. These porous shoulders were placed with a small Gunttert-Zimmerman paver equipped with a vibratory compactor.

Edens Expressway - Chicago

In the north suburbs of Chicago, the Illinois Department of Transportation reconstructed the first major urban freeway in the United States.

The Edens Expressway was designed in the 1940's for an estimated 80,000 vehicles per day and was opened to traffic in 1951. In 1966, the 254 mm (10 in.) reinforced concrete was resurfaced with 76 mm (3 in.) of asphalt. Edens Expressway, which is a 6-lane divided expressway, is carrying 130,000 vehicles per day, of which 10% are trucks.

The expressway which was designed in the 1940's has no shoulders, 4.27 m (14 ft.) overhead clearance under overpasses, inadequate length of acceleration and deceleration lanes, and was subjected to frequent flooding in low spots under overpasses. The pavement with the asphalt overlay was in considerable distress. The original distress in the mesh reinforced concrete pavement developed due to the 30.5 m (100 ft.) contraction joint spacing. Serious infiltration at the joints had resulted in blowups and large joint spalls due to compression failures. The asphalt overlay had come off the pavement, resulting in severe potholes and bad cracking.

A decision was made that the contract for this work would involve removal and replacement of all existing pavement, removal and replacement of the existing crushed stone subbase, and removal and replacement of the subgrade in many locations. The contract called for widening and redecking six mainline bridges, lowering the grades under underpasses for a minimum of 4.42 m (14 ft. 6 in.) clearance, full width emergency shoulders, improving and modifying the drainage, correction of super elevations, new and improved lighting systems, full width shoulders on both bridges and pavement, and a permanent concrete safety shaped barrier in the median.

In 1979, the contract called for the installation of a temporary concrete safety shape barrier

in the middle of the southbound lanes so that two lanes could proceed in each direction, removal and replacement of the pavement on the northbound lanes, and repaving of the northbound lanes with 254 mm (10 in.) of continuously reinforced concrete pavement.

In 1978, an earlier contract was awarded to add a temporary asphalt lane on the west side of the southbound lanes to provide for four lanes of traffic separated by a precast median barrier. The precast barrier was placed in the center of the southbound roadway using the 3 lanes of the original pavement plus the temporary asphalt lane to handle both northbound and southbound traffic.

This is also the first major recycling project where a dowel-mesh pavement has been recycled.

Three hundred fifty thousand tons of the original pavement were crushed and recycled on site, producing two useful products. Approximately 85% has been graded for use as porous granular embankment, specified for backfilling undercuts and the remainder will be classified into Illinois CA-6 which is specified as a 76 mm (3 in.) lift under the new stabilized subbase.

The 254 mm (10 in.) mesh reinforced pavement was pulverized by two large mobile deisel hammers which had been fabricated by the contractor for this project. This equipment fractures the old slab into pieces about .61 m (24 in.) maximum size at a rate of between 457 m (1500 ft.) and 610 m (2000 ft.) of 11 m (36 ft.) wide pavement during a twelve-hour work shift. All crushing was accomplished in the cloverleaf area of a major intersection. Because of the limited space, a careful balance between the incoming and outgoing material was required.

The shattered concrete is then dozed into piles before loading into semi-trailer trucks and transporting to the crushing site established at mid-project. A portion of the steel mesh was broken by the deisel hammers but the major portion of the mesh was broken by the dozers pushing the broken concrete into piles on the existing broken pavement. The steel mesh is being removed with electromagnets operating above the conveyor belts along with hand picking of the mesh and other steel items.

This project is an excellent example of reuse of pavement materials into a new pavement structure. A considerable savings in energy and costs resulted from the recycling of the old pcc pavement on this project.

Recycling eliminated the cost of disposal of 350,000 tons of pavement rubble and provided material for the porous granular backfill and a granular base material. This project also illustrates the feasibility of complete reconstruction of a heavily travelled urban expressway.

Airport Pavement Recycling

Early in 1977, concrete recycling was used in construction of a new keel strip in a runway at the Jacksonville, Florida, International Airport. Rather than overlay the entire runway, it was decided to recycle the existing concrete in the two center 7.6 m (25 ft.) wide lanes. The 279 m (11 in.) concrete was broken up by drop hammers, removed and hauled to a crushing plant on the airport site. The concrete was crushed to 50 mm (2 in.) top size and separated on the 9.5 mm (3/8 in.) screen and stockpiled for use in a filter coarse and econocrete base.

After removal of the concrete, the old subbase and the subgrade were removed to a depth of 356 mm

(14 in.) below the old grade. Then a 152 mm (6 in.) filter course (9.5 mm (3/8 in.) plus material) of the recycled coarse aggregate was placed and compacted. On the filter course, a 152 mm (6 in.) layer of econocrete base was placed by a slipform paver. The lean concrete used the two sizes of recycled concrete as aggregate with 148.3 Kg/m³ (250 lb./yd.³) of cement, water, and an admixture for greater workability. The lean concrete, which had a 28 day compressive strength of 6.9 MPa (1000 psi) was mixed in a 6.9 m³ (9 yd.³) central mixer and hauled by dump truck. Since the coarse aggregate for the new concrete had been hauled from Miami, a distance of 564 km (350 mi.), the economic gain from recycling the old pavement is obvious.

Commercial Recycling

Commercial concrete recycling operations are successful in many areas of the country. Among the commercial operations are Chicago; Detroit; New York; Washington, D. C.; Los Angeles; New Orleans; Savannah, Georgia; and Pontiac, Michigan.

In Chicago, one material company runs a regular concrete recycling operation. At two sites, wrecking contractors dump old concrete at a fee of \$16 for a large trailer load. A portable crusher is then moved from site to site when a large enough stockpile is accumulated. The crushed material meeting Illinois CA-6 (grade 8) coarse aggregate gradation is sold for base course aggregate and railroad ballast.

Conclusion

In a growing number of areas in the United States, it is becoming increasingly advantageous to recycle old concrete. The conservation of materials, the problem of solid waste disposal, the reduction in construction costs and conservation of energy all enter in an increased interest in recycling of old pcc pavement and concrete rubble.

The projects constructed to date have included the use of recycled concrete aggregates for an econocrete (lean concrete) base (highways and airports), shoulder concrete, mainline pavement concrete, porous granular fill, granular base course and porous concrete shoulders. Much has been learned about mixture design using these aggregates to obtain workable mixtures.

Contractors, equipment manufacturers and commercial aggregate producers will continue to develop and improve the techniques for breaking, crushing, removal of embedded items and handling of recycled concrete aggregates. These improvements will make recycling more and more attractive as a construction option.

References

1. Buck, A. D., "Recycled Concrete" Miscellaneous paper C-72-14, U. S. Army Engineer Waterways Experiment Station, C. E., Vicksburg, Mississippi.
2. Buck, A. D., "Recycled Concrete" Miscellaneous paper C-72-14, report 2, additional investigation, Su. S. Army Engineer Waterways Experiment Station, C. E., Vicksburg, Mississippi.
3. U. S. Army Engineer Waterways Experiment Station, C. E., "Handbook of Concrete & Cement," August, 1949, with quarterly supplements,

Vicksburg, Mississippi.

4. Bergren, Terry V., Ralph A. Britson, Iowa Department of Transportation, Division of Highways, "Portland Cement Concrete Utilizing Recycled Pavement," January, 1977.