Report NO. FAA-RD-81-5

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AD A101482

RECYCLING OF PORTLAND CEMENT CONCRETE AIRPORT PAVEMENTS
A State-of-the-Art Study

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APRIL 1981
FINAL REPORT

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-81-5	AD-A101482	

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
RECYCLING OF PORTLAND CEMENT CONCRETE AIRPORT PAVEMENTS — A State-of-the-Art Study	April 1981

7. Author(s)	8. Performing Organization Report No.
M. C. Hironaka, R. B. Brownie, and G. Y. Wu	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS) / 11. Contract or Grant No.
Civil Engineering Laboratory Naval Construction Battalion Center Port Hueneme, CA 93043	DOT-FA77WAI-704

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation, Federal Aviation Administration, Washington, D.C. and Naval Facilities Engineering Command, Alexandria, VA	Final Report Oct 1979 — Sep 1980
	14. Sponsoring Agency Code ARD - 500

15. Supplementary Notes

16. Abstract

An investigation was performed to assess the state-of-the-art of recycling Portland cement concrete (PCC) airport pavements. Previous laboratory studies have shown that recycling of PCC pavements is technically and economically feasible. This has been demonstrated in airport reconstruction projects at Jacksonville International Airport (Florida), Love Field (Texas), and Coffeyville Municipal Airport (Kansas), where PCC was recycled into econocrete base and aggregate subbase, cement stabilized base, and part of the aggregate base course, respectively. Recycling of PCC for surface courses in airport pavement construction has not yet been performed, but this should also prove to be beneficial as has been experienced by the Iowa DOT and other state highway agencies who have recycled PCC for surface courses. Equipment for recycling PCC pavements is currently available in the construction industry; however, these, along with the technology of PCC recycling, could be improved substantially. Recommendations for specific improvements are therefore made.

17. Key Words	18. Distribution Statement
Airport pavements Portland cement concrete pavements Pavement recycling Pavement reclamation Solid waste recycling	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

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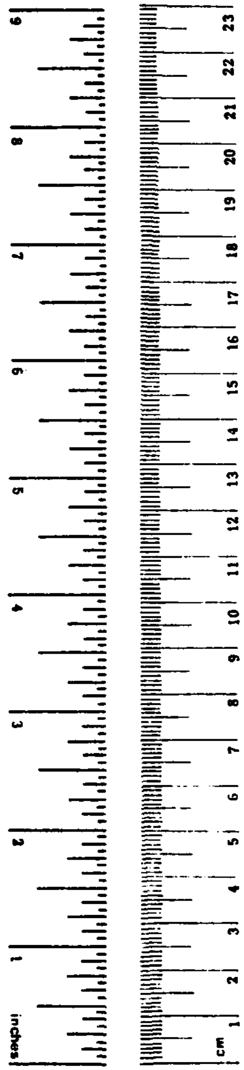
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

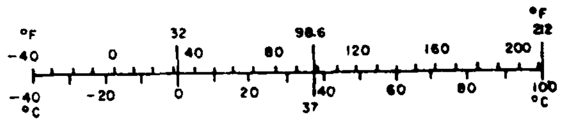
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

INTRODUCTION

Objective

The objective of this study is to assess the state-of-the-art of recycling Portland cement concrete (PCC) pavements for use as a base course or as aggregate in new PCC or asphalt concrete (AC) airfield/airport pavements. This investigative effort is to include a literature search as well as an assessment of field experience with recycling of PCC pavements.

Background

For various reasons, PCC runways and other airport pavements sometimes require reconstruction. Reasons for reconstruction include: (1) the anticipation of larger, heavier aircraft; (2) a greater volume of traffic; or (3) deterioration of the pavement. Regardless of the reason, recycling of the aged PCC pavement could possibly be an economically viable reconstruction alternative. Recycling may be especially attractive in projects where the subgrade requires reworking or where overlays cannot be used because of certain controlling restrictions (e.g., grades and elevation must be maintained).

Recycling of PCC pavements affords certain advantages and benefits; it promotes conservation of funds, energy, and natural resources, while it minimizes problems of solid waste disposal and aggregate acquisition. Because of these advantages, the Civil Engineering Laboratory (CEL) was tasked jointly by the Federal Aviation Administration (FAA) and the Naval Facilities Engineering Command to investigate the state-of-the-art of recycling PCC airport pavements.

Recycling of PCC pavements is not a new technology. Research on recycling of PCC pavements was performed in Europe and Russia shortly after World War II (Ref 1). More recently, laboratory studies were performed at the Waterways Experiment Station (Ref 2,3,4), Massachusetts

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1. G. K. Ray. Concrete Recycling: An Historical Overview, Rural and Urban Roads, Mar 1980, pp 70-71.

2. Waterways Experiment Station. Miscellaneous Paper C-72-14: Recycled Concrete, by A. D. Buck. Vicksburg, Miss., May 1972.

3. ________. Miscellaneous Paper C-72-14 (Report 2): Recycled Concrete - Additional Investigations, by A. D. Buck. Vicksburg, Miss., Apr 1976.

4. ________. Miscellaneous Paper C-76-2: Recycled Concrete as a Source of Aggregate, by A. D. Buck. Vicksburg, Miss., Apr 1976.

Institute of Technology (Ref 5), and Mineral Sciences Laboratories (Ref 6) in Canada. All of these previous efforts have shown that recycling of PCC material is both technically and economically feasible.

Recycled PCC has been used in actual reconstruction projects successfully. Examples of such projects include:

Location	Recycled as:	Ref
U.S. Route 66 (Ill.)	Base course	1
Highway (Calif.)	Lean concrete (econocrete) base	1
U.S. Route 75 (Iowa)	Surface course	1
Love Field (Dallas, Tex.)	Cement-treated subbase	1
Eden Expressway (Ill.)	Improved subgrade	7
Jacksonville International Airport (Fla.)	Lean concrete base	8
Interstate 84 (Conn.)	Surface course	9

In a study on the availability of aggregates in the United States, it was found that in about one-third of the states, aggregates are potentially in short supply (Ref 10). This is based on an analysis of the 97 physiographic sections (shown in Figure 1) comprising the 48 states. However, the actual or true availability may be more limited than reported. For example, in the western areas, good potential aggregate sources exist, but in many cases the sources are practically inaccessible because of the extremely rugged mountainous terrain. Also, by

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5. Massachusetts Institute of Technology. Use of Concrete Demolition Waste as Aggregates in Areas That Have Suffered Destruction, a Feasibility Study, by S. A. Frondistou-Yannas and H. T. S. Ng. Boston, Mass., Nov 1977.

6. Mineral Sciences Laboratories, Canada Center for Mineral and Energy Technology. CANMET Report 76-18: Use of Recycled Concrete as a New Aggregate, by V. M. Malhotra. Ottawa, Canada, May 1976.

7. G. K. Ray. Concrete Recycling: An Historical Overview (Part 2), Rural and Urban Roads, Apr 1980, pp 28-29.

8. Jensen of Jacksonville, Inc. Rehabilitation of Runway 13-31 (Jacksonville International Airport), a Concrete Recycling Project, by J. G. Dresser, Jr. Jacksonville, Fla., Jan 1978.

9. Anonymous. State Pours Recycled Pavement, Engineering News Record, 5 Jun 1980, p. 29.

10. M. W. Witczak, C. W. Lovell, Jr., and E. J. Yoder. A Generalized Investigation of the Potential Availability of Aggregate by Regional Geomorphic Units Within the Conterminous 48 States, Highway Research Record No. 353, 1971, pp 31-42.

virtue of their distant location from the areas of population where the aggregate is needed, some sources are economically unusable. As a further example, in the East, good aggregate sources may not be further exploited because they are in the midst of developed urban areas. Since airports are generally located near or in urban areas where good aggregate sources are becoming scarce or are not available, aggregate haul costs for new PCC pavement mixes are becoming economically unacceptable. Recycling of aged PCC pavements can possibly be an economical alternative.

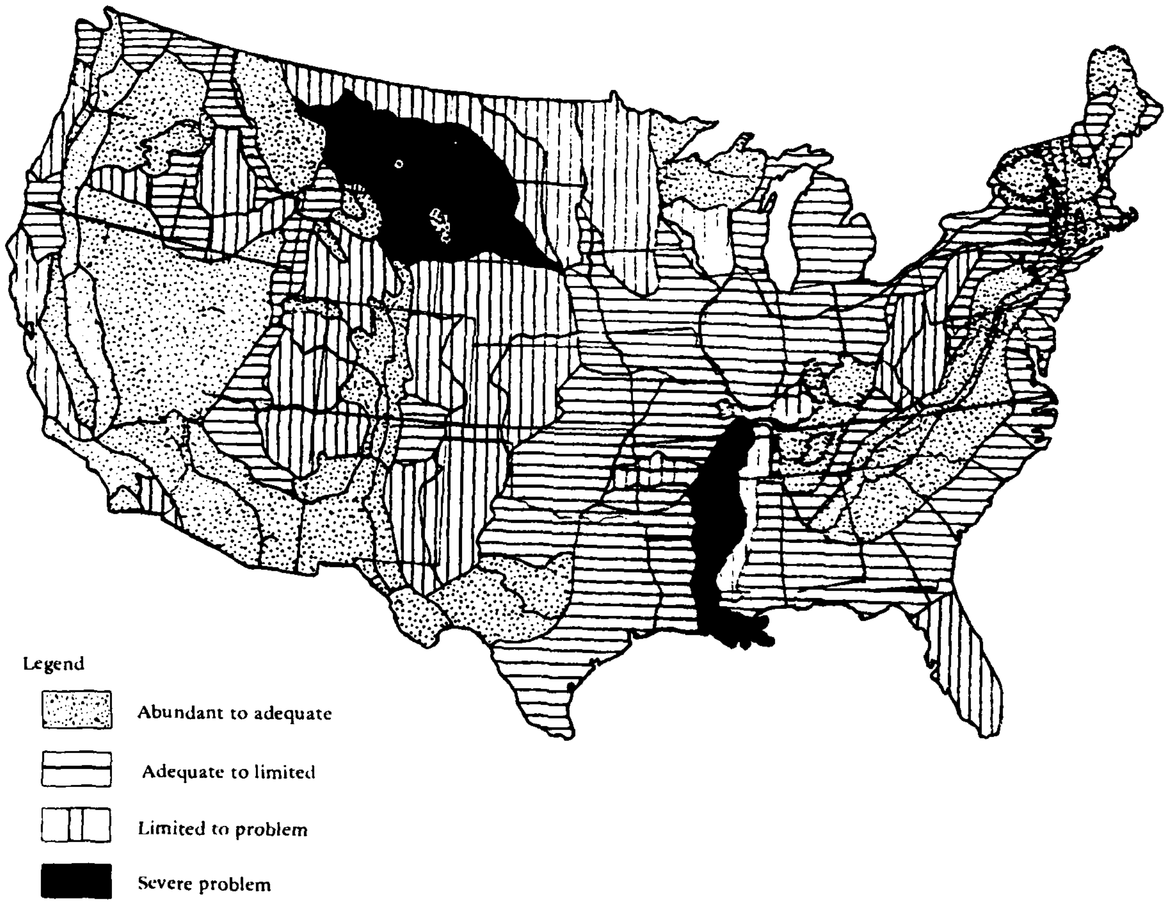

Figure 1. Estimated potential availability rating of quality aggregate resources by physiographic unit (from Ref 10).

Primary questions dealt with in this report regarding the use of recycled PCC material are:

1. How does the quality of pavements constructed with recycled PCC compare with pavements constructed with virgin material?
2. Where has recycled PCC been used and how is it performing?
3. What types of equipment and procedures were used in those construction projects?

QUALITY OF RECYCLED PCC

In previous studies, the properties of mixes prepared with recycled PCC material as well as the mechanical properties of the cured concrete have been investigated. Laboratory studies have been made with PCC material processed from concrete test cylinders (Ref 6), laboratory test beams and panels and a concrete driveway slab (Ref 3), and a laboratory test slab (Ref 11). Additionally, the recycling of actual highway PCC pavements into new PCC pavements has been accomplished (Ref 12,13).

Mineral Sciences Laboratories Study

In the study by the Mineral Sciences Laboratories (Ref 6), the PCC recycled material was obtained by processing used, previously tested 6 x 12-inch concrete test cylinders through jaw crushers. Three different strength level (low, medium, and high) test cylinders were processed and retained separately. (The cylinders were originally made with crushed limestone as coarse aggregate and natural sand as fine aggregate.) All of the materials used in the study as well as the mix proportions and properties are shown in Table 1.

Six 6 x 12-inch (152 x 305-mm) cylinders and six 3.5 x 4 x 16-inch (89 x 102 x 406-mm) prisms were cast from each mix. After casting, all the specimens were covered with water-saturated burlap and left in the casting room for 24 hours at 75±3°F (25±1.7°C) and 50% relative humidity. The specimens were then removed from their molds and transferred to the moist-curing room until they were tested.

Various tests were performed on the molded cylinder and prism specimens. Two cylinders from each mix were tested in compression at 7, 28, and 91 days. Two prisms from each mix were subjected to third-point loading flexure tests at 14 days. The remaining four prisms from each

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11. S. Frondistou-Yannas. Waste Concrete as Aggregate for New Concrete, American Concrete Institute Journal, vol 74, no. 37, Aug 1977, pp 373-376.

12. Iowa Department of Transportation. Portland Cement Concrete Utilizing Recycled Pavement, by J. V. Bergren and R. A. Britson. Jan 1977.

13. ________. Recycled Portland Cement Concrete Pavement in Iowa, by V. J. Marks. Nov 1979.

mix were used in freeze-thaw durability tests (ASTM Standard C666-75); two prisms were subjected to a freeze-thaw environment, while the other two prisms (controls) were retained in the moist-curing room. The results of these tests on the cylinders and the prisms are shown in Tables 2 and 3, respectively. The compressive strength data from tests on the cylinders are also shown in Figures 2 and 3.

Based on the test results as shown in Tables 2 and 3 and other investigations, the following findings evolved from the study (Ref 6).

1. Specimens prepared with recycled concrete as <u>coarse</u> aggregate had somewhat lower compressive and flexural strengths than those specimens prepared with crushed limestone as the coarse aggregate. The difference in strengths decreases with decreasing water-cement ratio. This can be seen in Figure 2.

2. Specimens prepared with recycled concrete as <u>fine</u> aggregate also had lower compressive and flexural strengths than those specimens prepared with Ottawa sand as the fine aggregate. In this case, the difference in strengths increases with decreasing water-cement ratio. This can be seen in Figure 3.

3. In general, based on measurements of flexural strength and pulse velocity of the test prisms, the durability of concrete specimens made with recycled material was comparable to those made with nonrecycled material with one exception. There is some indication that durability of concrete made with crushed limestone as coarse aggregate and recycled concrete as fine aggregate may be inferior to concrete made with recycled concrete as coarse aggregate and natural sand as fine aggregate.

4. Scanning electron microscope (SEM) photomicrographs and x-ray fluorescence analyses confirmed the presence of a coating of cement paste on the aggregate particles of the recycled material. It was also found in these analyses that cracks of 2 to 4 microns in width were present in the cement paste. The presence of these cracks may explain the high absorption and low specific gravity of aggregates prepared from recycled concrete.

5. In the photomicrographs, it appears that crushed coarse and fine recycled concrete aggregate had rounder particle shapes and smoother surface textures than the crushed limestone or Ottawa sand aggregate used.

6. In appearance, the concrete mixes prepared with recycled material were identical to those prepared with the nonrecycled aggregates. No unusual harshness or lack of workability was noticed.

7. Air-entraining agent requirements were identical for specimens prepared with coarse aggregate of recycled concrete or crushed limestone. However, in specimens where recycled concrete was used as fine aggregate, the required quantity of air-entraining agent was more than twice that of specimens using natural sand as fine aggregate.

<u>Waterways Experiment Station Study</u>

In the investigations by the Waterways Experiment Station (Ref 2,3), PCC recycled samples were obtained from the following sources:

Table 1. Proportions and Properties of Fresh Concrete Test Mixes (after Ref 6)

Mix Series	Mix No.	Mix Composition[a]		Mix Proportions		Properties of Fresh Concrete						
		Coarse Aggregate (Minus 1 in. - Plus No. 4)	Fine Aggregate (Minus No. 4 - Plus No. 100)	Water-Cement Ratio (by weight)	Aggregate-Cement Ratio (by weight)	Temp		Slump		Unit Weight		Air Content (%)
						°F	°C	in.	mm	lb/ft³	kg/m³	
A	1[b]	crushed limestone	Ottawa sand	0.69	7.77	76	24.4	2.0	50	138.0	2,210	6.2
Low	2	recycled concrete	Ottawa sand	0.69	7.92	76	24.4	2.5	60	132.0	2,115	6.9
Strength	3[b]	crushed limestone	Ottawa sand	0.67	7.80	77	25.0	1.75	40	142.0	2,275	5.3
	4	crushed limestone	recycled concrete	0.67	8.10	77	25.0	2.0	50	140.0	2,240	3.5
B	5[b]	crushed limestone	Ottawa sand	0.56	6.50	71	21.7	2.5	60	140.0	2,240	6.1
Medium	6	recycled concrete	Ottawa sand	0.56	6.63	72	22.2	2.5	60	134.8	2,160	6.3
Strength	7[b]	crushed limestone	Ottawa sand	0.57	6.51	74	23.3	2.5	60	141.6	2,270	5.9
	8	crushed limestone	recycled concrete	0.57	6.76	76	24.4	2.5	60	135.2	2,165	6.0
C	9[b]	crushed limestone	Ottawa sand	0.41	4.45	72	22.2	2.75	70	148.0	2,371	4.2
High	10	recycled concrete	Ottawa sand	0.41	4.54	71	21.7	3.0	75	140.4	2,250	4.5
Strength	11[b]	crushed limestone	Ottawa sand	0.41	4.45	76	24.4	2.0	50	148.0	2,370	4.9
	12	crushed limestone	recycled concrete	0.41	4.57	72	24.4	2.5	63.5	138.8	2,223	4.8

[a]ASTM Type I Portland cement and an air-entraining agent were used in all mixes.

[b]Control mixes.

Table 2. Compressive Strengths of 6 x 12-Inch Test Cylinders at Various Ages (after Ref 6)

Mix Series	Mix No.	Mix Composition: Coarse Aggregate (Minus 1 in. - Plus No. 4)	Mix Composition: Fine Aggregate (Minus No. 4 - Plus No. 100)	Water-Cement Ratio (by weight)	Compressive Strength: 7 Days psi	7 Days MPa	28 Days psi	28 Days MPa	91 Days psi	91 Days MPa
A	1[a]	crushed limestone	Ottawa sand	0.69	2,035	14.0	2,555	17.6	2,600	17.9
	2	recycled concrete	Ottawa sand	0.69	1,310	9.0	1,986	13.6	2,030	13.9
	3[a]	crushed limestone	Ottawa sand	0.67	2,360	16.2	2,840	19.5	3,265	22.4
	4	crushed limestone	recycled concrete	0.67	1,855	12.7	2,380	16.3	2,605	17.9
B	5[a]	crushed limestone	Ottawa sand	0.56	2,585	17.6	3,190	21.9	3,340	22.9
	6	recycled concrete	Ottawa sand	0.56	2,330	16.0	2,905	20.0	3,015	20.7
	7[a]	crushed limestone	Ottawa sand	0.57	--	--	2,950	20.3	3,255	22.4
	8	crushed limestone	recycled concrete	0.57	--	--	2,470	17.0	2,595	17.8
C	9[a]	crushed limestone	Ottawa sand	0.41	4,525	31.1	4,730	32.5	5,160	35.4
	10	recycled concrete	Ottawa sand	0.41	4,140	28.4	4,700	32.3	5,440	37.4
	11[a]	crushed limestone	Ottawa sand	0.41	4,635	31.8	5,270	36.2	5,920	40.7
	12	crushed limestone	recycled concrete	0.41	3,780	26.0	4,615	31.7	4,905	33.7

[a]Control mixes.

Table 3. Flexural Strengths of Moist-Cured and Freeze-Thaw Cycled Test Prisms (after Ref 6)

Series No.	Mix No.	Mix Composition: Coarse Aggregate (Minus 1 in. - Plus No. 4)	Mix Composition: Fine Aggregate (Minus No. 4 - Plus No. 100)	Water-Cement Ratio (by weight)	Flexural Strength[a]: Moist-Cured Prisms: After 14 Days (psi)	After 14 Days (MPa)	At age Corresponding to the End of Freeze-Thaw Cycling (psi)	At age Corresponding to the End of Freeze-Thaw Cycling (MPa)	Prisms After Exposure to Freeze-Thaw Cycling: No. of Freeze-Thaw Cycles	Age at End of Freeze-Thaw Cycling (days)	Strength (psi)	Strength (MPa)	Residual Strength (%)
A	1	crushed limestone	Ottawa sand	0.69	645	4.4	745	5.1	760	100	675	4.6	90.6
	2	recycled concrete	Ottawa sand	0.69	540	3.7	595	4.1	760	100	545	3.8	91.6
	3	crushed limestone	Ottawa sand	0.67	715	4.9	780	5.4	684	93	725	4.9	92.9
	4	crushed limestone	recycled concrete	0.67	655	4.5	760	5.2	684	93	655	4.6	86.2
B	5	crushed limestone	Ottawa sand	0.56	840	5.8	825	5.7	603	82	770	5.3	93.3
	6	recycled concrete	Ottawa sand	0.56	675	4.7	670	4.6	603	82	745	5.1	111.2
	7	crushed limestone	Ottawa sand	0.57	730	5.0	800	5.5	603	82	760	5.2	95.0
	8	crushed limestone	recycled concrete	0.57	620	4.3	680	4.7	603	82	670	4.7	98.5
C	9	crushed limestone	Ottawa sand	0.41	940	6.5	1,095	7.5	750	96	1,040	7.2	95.0
	10	recycled concrete	Ottawa sand	0.41	970	6.7	1,000	6.9	750	96	970	6.7	97.0
	11	crushed limestone	Ottawa sand	0.41	995	6.9	1,200	8.3	750	100	1,105	7.7	92.1
	12	crushed limestone	recycled concrete	0.41	800	5.5	1,050	7.2	750	93	860	5.9	81.9

[a]Each result is a mean of tests on two prisms, with testing being done at third-point loading.

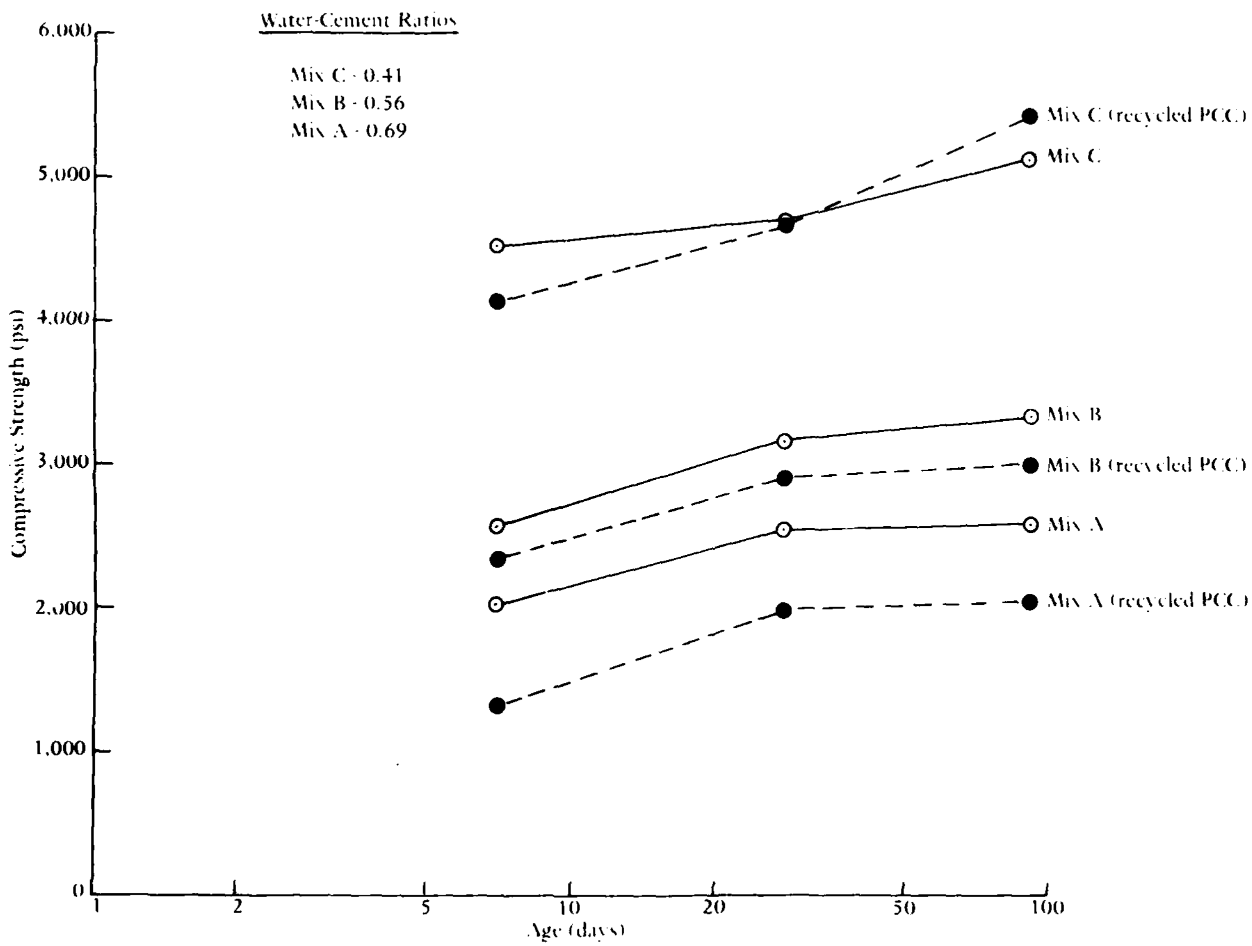

Figure 2. Compressive strength at various ages of test cylinders made with coarse aggregate of crushed limestone or recycled PCC and fine aggregate of Ottawa sand (after Ref 6).

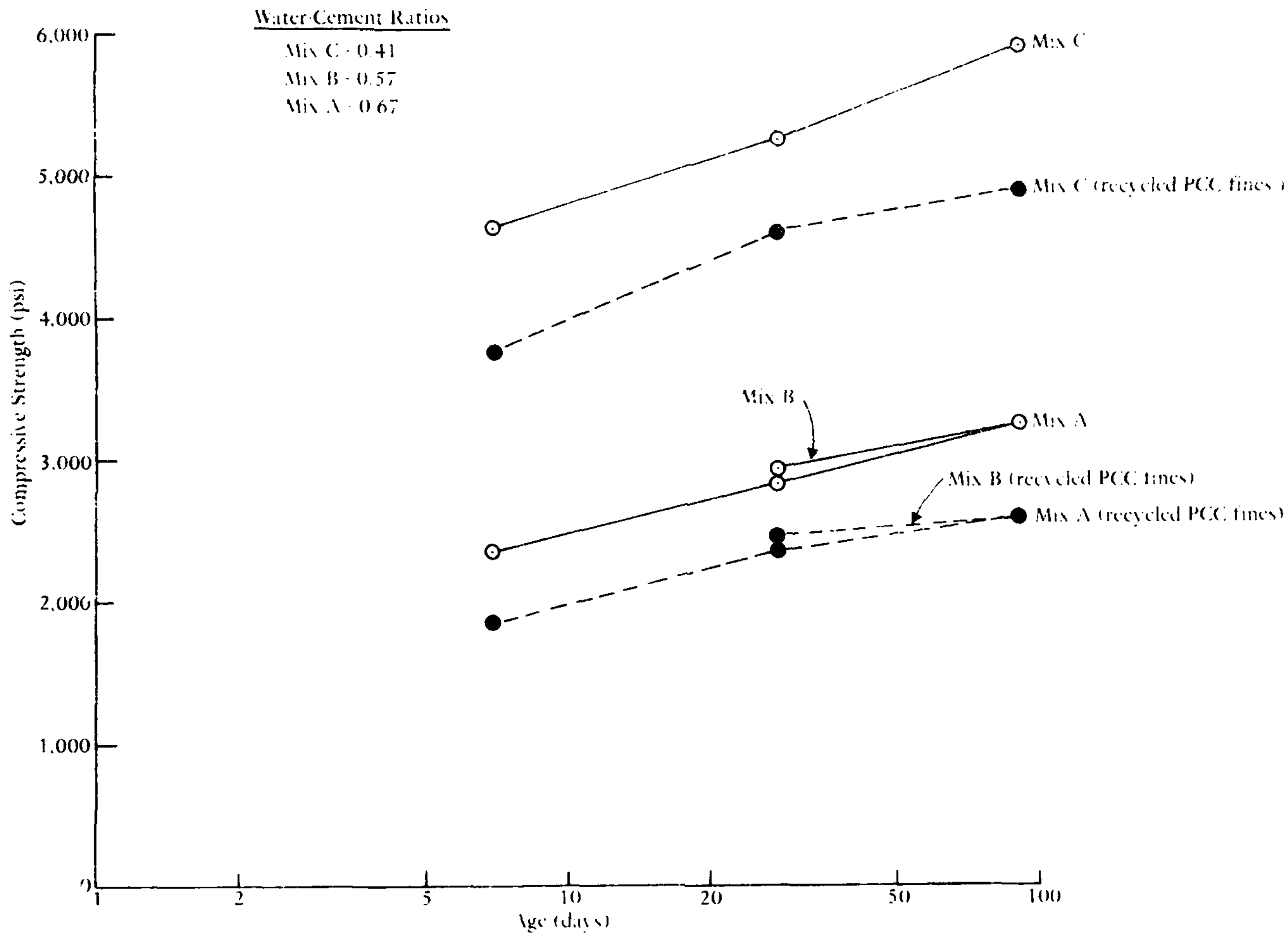

Figure 3. Compressive strength at various ages of test cylinders made with crushed limestone as coarse aggregate and fine aggregate of either Ottawa sand or recycled PCC (after Ref 6).

1. A 2-1/2-year-old, low-strength laboratory concrete beam made with natural gravel and sand of largely granite composition and cementitious material of 35% fly ash and 65% Portland cement by volume. The low compressive strength of 1,860 psi was verified by testing two 6 x 12-inch cores drilled from the beam.

2. Two 238-day-old concrete panels containing chert gravel. The panels had a compressive strength of 3,300 psi.

3. Waste concrete from an 8-year-old driveway slab. It had a compressive strength of 6,000 psi.

4. A 9-1/2-month-old concrete beam with carbonate aggregate; compressive strength equalled 8,000 psi.

Other materials used in the investigation were chert gravel, natural sand, three types of Portland cement, one type of fly ash, a water-reducing admixture, and gypsum (to simulate calcium sulfate contaminants that may occur in building rubble as plaster and wallboard debris).

As in the study of Ref 6, cylinders and prisms were cast from the various mixes for testing. Compressive strength tests were performed on 3 x 6-inch cylinders. The freeze-thaw durability tests were performed on 3-1/2 x 4-1/2 x 16-inch prisms.

The following findings evolved from the tests on the cylinders and prisms that were fabricated from the various mixes (Ref 3).

1. Low-compressive-strength concrete can be recycled into concrete of higher strength. This was demonstrated by the tests on cores taken from the 2-1/2-year-old beam and on cylinders made from recycling the beam as coarse and fine aggregate. The results of the tests are shown in Figure 4.

2. For recycled aggregates, density tends to be lower and absorption tends to be higher than for aggregate that originates from nonrecycled material. Those differences, however, have not created any problems as a result of using recycled concrete as aggregate.

3. Petrographic examination of crushed concrete showed that: (a) for low-strength concrete (e.g., 1,860 psi), the original aggregate tended to shell out intact during crushing, and (b) for concrete of high compressive strengths (e.g., 6,000 to 8,000 psi), a greater breakage of the original aggregate particles tended to occur during crushing for recycling purposes.

4. For concrete that contains chert gravel that has been recycled, the durability factor at 300 cycles (DFE_{300}) is increased by a factor of about 5 (from 15 to 80 DFE_{300}). (Freezing and thawing tests were performed in accordance with CRD-C 114 of Reference 14.)

5. If fine aggregate made from recycled concrete is used, the concrete mix may require about 100 lb/yd^3 more cement than if conventional sand is used. This may be required to increase workability.

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14. Waterways Experiment Station. Handbook for Concrete and Cement. Vicksburg, Miss., Aug 1949.

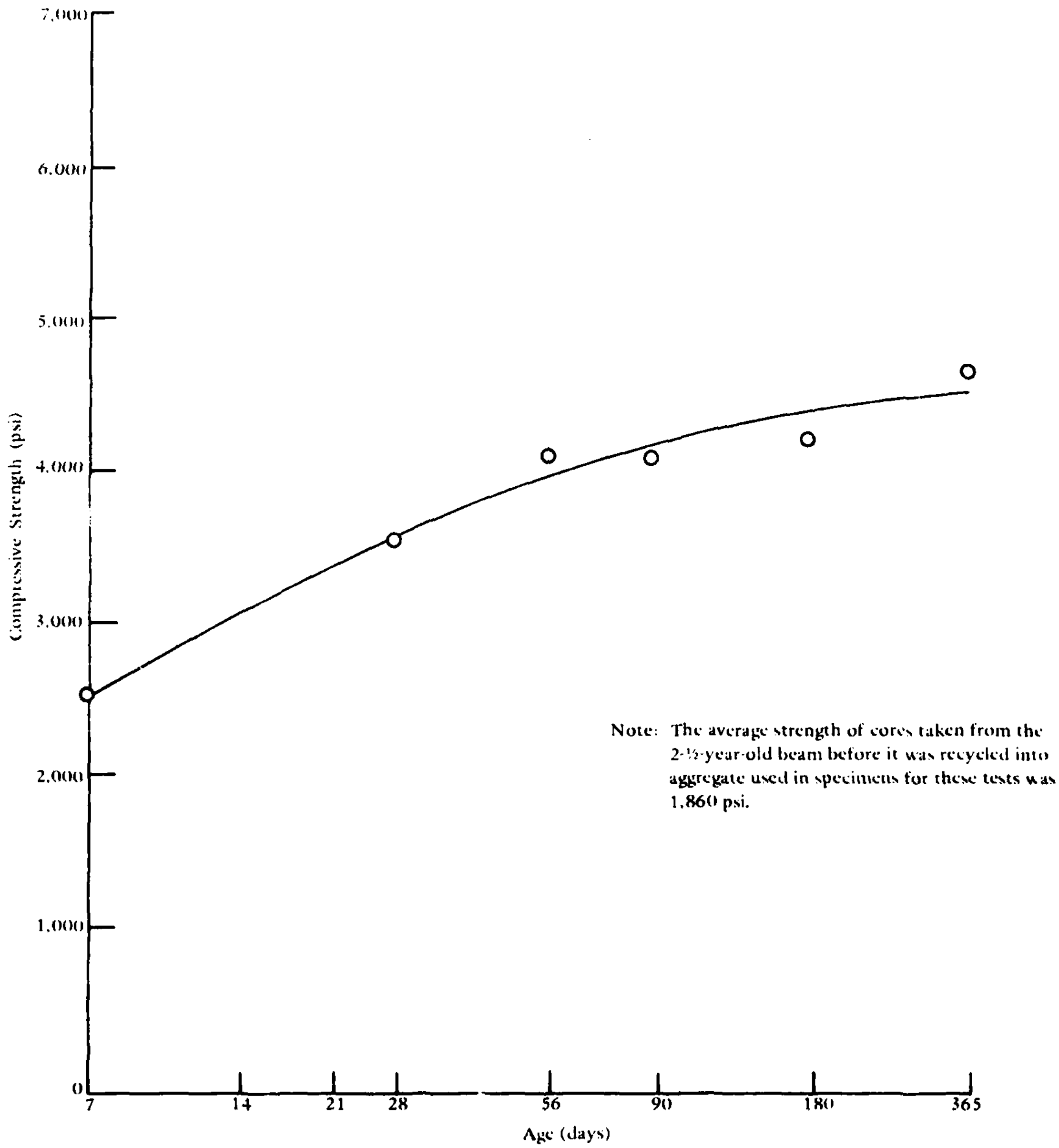


Figure 4. Compressive strength of cylinders made with low-strength recycled concrete (after Ref 3).

6. Water-reducing admixtures are effective in lowering the amount of water required in the mixes and thereby increasing the strength of concrete made with recycled concrete as aggregates.

7. The presence of sulfate contaminants (as simulated by the gypsum in the recycled mix) resulted in deleterious sulfate reactions. This may be a problem if building rubble is used along with airport pavement that is being recycled. If it is necessary to use such material, the total sulfate content should be restricted to 1% or less of the aggregate weight.

MIT Study

In the study by Frondistou-Yannas at MIT, coarse aggregate was obtained by crushing a 2-year-old laboratory-produced concrete slab (Ref 11). The crushed, recycled concrete had a maximum size of 1 inch and a minimum size larger than the No. 4 sieve. Fifty percent crushed granite gravel was used as the coarse aggregate control. The gradation of this material was the same as the recycled PCC coarse aggregate. Fine aggregate used was either Ottawa sand (ASTM C109) or a granite sand (50% crushed). Cement used was either Type I or Type III Portland cement.

Concrete cylinders and mortar briquettes were cast with various mixtures of the above components. Compressive strength tests were performed on 3 x 6-inch cylinders. The mortar briquettes were prepared with aggregate pieces about 3/4 inch in size to test aggregate-mortar bond strength.

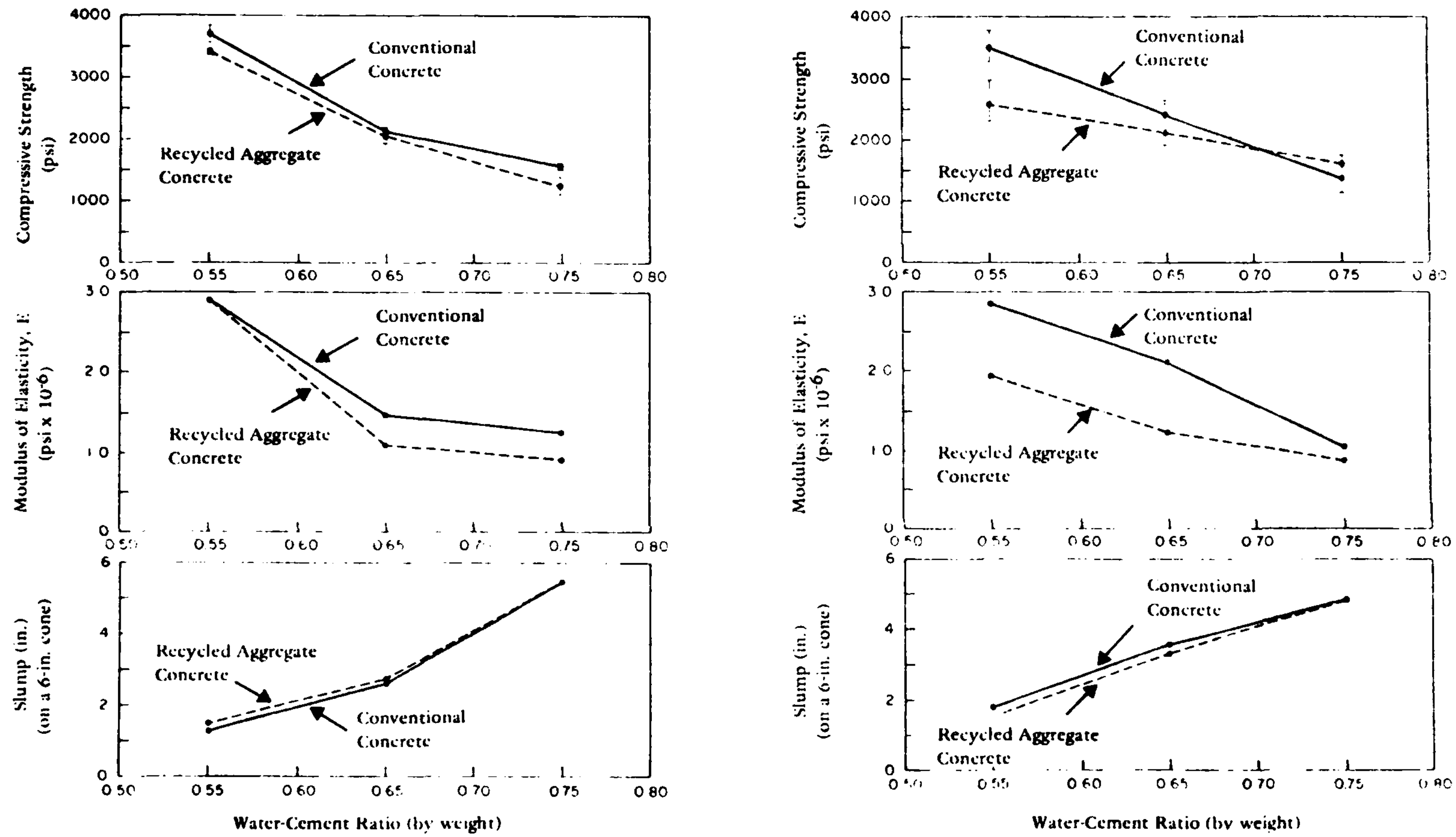
The results from the tests on the various mixes and test cylinders are shown in Figure 5. Results of tests on the briquettes to determine aggregate-mortar bond strengths are shown in Table 4. By comparing the test results shown in Figure 5(a) and 5(b) and Table 4, the following can be concluded:

1. The workability (consistency), as measured by the slump test, of mixes prepared with recycled PCC aggregate was the same as for mixes using new aggregate. Also, the workability was influenced more by the fine aggregate used in the mixes rather than whether recycled PCC was used.

2. For a given water-cement ratio, the compressive strength and modulus of elasticity of test cylinders made with recycled PCC aggregate were generally lower than those for test cylinders made with new aggregate.

3. By varying the water-cement ratio, the type of cement, and the aggregate composition used in the mix, the workability, compressive strength, and modulus of elasticity could be adjusted to suit specific requirements. This is valid for concrete prepared with either PCC recycled or new material.

4. The tensile strength of the mortar in the recycled PCC aggregate was lower than the tensile strength (at 7 days) of the mortar used to prepare the aggregate-mortar bond strength briquettes. This probably explains why the compressive strength and modulus of elasticity were lower for those specimens containing recycled PCC (containing the old mortar) than those using only new material.



(a) Cement: Portland cement, Type III; fine aggregate: Ottawa sand.

(b) Cement: Portland cement, Type I; fine aggregate: granite sand.

Figure 5. Relationship between water-cement ratio and various properties (from Ref 11).

Table 4. Results of Tensile Tests on Aggregate-Mortar Briquette Specimens (from Ref 11)

Type of Aggregate	Ultimate Load (lb)[a]	Type of Failure
New granite gravel[b]	56 ± 15	Aggregate-matrix interface
Recycled granite gravel[c]	49 ± 18	Aggregate-matrix interface
Recycled gravel with mortar[c]	39 ± 14	Usually aggregate
Recycled mortar[c]	31 ± 8	Always aggregate

[a]Average of at least nine measurements. The reported uncertainty is equivalent to one standard deviation.

[b]From the quarry.

[c]Sorted out from the demolished concrete slab.

PROJECTS USING RECYCLED PCC

Iowa Highway Projects

A number of state highway departments have used recycled PCC. The Iowa DOT has been one of the more aggressive agencies that has recycled old PCC into new PCC surface courses (Ref 12 and 13). They have recycled PCC in Lyon, Pottawattamie, Page, and Taylor counties in Iowa. All of the original pavements were generally in good condition. However, it was necessary to reconstruct the pavement because of required width and alignment adjustments or other reasons. The pavements that were recycled had thicknesses ranging from 7 to 10 inches and contained reinforcing steel. Two of the three projects contained an overlay of asphaltic concrete.

The Iowa DOT has shown that recycled PCC materials can be effectively used. Some of the more significant findings from their work include:

1. It was necessary to use some natural sand to provide a more workable mix.

2. Conglomerated crushed PCC fines, which aggregated during the stockpiled period and did not break down during mixing, caused some surface popouts. These popouts had little effect on the integrity of the pavement.

3. The evaluation of the recycled pavements shows that (a) riding quality was not affected by the use of recycled aggregate, (b) initial friction values were exceptionally good, and (c) a field review of the pavements after about a year showed that the general surface appearance

was very similar to that of pavements using conventional mixes. There was a very minor amount of random cracking, and the joints were in good condition.

Thus, the Iowa DOT has shown that recycling of aged PCC material into new PCC highway surface courses is a viable reconstruction alternative.

The equipment and procedures used in the recycling of PCC pavements in Iowa are presented in Figure 6. The same equipment and procedures could be used for recycling airport pavements.

Jacksonville International Airport, Florida

Runway 13-31 at Jacksonville International Airport was originally constructed in 1966-1968 (Ref 8). The pavement structure consisted of 11 inches of Portland cement concrete on a limerock base. In 1975, it was decided to reconstruct the center 50 feet of the runway because of its poor condition. The pavement exhibited load-caused longitudinal and transverse cracking, corner cracking, spalling along keyed longitudinal joints, and differential settlement. In addition, the presence of water stains along pavement joints indicated upward seepage of water.

Based on detailed field and laboratory investigations, a new pavement structure was designed for the center 50 feet of the runway. The design consisted of replacing the existing pavement structure in this area with 14 inches of PCC pavement, 6 inches of econocrete base using recycled PCC material, and 6 inches of coarse recycled concrete aggregate subbase.

The salvaged old PCC pavement provided enough aggregate material for both the econocrete base and the subbase, which also functioned as a drainage layer. Approximately 21,500 tons of old PCC was crushed during the project using the procedure and equipment described in Figure 7. Some of the remaining stockpiled material is shown in Figure 8.

A visual inspection of the reconstructed pavement was made in July 1980. The pavement was found to be in excellent condition as can be seen in Figure 9. No maintenance has been required since construction was completed in April 1977. In 1980, the runway surface was grooved.

The designers of this reconstruction project estimate that by using recycled PCC as aggregate in the econocrete base and subbase layers, approximately 50% of the cost of aggregate material was saved (Ref 8).

Love Field, Dallas, Texas

Runway 13R-31L and its associated taxiways were constructed in 1963-1964 using recycled PCC in the base portion of the pavement structure (Ref 15,16). The pavement structure as constructed consists of 13 inches of reinforced PCC, 6 inches of cement-stabilized base, and 18 inches of select fill material, the top 6 inches of which was lime treated. The procedure and equipment used in the construction process of the runway are shown in Figure 10.

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15. Runway Rx: Lime, Cement, Concrete, Steel, Engineering News-Record, 24 Sep 1964, pp 28-31.

16. H. B. Zachry 80% Complete on Dallas Love Field Expansion, Engineering Construction, Oct 1964, pp 8-10, 36.

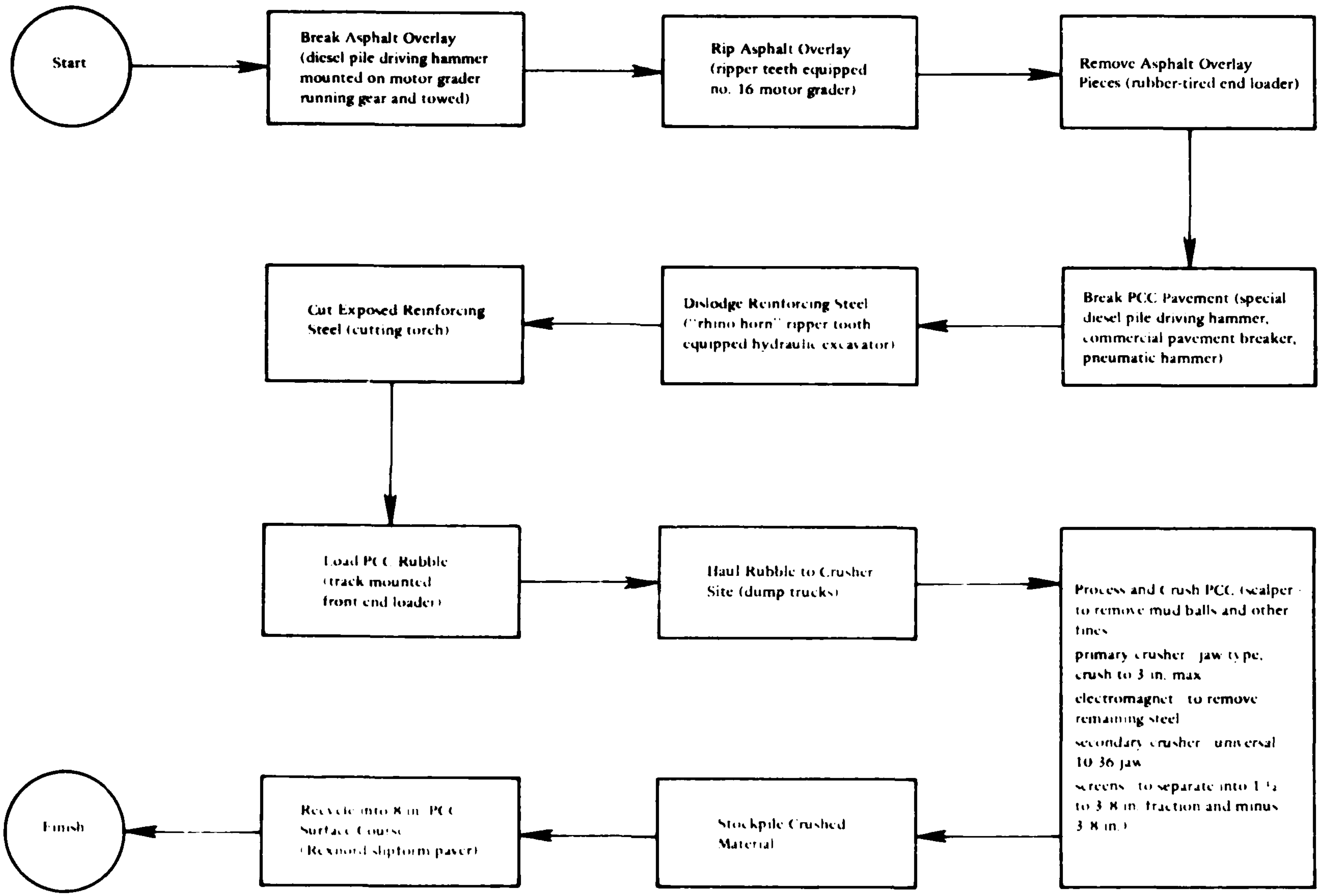

Figure 6 Procedure and equipment used to recycle PCC highway pavements in Iowa (after Ref 12 and 13)

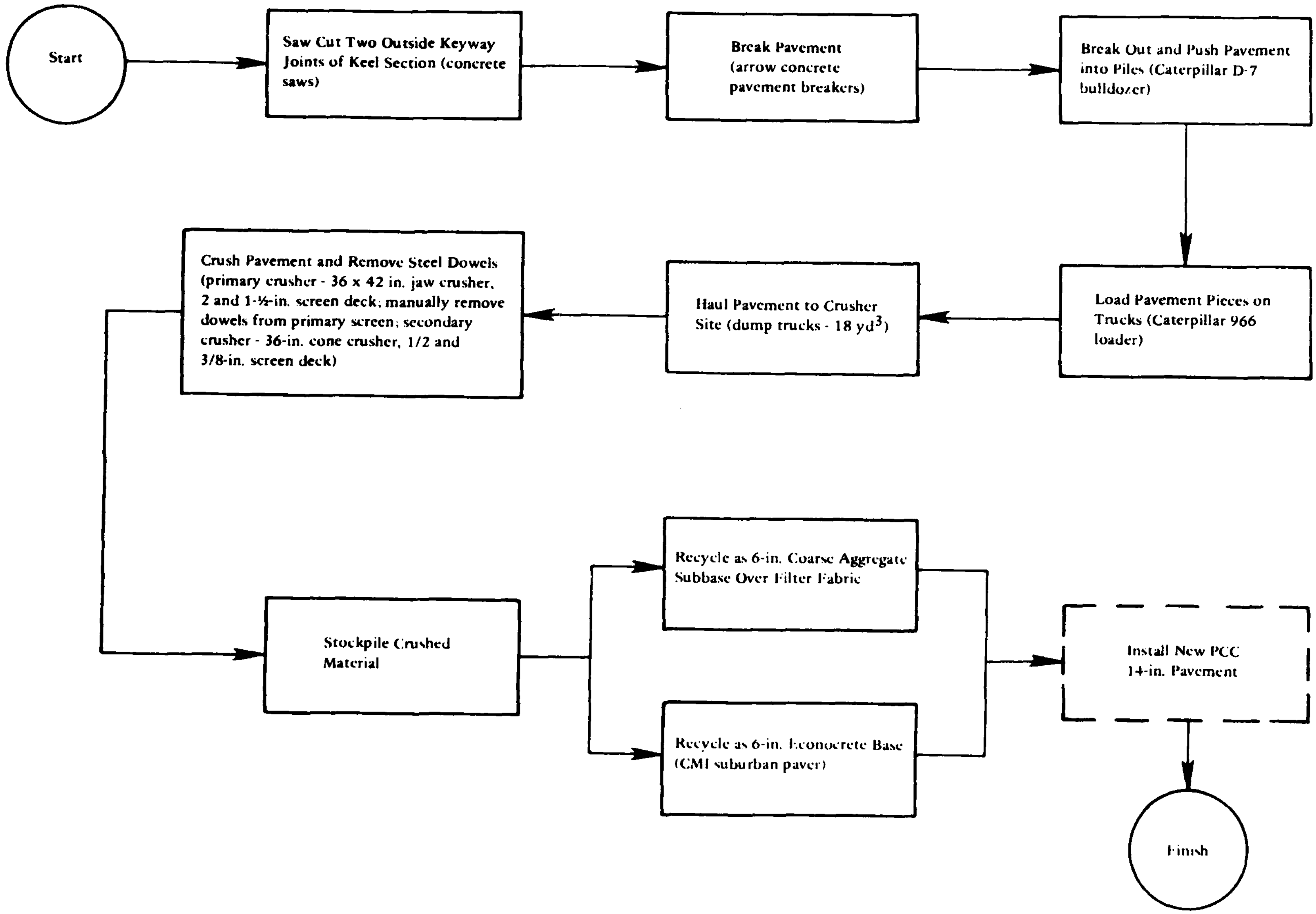

Figure 7. Procedure and equipment used to recycle the center 50-feet keel section of Runway 13-31, Jacksonville International Airport (after Ref 8).

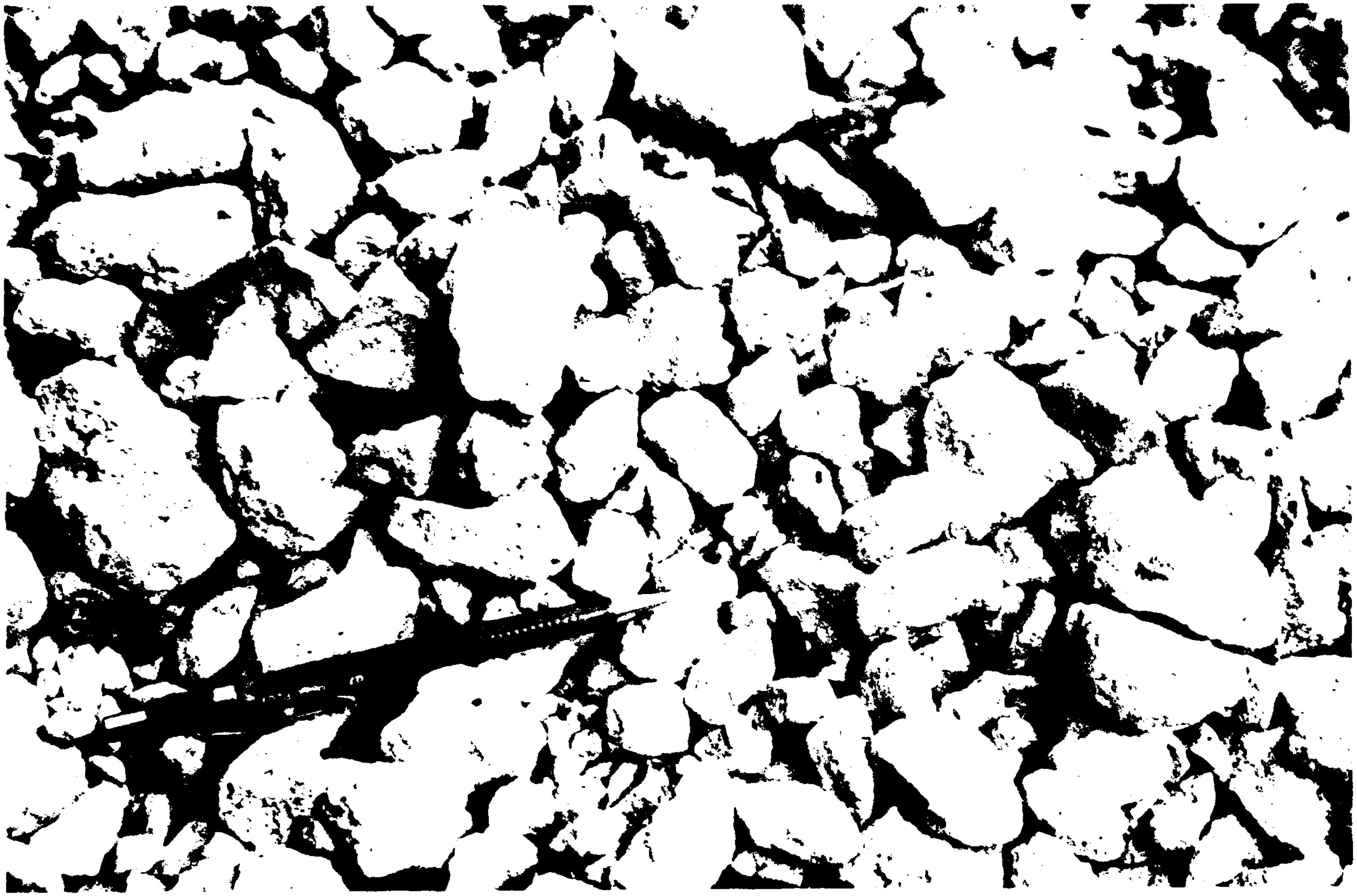

Figure 8. Stockpiled excess material obtained from crushing the old PCC pavement at Jacksonville International Airport.

Figure 9. Runway 13-31 at Jacksonville International Airport (July 1980).

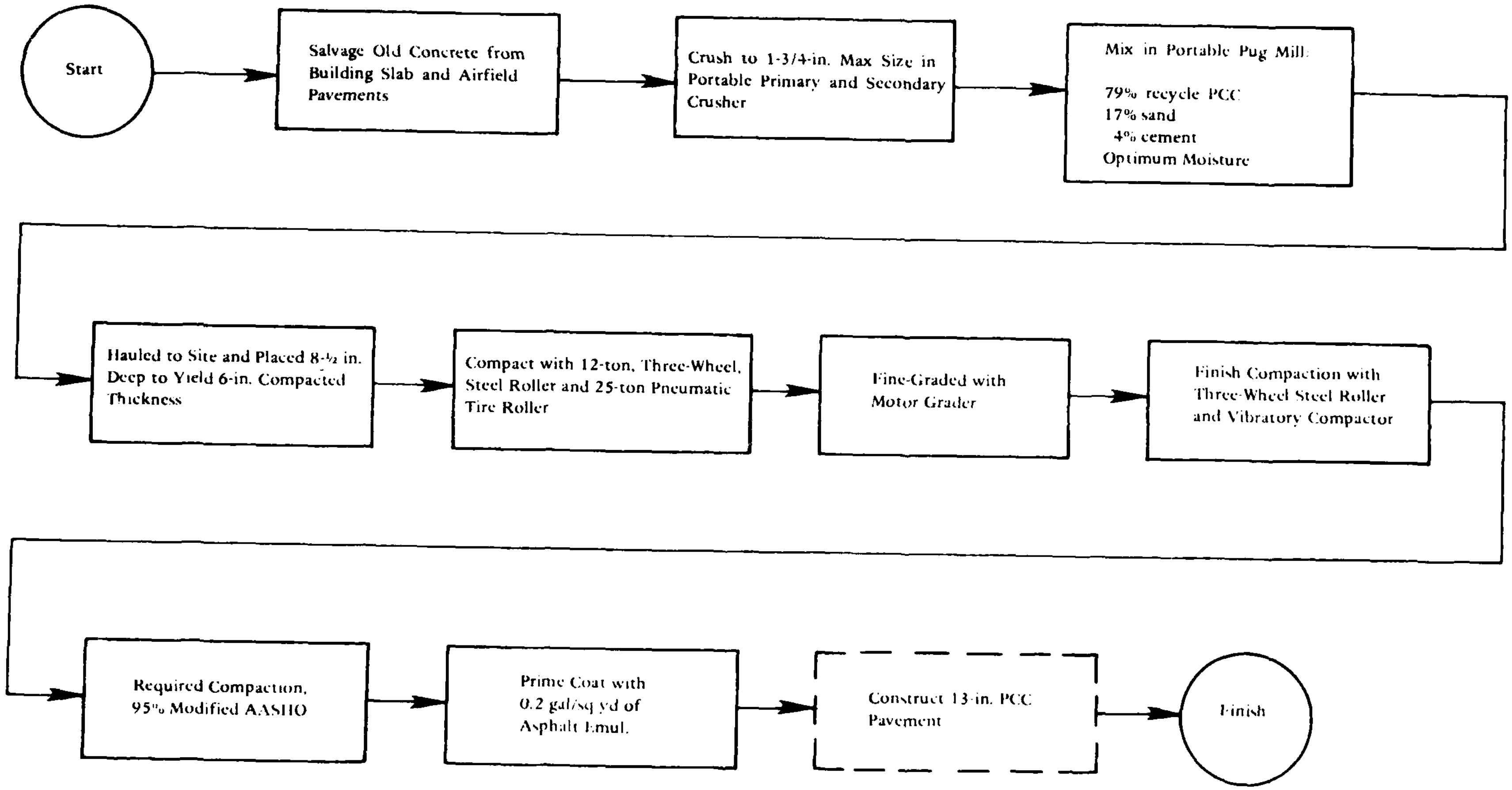

Figure 10. Procedure used to recycle waste Portland cement concrete into cement stabilized base, Love Field, Dallas, Tex. (after Ref 15 and 16).

Because of a shortage of gravel, the contractor, H. B. Zachry Co., elected to use recycled PCC in the cement-stabilized base portion of the pavement structure. The recycled PCC material was obtained by processing old PCC from building slabs and airfield pavements. The resulting mix for the stabilized base layer using this recycled material yielded an average compressive strength of 1,100 psi after 45 days.

Love Field was the primary air carrier airport for Dallas until the completion of Dallas-Fort Worth International Airport (DFW). Since 1964, Runway 13R-31L was used by all the aircraft, including 747s, DC-10s, and L-1011s. Since the completion of DFW, the aircraft traffic has been primarily Boeing 737s. The traffic has caused some load-associated damage to Runway 13R-31L, such as corner breaks and longitudinal cracks, particularly on the parallel taxiway. Typical corner breaks on the taxiway are shown in Figure 11. The taxiway section shown in this figure is scheduled to be reconstructed in 1980. Other types of distress observed in the pavement consisted primarily of transverse cracks. The development of these cracks is attributed to the large size of each slab (25 feet by 75 feet). The majority of the slabs (some of which can be seen in Figure 12), however, are in excellent condition.

Coffeyville Municipal Airport, Kansas

The runway at Coffeyville Municipal Airport was originally constructed of Portland cement concrete during World War II. As a result of severe deterioration from D-line cracking similar to that shown in Figure 13, a project was initiated in 1978 to overlay the runway with asphaltic concrete. After construction started, it was found that it was difficult to compact the asphaltic concrete overlay because of the poor condition of the existing underlying pavement. It was, therefore, decided to break up the existing PCC pavement to correct this problem. The PCC pavement was broken up with a sheepsfoot roller and combined with base course material conforming to specifications for the State of Kansas. The combined material was then compacted as an aggregate base course. The asphaltic concrete overlay was then successfully placed.

The reconstructed runway has been used by general aviation aircraft. In July 1980, the runway was in excellent condition, as can be seen in Figure 14.

RECYCLING EQUIPMENT AND PROCEDURES

In general, equipment and procedures used to batch, haul, and place recycled PCC mixes are the same as those used to construct pavements with new PCC mixes. Therefore, it is not necessary to discuss the equipment or procedures. However, equipment and procedures used to break up, crush, and process aged PCC pavement as aggregate are somewhat unique to recycling and, therefore, will be discussed.

Equipment that has been used to break up in-place aged PCC pavement includes the following:

1. Diesel pile driving hammer mounted on a motor grader running gear

Figure 11. Typical corner breaks on the taxiway to Runway 13R-31L at Love Field (July 1980).

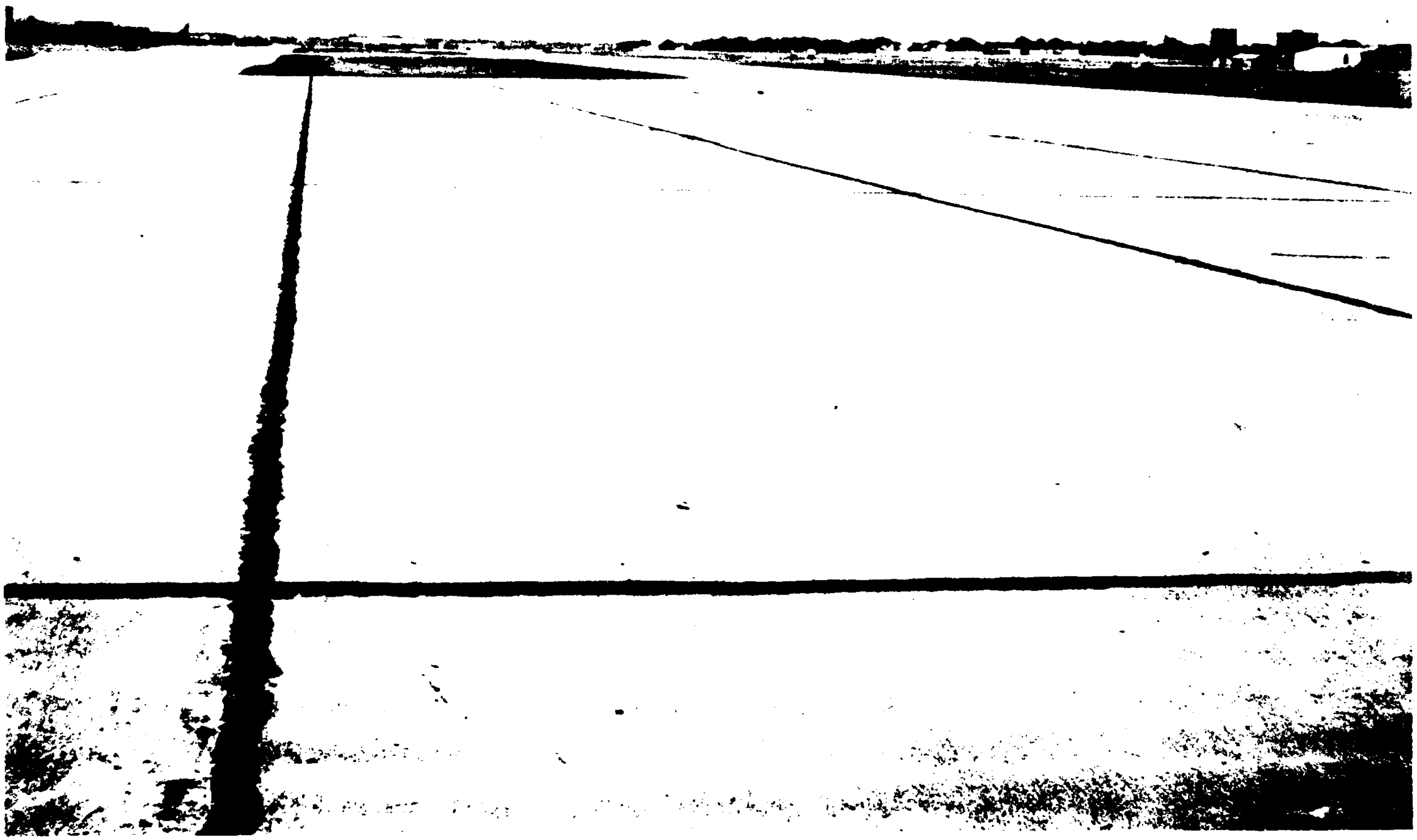

Figure 12. Runway 13R-31L at Love Field (July 1980).

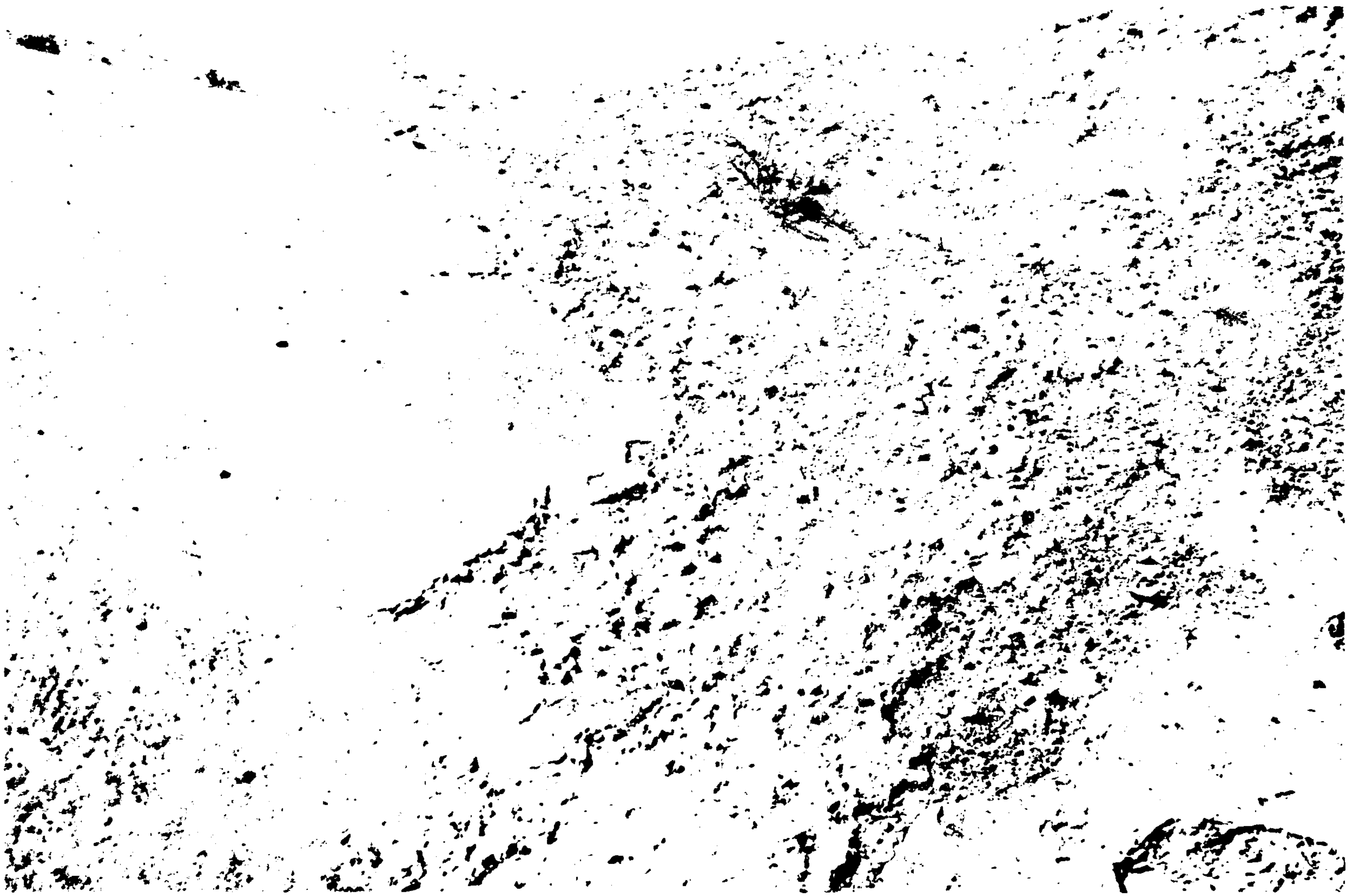

Figure 13. Example of D-line cracking similar to that which existed in the runway prior to reconstruction at Coffeyville. (This is an area of the apron which is adjacent to the reconstructed runway, July 1980).

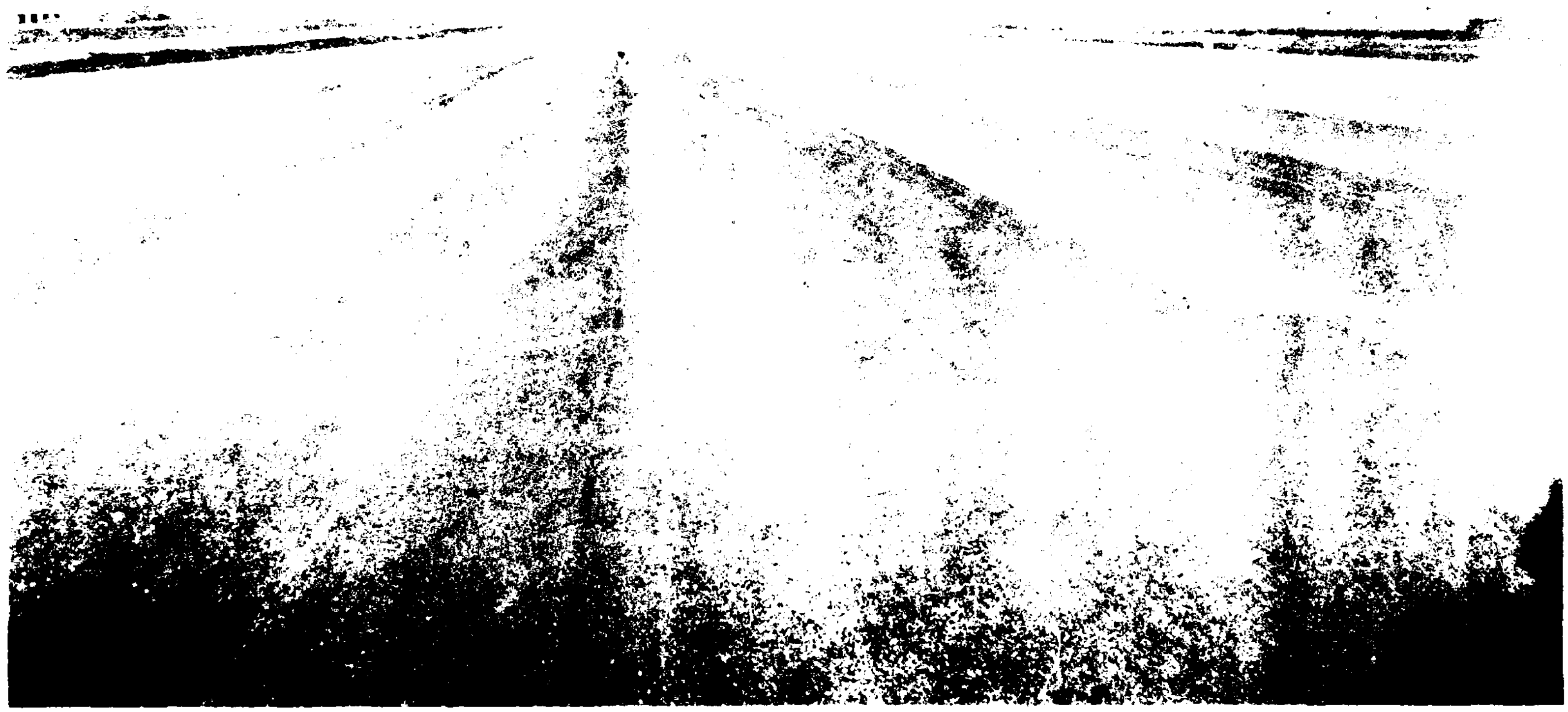

Figure 14. Runway at Coffeyville Municipal Airport (July 1980).

2. Concrete pavement breaker (Arrow Brand)

3. Sheepsfoot roller

4. Pavement milling machines

A "rhino horn" ripper-tooth-equipped hydraulic excavator has been used to dislodge and expose reinforcing steel after the pavement has been fractured with one of the above pieces of equipment. The exposed steel is then cut manually with a cutting torch or shears, depending on the size of the reinforcement.

Equipment used to crush and size the PCC pavement pieces has also been of a common type utilized in the construction industry. The removal of any remaining reinforcing steel in the pavement material is done during this crushing and sizing phase. Reinforcing steel pieces are removed by electromagnets or manually.

After the crushed PCC has been placed in individual stockpiles according to the desired size, equipment and procedures to complete the recycling process of the material (mixing, hauling, placing, finishing) are the same as for conventional mixes. The development of a mix design with the recycled materials also follow procedures used in obtaining mix designs with virgin materials.

ECONOMICS OF RECYCLING

There are many factors peculiar to each specific project that determine whether or not recycling is the most cost-effective alternative. It is, therefore, difficult to make any general conclusions (e.g., that recycling of PCC pavements will always be the most cost-effective alternative) regarding PCC pavement recycling. However, some specific items related to the economics of pavement recycling should be considered.

The economic feasibility of concrete recycling has been studied by Frondistou-Yannas and Itoh (Ref 17). Some of their most significant findings that are applicable to PCC airport pavement recycling include:

1. Recycled concrete aggregate plant price of $2.20/ton (conservative estimate) is significantly lower than natural aggregate plant price of $3.30/ton (as of April 1977).

2. If the source of natural aggregate is at least 15 miles farther away than the source of recycled PCC aggregate, it is more economical to use recycled aggregate.

3. Given that natural aggregates are scarce in many metropolitan areas and 15 miles is a relatively short distance, recycling of PCC for aggregate will be advantageous in many areas of the U.S.

Actual field experience by the Iowa DOT on highway reconstruction projects has shown that savings can be realized by recycling PCC pavements (Ref 13). The use of recycled PCC has also resulted in a savings

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17. S. Frondistou-Yannas and T. Itoh. Economic Feasibility of Concrete Recycling, ASCE Structural Division Journal, vol 103, no. ST4, Apr 1977, pp 885-899.

of 50% of aggregate material costs in an airport reconstruction project (Jacksonville International). Thus, recycling of PCC pavements has proven to be economical in both highway and airport pavement reconstruction projects.

FINDINGS

Laboratory investigations have shown that aged PCC pavements can be recycled into new PCC pavements. General findings from these investigations include:

1. Strength and durability of test specimens made with recycled PCC as aggregate may or may not be lower than those for specimens made only with virgin material. This statement is based on tests performed at the Waterways Experiment Station, MIT, and Mineral Sciences Laboratories, which showed mixed results.

2. The use of recycled PCC as fine aggregate tended to degrade concrete properties (see Table 3 and Reference 3).

3. SEM photomicrographs and x-ray fluorescence analyses confirmed the presence of a coating of cement paste on aggregate of recycled material, and that cracks of 2 to 4 microns in width were present in the cement paste. The presence of these cracks may explain the high absorption and low specific gravity of recycled PCC as aggregate.

4. Water-reducing admixtures were effective in lowering the required amount of water in mixes, thereby increasing the strength of concrete made with recycled PCC material.

5. Air-entraining agent requirements were the same for specimens made with coarse aggregate of either recycled PCC or new material, but if recycled PCC fines were used, the requirement for air-entraining agents more than doubled.

6. The workability of mixes prepared with coarse recycled PCC as aggregate was the same as that made with new aggregate material. However, if recycled PCC fines were used, more cement was required in the mix to increase workability.

Field experience has also shown that aged PCC pavements can be recycled into the structures of new PCC and AC pavements. Airport reconstruction projects that have successfully utilized recycled PCC in their pavement structure include:

1. Jacksonville International Airport (Fla.) - recycled PCC used in econocrete base and aggregate subbase (surface course is PCC)
2. Love Field (Tex.) - recycled PCC used in the cement-stabilized base (surface course is PCC)
3. Coffeyville Municipal Airport (Kan.) - part of the aggregate base course is composed of recycled PCC (surface course is AC)

In general, all of the above pavement structures utilizing recycled PCC are in excellent condition. There are no deterioration features in the structures to indicate that recycled PCC should not be used in future airport pavement reconstruction projects.

The Iowa DOT has successfully recycled aged highway PCC pavement into a new PCC surface course and other courses in highway pavement structures. Their experience has shown that recycling of PCC into new PCC surface courses is technically feasible and practical. Therefore, PCC recycling for surface courses should also be considered as a reconstruction alternative for airport pavements.

The equipment and procedures that are somewhat unique to PCC pavement recycling are those used for breaking the pavement, dislodging the reinforcing steel, and removing the steel. The equipment used to initially break the pavement includes a diesel pile driving hammer, arrow concrete pavement breaker, and sheepsfoot roller. A "rhino horn" ripper tooth mounted on an excavator has been used to hook onto reinforcing steel to dislodge and expose the steel from the concrete matrix. Electromagnets have been used to remove any remaining reinforcing steel during crushing and sizing of the salvaged PCC pavement. Equipment and procedures that have been used to complete the recycling process of PCC pavements of mixing, hauling, placing, and finishing are the same as those used for mixes prepared with virgin materials.

For any given PCC pavement proposed to be recycled into a new PCC pavement, a specific mix design will have to be developed.

CONCLUSIONS

Based on this study, aged PCC airport pavements can be recycled as aggregate into stabilized and unstabilized base courses. The recycling of such pavements is technically feasible and can be cost effective. Equipment and procedures are currently available to perform recycling operations; however, these along with the technology of recycling could be substantially improved to enhance their effectiveness.

When the <u>fines</u> from the PCC recycling process are used as aggregate, concrete properties are degraded. Also when such fines are used, the requirements for air-entraining agents and cement are increased.

Recycling of PCC for surface courses of airport pavements has not yet been performed. Design of such surface courses should not be undertaken until additional laboratory investigations have been performed on the durability of recycled PCC.

RECOMMENDATIONS

The following recommendations are offered:

1. Perform additional laboratory studies in the areas of strength, durability, and fatigue of recycled PCC to determine suitability for surface courses in heavy duty airport pavements.

2. Develop design criteria and guidelines for recycling of PCC airport pavements. The criteria and guidelines should include such items as quality assessment of candidate materials, evaluation of mix designs, strength and durability requirements, assessment of recycling economics, and equipment specifications.

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