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PORTLAND CEMENT CONCRETE RECYCLING: TECHNOLOGY REVIEW.(U)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A review of current technology pertaining to the recycling of existing portland cement concrete pavements was conducted. The purpose was to assess the applicability of recycling to U.S. Air Force pavement rehabilitation work. Costs of alternatives were reduced to simple models for use in evaluating sensitivity to cost factors. A study of projects on which this technology was used identified aggregate cost and haul distance as key factors. Numerous other factors		

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also affect the results. Technological deficiencies were studied, and most were found to be the result of lack of experience with the technology. No substantially new technology is involved in recycling portland cement concrete.

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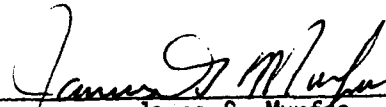
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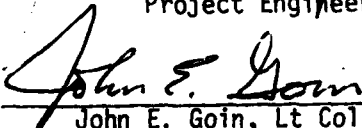
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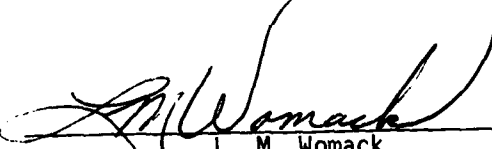
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This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

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SECTION I INTRODUCTION

BACKGROUND

During the past decade, dramatic increases in the cost of petroleum have triggered an interest in reducing the costs of many activities by reusing existing materials. Following the trend toward conservation, the U.S. Air Force has investigated recycling technology as it applies to airfield pavement construction and rehabilitation (References 1 and 2). The authors of the most recent study of this technology for the Air Force Engineering and Services Center (AFESC) recommended that portland cement concrete (PCC) recycling was a sufficiently unique and important subject to warrant a separate investigation. The investigation was subsequently conducted by the New Mexico Engineering Research Institute (NMERI).

OBJECTIVES

Several specific tasks were designated as technical requirements for the PCC recycling study. The state of the art was to be established by means of a review of the technical literature and contacts with experts in the field. Specifications used by other agencies were to be evaluated. Representative projects completed during the past five years or planned for the next three years were to be evaluated in a study of the cost-effectiveness of PCC recycling. Technological deficiencies, as well as the research required to correct them, were to be identified, and cost-benefit estimates were to be prepared. The results of the study are presented in this report.

SECTION II

TECHNOLOGY REVIEW

INTRODUCTION

PCC recycling is the use of an existing PCC structure as a source of aggregate to be used in the construction of new facilities. The application of PCC recycling has involved all types of structures made from PCC and from brick and other masonry materials. The structures are broken up, and the material is stockpiled and then crushed when sufficient quantities accumulate. The crushed materials are used as aggregate for fills, unbound pavement bases, stabilized pavement bases, asphalt concrete (AC), and PCC. The technical literature reveals that the current technology has evolved during the construction of highways and airfield pavements and during various kinds of urban construction. Although PCC recycling was originally developed to provide aggregate for areas having unacceptable or marginal sources of the material, it appears to be cost-effective in many other cases where existing PCC is available.

The study described here was concerned with the application of PCC recycling to the construction and rehabilitation of U.S. Air Force pavements. The technology may be employed in several different ways as illustrated in Table 1. The source of material to be recycled does not have to be the existing pavement. Any structure that is to be removed can be broken up and crushed. Pavements are particularly attractive, however, because of their light reinforcement and high-quality original materials. Heavily reinforced structures should not be considered for recycling. Conceivably, base personnel could stockpile old PCC for years in order to use it in pavement work.

TABLE 1. POSSIBLE SOURCES AND END USES
OF PCC RECYCLING MATERIALS.

Source of PCC	End Use of Crushed PCC
Existing Pavement	Use in New Pavement, Base, or Fill
Other Pavement or Structure	Stockpile for Future Use
Stockpiled Concrete	Sell as Aggregate
Stockpiled Rubble	Sell to Contractor for Other Use

In considering the rehabilitation of an airfield pavement, it is necessary to evaluate the condition of the existing pavement structure. The Air Force currently uses the Pavement Condition Index (PCI) to evaluate pavement features in accordance with standardized procedures (Reference 3). The decision to rehabilitate or reconstruct an airfield pavement will be the result of evaluations of this type. These evaluations are an integral part of the overall decision process and will affect the recycling alternatives considered in a particular situation as illustrated in Figure 1. The condition of the existing pavement is the starting point. Three options are presented. "No Upgrade" indicates that the overall pavement condition does not warrant rehabilitation at present. This decision may be based on performance, operational, or fiscal considerations. "Upgrade Surface" indicates that the surface characteristics are unacceptable but the underlying pavement layers are structurally sound. Here, the restoration of surface riding quality is the only requirement. "Upgrade Structure" indicates that the pavement is in need of structural rehabilitation because of failure or anticipated failure under future operational requirements. Thus three possible condition evaluation recommendations are considered.

The second column in Figure 1 identifies options for satisfying the requirements of the evaluation. The "No Upgrade" finding obviously warrants no construction activity. The "Upgrade Surface" recommendation may be accomplished by surface milling, overlaying, or both. The milled PCC may be used in a variety of ways for constructing the new facility. An overlay may be placed directly on the existing pavement, or it may be put down after the pavement is milled. Such an overlay would usually be thinner than an overlay intended to increase the load-carrying capacity of the pavement structure. The "Upgrade Structure" recommendation may be achieved by either overlaying or reconstructing the existing pavement structure. An important advantage of recycling is found in this category. A pavement overlay usually must cover the entire runway, taxiway, or apron being upgraded. When the area exhibiting distress is recycled, only a portion of the total area needs be reconstructed and grade is maintained.

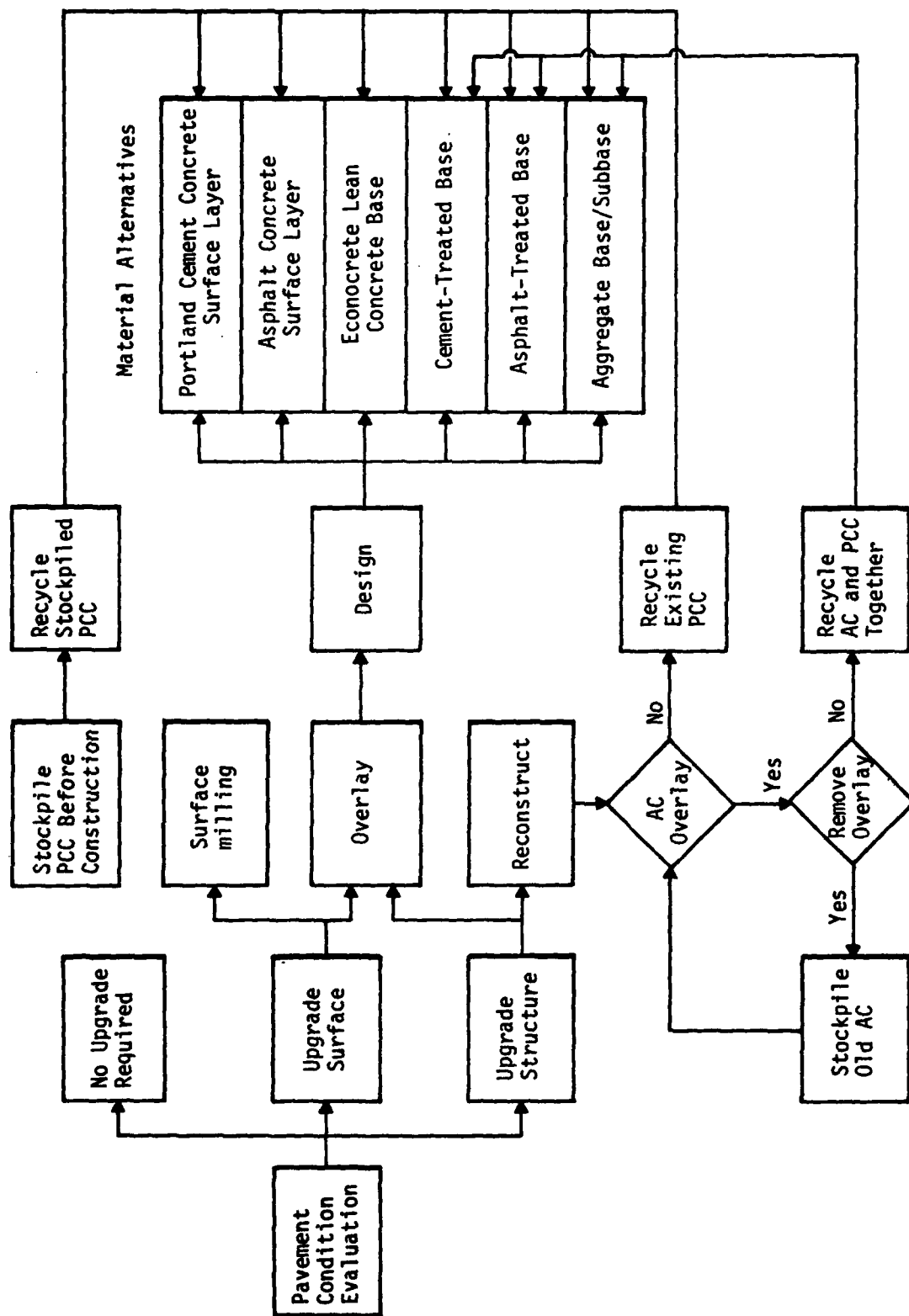


Figure 1. Relationship of Condition Evaluation to Recycling Alternatives.

Another structure illustrated in Figure 1 is PCC pavement with an AC overlay. The overlay may or may not be crushed with the PCC, depending on the end use. Also illustrated in Figure 1 is the use of PCC from other sources, such as an existing stockpile, as aggregate in the new structure.

STATE OF THE ART

Early in the development of PCC pavement recycling, several technological problems were encountered (Reference 4). These were identified as difficulty in breaking the old pavement and removing and crushing the broken concrete. In some cases, contractors have developed satisfactory solutions on a trial-and-error basis. At this time, the equipment and expertise developed are not widely available. As contractors are offered recycling alternatives, it is expected that sufficient incentive will exist for most contractors to develop the required capability.

The specific tasks required in the recycling of PCC pavements are illustrated in Figure 2. They are discussed in the following paragraphs.

A heavy ball, a drop hammer, or a ripper has traditionally been used for concrete breaking. The requirements for recycling demand a smaller size of material than these devices normally produce. The most widely used current system was developed by Iowa contractors working on highway construction jobs. A diesel-powered pile driver was modified so that it delivers 86 to 90 blows per minute to the pavement surface at energy levels of 20.3 to 24.4 kJ (15,000 to 18,000 ft-lb) (Reference 4). An anvil remains in contact with the surface to distribute the energy; as a result, the material is more thoroughly shattered. The shattering creates horizontal laminations separating the concrete and the steel reinforcement and yields pieces about 0.3 by 0.5 meter (1.0 by 1.5 feet) in size. The size may be controlled by the speed at which the pavement breaker is advanced. Rates of 2090 to 2508 meters² (2500 to 3000 yards²) per machine per day for pavement 305 millimeters (12 inches) thick (Reference 4) are maximum rates experienced. Unreinforced pavements will require lower energy levels for satisfactory breaking. A drop hammer system proved satisfactory for work at the Jacksonville International Airport, discussed later.

Steel cutting is the next task to be done (Figure 2). This job varies according to the type of reinforcing material found in the pavement. In plain

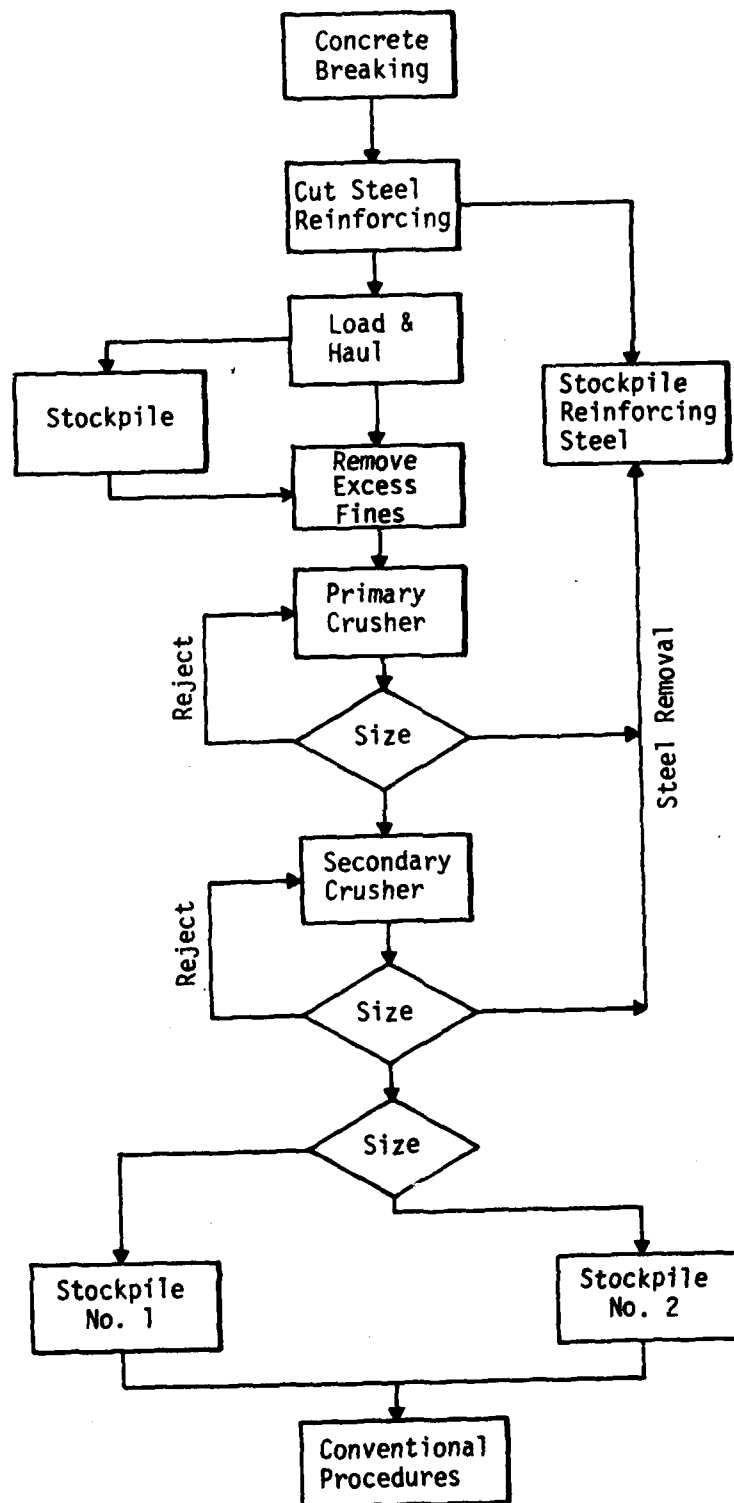


Figure 2. PCC Recycling Tasks.

PCC pavements, the dowel bars may be removed by hand, and many can be reused in the new pavement. Mesh reinforcement will often require additional cutting, by torches or hydraulic shears, near the edge of the concrete blocks. Exposed steel must be trimmed off to simplify handling and primary crushing. Iowa contractors also drag a rhino horn through the crushed material to break up the steel and pile the material (Reference 4). A 90- to 95-percent recovery is expected for reinforcing steel. Mesh may or may not be recovered.

After the existing PCC pavement is broken, it must be loaded and hauled to a crushing facility. Reference 4 recommends that tracked loaders be used on subgrade and that rubber-tired loaders be used if there is a base on which to work. Care must be taken to minimize the mixing of base or subgrade with the broken concrete. One technique used successfully is to push the broken material onto the broken slab for loading, thus reducing contamination (Reference 5). A special loader bucket with openings in the bottom would be useful because it would allow fines to pass through. Experience indicates that a good operator should be able to load 95 percent of the broken PCC. Trucks used for hauling should be lined inside to reduce damage to truck beds and noise during loading.

Once the concrete is broken, nothing remains to prevent surface water from infiltrating into the subgrade. Contractors must make some provision for draining water out of the broken pavement to avoid muddy working conditions that will result in the contamination of the material to be recycled. In highway applications, the water is drained by blading away the shoulders. The problem may be harder to solve in the case of airfield pavements and should be carefully studied.

Crushing is the next step (Figure 2). In order to reduce the fines, dirty or muddy material may have to be passed over a grizzly before it is crushed. A water spray may have to be used to reduce dust emissions. Material too large for the primary crusher will require the use of additional breaking equipment, such as a jackhammer, at the crusher. After primary crushing, the steel is removed either manually or by an electromagnet suspended above the conveyor system. The secondary crusher reduces the material to the required gradation. The percentage of material smaller than the number 200 sieve (0.074 millimeter [0.0029 inch]) should be minimized.

The crushed material should be screened and then stockpiled according to particle size so that no single pile contains a large enough range of sizes to cause segregation of the materials within the pile (Reference 6). Once it has reached the stockpile, the recycled PCC may be treated exactly as any other aggregate material used in construction.

MATERIAL PROPERTIES OF CONCRETE MADE FROM RECYCLED AGGREGATE

Several studies of the use of recycled concrete as aggregate in new concrete are reported in the literature. The earliest and one of the most comprehensive was conducted by Buck (References 7, 8, and 9) at the Waterways Experiment Station (WES). The following conclusions are presented in the WES study:

1. Pavement concrete and building rubble should be considered separately because rubble is contaminated with gypsum.
2. Additional cement is required when recycled concrete is used for fine aggregate.
3. The compressive strength of concrete containing recycled aggregate is lower than that of conventional concrete for similar mix designs.
4. Aggregate made from recycled concrete has a lower specific gravity and higher absorption than conventional aggregates.
5. The use of natural sand as all or part of the fine aggregate improves the workability of the material significantly.
6. Concrete containing recycled aggregate exhibited better freeze-thaw durability than did conventional mixtures. (Buck used a chert aggregate, which is highly susceptible to freeze-thaw deterioration, for the control.)

A similar investigation was made by Frondistou-Yannes and Ng (Reference 10) at the Massachusetts Institute of Technology. The authors report the following conclusions:

1. The strength of concrete containing recycled aggregate is between 71 and 100 percent of control; by manipulation of the mix design, the desired strength is obtainable.

2. Standard equipment can be used to produce aggregate from concrete debris.

Malhotra (Reference 11) of the Canada Centre for Mineral and Energy Technology supervised another laboratory study of concrete containing aggregate made from recycled concrete. He found that

1. Satisfactory compressive strength in recycled-aggregate concrete may be obtained by using the proper mix design.
2. Fine aggregate (smaller than No. 100 mesh) should be replaced with natural sand for workability.
3. The durability of concrete containing recycled aggregate is comparable to that of conventional concrete.
4. Additional air entrainment is required when recycled fine aggregates are used.

Christman and Lane (Reference 6) reported results of a Connecticut Department of Transportation (DOT) study of the use of PCC recycling in highway reconstruction. Their conclusions:

1. If the salvaged material meets conventional aggregate specifications, no special procedures are required in the production of PCC.
2. Pavements to be recycled should be tested for chloride content (de-icing salt buildup).
3. After it is crushed, the recycled material should be screened and placed in two or more stockpiles, according to particle size, to prevent segregation within the piles.
4. Recycled-concrete aggregate passed all tests required of normal concrete aggregates (soundness, abrasion, absorption, gradation).

Fergus (References 12 and 13) reported the results of an extensive study of the material properties of recycled PCC, which was conducted in support of

a highway rehabilitation project in Michigan. His conclusions are summarized here:

1. Aggregates produced by crushing existing PCC pavements were equal in quality to conventional aggregates.
2. All PCC mixtures proportioned with coarse recycled PCC aggregate and various ratios of natural sand to recycled PCC fines exceeded minimum design standards.
3. Systematic experiments on pavement cores can provide adequate data for predetermining the properties and mix design requirements of aggregates obtained by recycling any existing PCC material.
4. Experiments indicate that re-recycled PCC exhibits high quality and durability. Thus the potential exists for repeated recycling at any given site.
5. Recycling an existing pavement produces up to 150 percent of the total aggregate volume required for the amount of concrete needed to replace the existing concrete.

With regard to the final conclusion, an example of potential aggregate production from an existing pavement is presented as Appendix A.

The results cited above indicate that if aggregate made from recycled concrete meets the quality requirements established for PCC aggregate, it should be satisfactory for all conventional applications. Uses envisioned are fill, embankment, base, stabilized base, lean concrete or econocrete base, AC, and PCC. The evidence available reflects a need to ensure that the material conforms to the specifications ordinarily used for aggregates.

An attempt was made in the present study to compile the existing data on recycled-aggregate concrete and to study quantitatively the material properties reported in these investigations. The data used were found in the technical literature (References 6, 7, 8, and 11). The objective of the analysis was to determine whether the factors influencing the performance of PCC made with recycled-concrete aggregate were similar to those influencing the performance of conventional concrete.

Data presented by Buck (References 6 and 7) revealed that compressive strength is dependent on the coarse and fine aggregate types. The control mix had the highest compressive strength, all recycled aggregate had the lowest, and a mixture of recycled coarse with natural fine was intermediate. No differences in strength development with time were noted. The analysis also revealed that a significant variable in Buck's work was the test number. Three batches of each type of mixture were prepared, and the discrepancies from batch to batch indicate a significant problem in laboratory control. With normal quality control, the repetition-to-repetition variation should not be significant. Therefore, it was concluded that these data should not be used for further studies of material performance.

In Malhotra's data (Reference 11), the significant variables were the water-cement and the aggregate-cement ratios. These are normal factors involved in concrete strength studies. It can be concluded that the type of aggregate used (recycled or conventional) made no significant difference in the compressive strength obtained.

Data from the Connecticut DOT study (Reference 6) were also reviewed. The variables reported were the same as those measured by Malhotra (Reference 11). Significant variables found in the analysis were air content and aggregate-cement ratio. The water-cement ratio was not varied sufficiently to influence the results; therefore, it was not considered a significant variable in the analysis. The statistical model fits these data very poorly, accounting for only about one-half of the variation in compressive strength ($R^2 = 0.56$).

SPECIFICATIONS

An attempt was made to obtain specifications and standards used by such agencies as the Federal Aviation Administration (FAA), the U.S. Navy, the U.S. Army, and the DOT. Contacts with these agencies, however, disclosed no specifications related to the recycling of PCC pavement. Specifications were obtained from the State of Iowa, the Edens Expressway Project, and the National Cooperative Highway Research Program of the Transportation Research Board. These specifications, which are presented in Appendix B, provide a

guide to the use of recycled concrete in granular embankments, bases, and surface PCC. From this material, a set of specifications for Air Force use in pavement contracts could be developed.

CONCLUSIONS

All of the data found in the literature on concrete containing recycled PCC aggregate indicate that normal compressive strength performance is obtained. The variables that are important in making conventional concrete are also important in making concrete from recycled aggregate. Some durability data were also reported in the literature, but not enough for an analysis. The areas in which a comprehensive investigation remains to be made include durability, tensile strength behavior, and the ratio of flexural (modulus of rupture) to compressive strength. Another significant problem not yet studied is the existence of alkali-reactive aggregates in the existing PCC.

SECTION III CASE STUDIES

INTRODUCTION

The technical literature describes numerous cases in which PCC recycling has been used in construction projects. Many of the cases are not well documented and are therefore of little value in assessing the technology. Some, however, are well documented and provide a basis for evaluating the application of PCC recycling to the rehabilitation of airfield pavements. In this section the most important cases are reviewed in some detail, and an overview of the others is provided.

JACKSONVILLE INTERNATIONAL AIRPORT

Much of the information on the Jacksonville International Airport was reported by Dresser (Reference 14). The airport opened Runway 13-31 in October 1968. The structure was 2347 meters (7700 feet) long by 46 meters (150 feet) wide. The surface was a 280-millimeter (11-inch)-thick layer of PCC on the central 2042 meters (6700 feet) and a 330 millimeter (13 inch)-thick layer on the two 152-meter (500-foot) end sections. A 150-millimeter (6-inch) limerock stabilized base on a compacted silty fine sand supported the surface layer. The 15-meter (50-foot) center keel section of the 280-millimeter (11-inch)-deep PCC suffered distress as indicated by longitudinal and transverse cracking, corner cracking, spalling along the female keyways of the longitudinal joints, and differential subsidence. Pumping was evident at numerous joints. Field and laboratory testing disclosed three specific conditions that had to be addressed:

1. The high moisture content and fluctuating water table level in the base and subgrade.
2. The low bearing capacity of the base.
3. The location of the damage primarily in the central 15 meters (50 feet) of the runway.

Several parameters affected the design and construction of this rehabilitation project. The lack of available land for disposal of the old concrete was a significant problem in Jacksonville. The cost of new aggregate, which had to be shipped 563 kilometers (350 miles), was almost prohibitive.

Through the help of the American Concrete Pavement Association and others, it became apparent that if the runway were to be rebuilt at a reasonable cost, new materials and concepts would have to be used. Many of these materials and concepts were not in accord with FAA specifications and thus had to be documented for the FAA.

Several designs were considered. They included replacing the keel section with a rigid or flexible pavement and strengthening the existing pavement with a flexible or rigid overlay. The selected design was a 355-millimeter (14-inch) PCC pavement, a 150-millimeter (6-inch) econocrete base, and a 150-millimeter (6-inch) coarse recycled aggregate subbase and drainage layer. A fabric was placed between the subbase and the subgrade to prevent infiltration of the fines into the subbase.

Concrete removal commenced with saw-cutting the outside two keyway joints simultaneously. The pavement breaking was done by two Arrow concrete pavement breakers with round, blunt points. Eighty-five percent of the resulting rubble was smaller than 460 by 460 by 280 millimeters (18 by 18 by 11 inches). It took 21 working days and two machines to break up the 31,146 meters² (37,250 yards²) of pavement. The broken pavement was piled and loaded with conventional equipment. About 25 millimeters (1 inch) of base was removed with the concrete.

Approximately 19,500 metric tons (21,500 tons) of old concrete were crushed during the project. The primary crusher was a 1070- by 910-millimeter (42- by 36-inch) jaw crusher. The secondary crusher was a 910-millimeter (36-inch) cone crusher. Some problems were encountered with overcharged screens because of contamination by the base-course material. (In future operations, a grizzly should be used ahead of the primary crusher to remove fines.) The dowel bars were easily removed by hand, and about 80 percent were reusable.

The econocrete design mix for the project is shown in Table 2.

TABLE 2. DESIGN MIX FOR JACKSONVILLE
INTERNATIONAL AIRPORT PROJECT.

Cement:	148 kg/m ³ (250 lb/yd ³)
Water-Cement Ratio:	1.14
Fine Aggregate (100% passing 3/8 in):	884 kg/m ³ (1490 lb/yd ³)
Coarse Aggregate (100% passing 2 in):	841 kg/m ³ (1417 lb/yd ³)
Water:	168 kg/m ³ (284 lb/yd ³)
Water Reducer:	74.5 g/m ³ (2 oz/yd ³)
Slump:	450 mm (1-3/4 in)
28-Day Compressive Strength:	8308 kPa (1205 lb/in ²)
28-Day Flexural Strength:	1400 kPa (203 lb/in ²)

On the basis of the contractor mix designs, it was concluded that the base material mixed with the broken concrete probably contributed to an increase in econocrete strength and eliminated the requirement for an air-detraining agent. The base-course material also provided a mix that was more workable than the laboratory mixes.

The 150-millimeter (6-inch) econocrete base was placed with a Construction Machinery Incorporated Suburban Paver. All materials were mixed in 6.5-meter³ (8.5-yard³) batches at the on-site rotary drum plant and were hauled to the paving train by side dump trucks. The trucks dumped into a spreader that preceded the paver. Joints were struck every 7.6 meters (25 feet) by an aluminum T-bar. The joints were placed in line with the joints in both the existing pavement and the new pavement. The paver was used to finish the econocrete, and an emulsion was used as the curing compound.

The paving train was able to operate on the econocrete 36 hours after the pour. There was no evidence of any cracking of the econocrete except at the struck joints.

The following specific items significantly reduced the cost of the project:

1. The 15-meter (50-foot) keel section replacement in lieu of the traditional 23-meter (75-foot) section reduced not only the quantity of materials consumed but also the amount of labor required to remove the existing pavement. For instance, all saw cuts were made through existing joints instead of through the full depth of the concrete. Dowel bars were installed in the new pavement in such a way that no drilling of the old pavement was required.

2. Approximately 9070 metric tons (10,000 tons) of aggregate were required for the drainage blanket. The price of new aggregate at the time was \$7.77 per metric ton (\$7.05 per ton) FOB the airport. In addition, if the PCC thickness were to be reduced, another 9979 metric tons (11,000 tons) of aggregate would be required for the econocrete. The cost of crushing the removed PCC was estimated prior to the project at \$4.96 per metric ton (\$4.50 per ton), a savings of approximately \$54,825. The actual crushing costs were lower than the estimate, and greater savings were realized.

3. The use of filter fabric to lock the fines into the subgrade and preclude migration into the drainage system became a major emphasis. At the time of the project, the concept of using fabric for this purpose was relatively new and the total benefits were certainly unknown. However, in situ testing indicated that unless some way could be found to eliminate pumping, the pavement would fail again. The use of fabrics could preclude the pumping of fines and thus became a necessary part of the design concept.

The project was bid at a total price of \$1,499,622. Through the joint efforts of the contractor and the engineer, the final construction cost was \$1,418,836, an additional savings of \$80,786. The result was a quality project at an actual cost of \$38.69 per yard² of emplaced drainage system and pavement.

WILL ROGERS WORLD AIRPORT

The information provided here was obtained from several references in the literature (References 15, 16, and 17), as well as from conversations with

representatives of the organizations involved. The existing apron at the Will Rogers Airport, Oklahoma City, built in 1965, consisted of 305 millimeters (12 inches) of PCC mesh dowel pavement and 150 millimeters (6 inches) of lime-treated subbase. The pavement exhibited considerable distress caused by overloading at the gate positions. Because the pavement surrounds the airport terminal, it was necessary to divide the work into a number of phases in order to keep 10 of 12 gates available at all times. Work on this project is still in process.

The new design required a 410-millimeter (16-inch) plain PCC surface and a 200-millimeter (8-inch) cement-treated aggregate base. Options available to the contractors included using a lean concrete base, bituminous concrete, new crushed stone mixed with cement, or recycled material. The low bidder chose the recycling alternative.

A modified Link Belt power diesel pile-driving hammer is being used for pavement breaking. The blows are delivered to a square plate that remains in contact with the pavement and enhances the shattering effects. The breaker is mounted on a motor-grader chassis and towed across the pavement to be broken. No production rates have been reported on this project, but these machines are capable of breaking 2090 meters² (2500 yards²) per day (Reference 4). After the pavement is broken, an excavator equipped with a rhino horn is used to rake the material into piles and break much of the mesh reinforcing. The material is hauled about 1.3 kilometers (0.8 mile), and conventional equipment is used to stockpile it at the crusher.

The crushing plant consists of a primary jaw crusher, an electromagnet to remove the mesh reinforcing, and a secondary crusher to achieve a maximum size of less than 25 millimeters (1 inch). The crushed concrete is stockpiled until it is mixed for the cement-treated base material. The mixing equipment consists of a conventional 6-meter³ (8-yard³) central batch plant. The mix design for the cement-treated base is shown in Table 3.

TABLE 3. DESIGN MIX FOR WILL ROGERS
WORLD AIRPORT PROJECT.

Cement:	96 kg (213 lb)
Water-Cement Ratio:	1.95
Recycled Aggregate:	1630 kg (3594 lb)
Water:	188 kg (415 lb)
7-Day Compressive Strength:	5171 kPa (750 lb/in ²)

The dramatic cost savings on this project has created a great deal of publicity and should enhance the level of interest for all groups involved in airport reconstruction. The designer's original cost estimate was \$11.6 million. The contract was awarded for \$8.2 million, a 30-percent (\$3.4-million) savings for the airport owners. The next low bid, which did not propose recycling, was \$10.9 million. Thus, under the conditions existing at Oklahoma City, a direct head-to-head comparison of recycling versus nonrecycling alternatives reveals that recycling will reduce the cost of the project by \$2.7 million, or about 25 percent. As of this writing, the job is not complete and no final costs are available.

TULSA OKLAHOMA AIRPORT

In late 1981 a contract was let to replace the runway at the Tulsa Oklahoma Airport. Although the contractor has not yet begun work, several aspects of this project are worth noting. The design engineers included recycling the existing pavement as an alternative in the contract. A rock quarry that supplies aggregates is located within 4.8 kilometers (3 miles) of the airport, and as a result of the recycling option available to the contractor, the quarry reduced its aggregate prices significantly. The important point here is that economic factors such as aggregate price may be dramatically influenced by contract options provided to the contractor. These effects can only be estimated in an artificial analysis such as that required in the present study. In the Tulsa case, the paving contractor has decided not to use recycling.

EDENS EXPRESSWAY

Several major highway recycling projects are well documented in the literature. Although recycling highway facilities is quite different from recycling airport facilities from the standpoint of geometry, design considerations, and scheduling, several features of the work are sufficiently similar to make a review valuable. The following description of the Edens Expressway project is taken largely from References 15, 18, and 19.

The Edens Expressway was designed in the 1940s and opened in 1951. The original pavement was 254-millimeter (10-inch)-thick PCC with mesh reinforcement and 30.5-meter (100-foot) joints on a 150-millimeter (6-inch) granular base. A 76-millimeter (3-inch) bituminous concrete overlay was placed over the PCC pavement in 1966. In 1977 the facility was carrying 162 percent of the design traffic volume, and nearly \$750,000 per year was spent on maintenance. The pavement was distressed and required rehabilitation.

The following rehabilitation alternatives were considered: 1) construct a 76-millimeter (3-inch) overlay and patch as required, 2) construct a 127-millimeter (5-inch) structural resurface, 3) construct a continuously reinforced concrete (CRC) overlay, or 4) remove the pavement and replace it with a 254-millimeter (10-inch) CRC pavement. Several factors were considered important in the comparison of alternatives. Disposal areas for dumping materials were not readily available in the urban area. In order to correct for a lack of vertical clearance, inadequate super elevation, and pavement patching, 40 percent of the pavement had to be replaced. A major drainage problem required that the highway be upgraded to meet Federal Highway Administration (FHWA) standards. Traffic control was a major problem, and the contract required very tight schedules. Fourteen interchanges located along the project were permitted to be closed for only nine days. If the final design qualified the job as an FHWA demonstration project, the potential existed for 90-percent Federal funding of the project.

The pavement was broken in place by a variety of types of equipment. Custom-made diesel piledrivers were used for most of this work. The two machines averaged 418.1 meters² (5000 yards²) per day. These hammers

delivered 20,337 joules (15,000 ft-lb) of energy at the pavement surface. The mesh reinforcing was effectively broken. Conventional drophammers were used in low-clearance areas. Although much slower than the piledrivers, these devices worked well in the restricted areas and had no trouble breaking the pavement. Because it was very difficult to break the concrete with its 76-millimeter (3-inch) AC overlay, the overlay was stripped off the underlying PCC and handled separately. In the 1979 portion of the project, the AC was crushed along with the PCC. In the 1980 phase, the AC was used in an asphalt concrete mixture for base and shoulders on the project.

The crushing and screening plant consisted of two primary jaw crushers, 1070 by 1220 millimeters (42 by 48 inches) and 760 by 1070 millimeters (30 by 42 inches), with vibrating grizzly feeders; a secondary plant with a jaw crusher, 380 by 910 millimeters (15 by 36 inches), and a triple roll crusher, 760 by 760 millimeters (36 by 36 inches); two 5-kW, self-cleaning belt magnets on radial stacker belts; and some other belt conveyors and electrical supply equipment. The crushed material was stockpiled in three size fractions: 150 millimeters (6 inches), 75 millimeters (3 inches), and 25 millimeters (1 inch). Each size of material was used in the construction of a specific part of the porous granular embankment.

No data were provided that could be used for economic comparisons or to develop unit-cost data for the project. This particular job involved huge costs for traffic control and surveillance (more than 10 percent of the bid price) that destroy its value as a guide to airfield rehabilitation costs. It is clear, however, that recycling the PCC was advantageous in terms of fuel savings and that it fit the project schedule and provided the flexibility required by this complex job.

MINNESOTA U.S. HIGHWAY 59

Information about the U.S. 59 project was obtained from Reference 20 and from an unpublished Minnesota DOT report.* The Minnesota project was important for several reasons: 1) it was a major task involving 188,363 meters²

*Halverson, A. H., *Recycling Portland Cement Concrete Pavement*, 1981.

(225,280 yards²) of PCC pavement, 2) the pavement was D-cracked because of freeze-thaw failure of the material, and 3) the recycled concrete was used as aggregate for new PCC pavement. Thus, a thorough review of the project was justified.

The work was done on 25.7 kilometers (16 miles) of U.S. 59, between Fulda and Worthington in southwestern Minnesota. The existing pavement had been constructed in 1955 and consisted of a 229-179-229-millimeter (9-7-9-inch)-thick, 7.3-meter- (24-foot)-wide, nonreinforced PCC pavement. The pavement had been placed over an in-place bituminous surface.

The roadway exhibited extensive D-cracking. In Minnesota this form of distress is associated with poor quality aggregates that absorb water and deteriorate through freeze-thaw action. In early 1978 a surface determination was made for the reconstruction of the stretch of highway. Initially, ten alternatives were considered. These were reduced to the following five alternatives for the primary pavement:

1. Break the pavement in place and overlay with 178 millimeters (7 inches) of AC.
2. Construct a 127-millimeter (5-inch) CRC overlay.
3. Construct a 140-millimeter (5.5-inch) plain PCC overlay.
4. Construct a new 203-millimeter (8-inch) plain PCC pavement.
5. Construct a new 356-millimeter (14-inch) AC pavement.

Ten alternatives were obtained by varying the shoulder configuration permitted for items 1, 2, and 3 above between 50-millimeter (2-inch) AC shoulders and full-depth AC shoulders. For alternatives 4 and 5, the coarse aggregates considered were virgin and recycled aggregates. Later, a 267-millimeter (10.5-inch) full-depth AC pavement was also considered. The alternative selected was a 203-millimeter (8-inch) plain recycled concrete pavement. Factors considered important were the aggregate haul distance of 32 kilometers (20 miles) and the FHWA demonstration project support offered for PCC recycling projects.

A laboratory investigation was conducted to study the materials to be used in the project. A 0.9-meter (3-foot) section of the original slab, extending the full width of the roadway, was removed. This material was crushed and used in the trial mixes. Initially, five alternative concrete-mix designs were investigated:

1. Natural coarse and fine aggregates with 20-percent flyash substituted for 15 percent of the cement.
2. All recycled aggregates.
3. Recycled coarse and natural fine aggregate.
4. Recycled coarse and natural fine aggregate with flyash substituted for 10 percent of the cement.
5. Recycled coarse and natural fine aggregate with 20-percent flyash substituted for 15 percent of the cement.

The investigation yielded several significant findings. Estimates of the coarse aggregate available from the crushed pavement indicated that a 40 fine to 60 coarse aggregate ratio could be supplied. The minus No. 200 sieve material in the coarse aggregate was not deleterious; therefore, the coarse material would not have to be washed. Because of the D-cracking problem, only minus 18-millimeter (0.75-inch) coarse aggregate was used. The minus No. 4 sieve material dramatically increased the water demand of the mixes. Consequently, natural fine aggregate was used in the concrete mixtures, and the recycled fine aggregate was employed in base stabilization and shoulder construction. Contrary to previous findings, all strengths were above those of conventional mixes having similar water-cement ratios. Further studies of freeze-thaw durability indicated that a recycled-aggregate concrete in which 20 percent flyash had been substituted for 15 percent of the cement performed best. The mix design for the project and the actual project results are shown in Table 4 (Reference 20).

An elevating scraper and a scarifier on a motor patrol were used to remove the bituminous overlays. The PCC was broken by diesel piledrivers modified for pavement breaking (previously described). An energy of 24,676 joules (18,200 ft-lb) was delivered to the pavement surface. The broken

TABLE 4. RECYCLED CONCRETE MIX DESIGN AND ACTUAL PROJECT RESULTS, MINNESOTA U.S. HIGHWAY 59.

Material	Design, kg/m ³ (lb/yd ³)	Actual, kg/m ³ (lb/yd ³)
Cement	275.9 (465)	275.9 (465)
Flyash	64.7 (109)	64.7 (109)
Water	151.3 (255)	151.3 (255)
Sand (Specific Gravity 2.62)	710.7 (1198)	710.7 (1198)
Recycled Coarse Aggregate	963.0 (1632)	980.6 (1653)

(after Reference 20)

- Notes: 1. Specific gravity was 2.38 for the design mix; actual specific gravity was 2.41.
2. Absorption was 4.5 percent for the design mix; actual absorption was 4.4 percent.

concrete was nominally 0.6 by 0.6 meter (2 by 2 feet). A smaller drophammer was used to break the pavement over the drainage structures on the project. A backhoe with a wider than normal bucket (3 meters³ [4 yards³]) was used to load the broken concrete into trucks for hauling to the crusher site. A solid-bottom bucket was found to pick up too much base material and is not recommended for use on future projects. The broken concrete was stockpiled at the crushing plant.

Conventional loaders were used to charge the 914- by 1219-millimeter (36- by 48-inch) primary jaw crusher. The material was reduced to less than 152 millimeters (6 inches), and the reinforcing steel was removed. The concrete was then screened into two stockpiles, one for minus No. 4 sieve fragments and the other for No. 4 to 19-millimeter (0.75-inch) fragments. The plus-19-millimeter (0.75-inch) material was fed into a 1372-millimeter (54-inch) cone crusher and then rescreened. The stockpiled aggregates were used for PCC batching in a conventional dual drum central batch plant. All other aspects of the paving were conventional.

The Minnesota DOT performed a cost comparison on the project after it had been completed. The results, summarized in Table 5 (Reference 20), indicate cost savings of \$726,000 (about 27 percent of the conventional cost) and conservation of the equivalent of 154,000 liters (41,000 gallons) of gasoline (a savings of about 4.5 percent).

TABLE 5. COST ANALYSIS OF MINNESOTA U.S. HIGHWAY 59 PROJECT.

Factor	Recycling	Conventional	Difference
Concrete Cost, \$	82,239	2,121,158	+2,038,919
Total Cost, \$	1,968,031	2,693,680	+725,649
Energy Consumption ^a			
Materials Production	3,012,969 (796,097)	2,920,268 (771,537)	-92,701 (-24,560)
Materials Transportation	256,294 (67,713)	503,458 (133,015)	+247,164 (+65,302)
Total	3,312,810 (875,247)	3,466,515 (915,856)	+153,705 (+40,609)

(after Reference 20)

^aIn equivalent liters (gallons) of gasoline.

OVERVIEW OF OTHER CASES

A number of PCC recycling cases other than those discussed in the preceding pages are documented in the literature and are included in Table 6 (Reference 21). Some of these cases demonstrate unique aspects of PCC recycling and should be mentioned. The Coffeyville, Kansas, project involved in-place breaking and compaction of an old PCC pavement and an AC overlay (Reference 21). In the project at Love Field, both old pavement and an old concrete building foundation on the airport were crushed and used in a new cement-treated base. The project in Greenville, Texas, involved crushing the old PCC for incorporation into an AC base material. The Redondo Freeway project in California represents the first use of recycled concrete in an econo-concrete base. The French project was unique in that each lane was rehabilitated

TABLE 6. SUMMARY OF PCC RECYCLING CASES.

Site	Year	Pavement Feature	Use of Recycled Material	Remarks
<u>Airports</u>				
Coffeyville, Kansas	[No date given]	Runway	Crushed in place; compacted as base	General aviation facility; excellent condition 1980.
Love Field; Dallas, Texas	1964	Runway; Taxiways	Cement-treated base	Old building foundation used.
ANG Apron	1969	Taxiway; Apron	Cement-treated base	Existing pavement excellent condition 1980.
Gulfport, Mississippi	1977	Runway; Keel Section	Cement-treated base	300 miles to aggregate source.
Jacksonville, Florida	1981	Air Carrier Apron	Cement-treated base	80 miles to aggregate source.
Will Rogers; Oklahoma City, Oklahoma	1981	Apron; Taxiway	Econocrete base	
Jacksonville, Florida	1982	Runway	Cement-treated base	3 miles to aggregate source.
Tulsa, Oklahoma				
<u>Highways</u>				
Greenville, Texas	1972	I-35	Aggregate for AC base	
California	1975	Redondo Freeway	Econocrete base	First use of econocrete.
Lyon County, Iowa	1976	U.S. 75	Cement-treated base	
Paris, France	1976/77	Urban Freeway	Cement-treated base	
Council Bluffs, Iowa	1977	I-80	Econocrete; PCC shoulders	
Iowa	1977/78	S.H. No. 2	Aggregate for PCC	
Chicago, Illinois	1979	Edens Expressway I-94	Aggregate fill and base	
Minnesota	1980	U.S. 59	Aggregate for PCC	D-cracked pavement.
Connecticut	1980	I-95	Aggregate for PCC	De-icing salt buildup.
Michigan	1981	I-96	Aggregate for PCC	Recycling recycled-aggregate concrete feasible.

(after Reference 21)

in a different manner. The inside lane received joint sealing, joint and slab replacement was used on the middle lane, and the outside lane was recycled and used in an econocrete base and as aggregate shoulders.

The cases reported in the literature reveal that recycling has been included in many pavement projects. Urban recycling has become a common practice in many areas, among them Chicago; Detroit; New York; Washington, D.C.; Los Angeles; New Orleans; Savannah, Georgia; Pontiac, Michigan; and Minneapolis, Minnesota (Reference 22). Many people involved in recycling do not consider the process unique and therefore do not bother with careful documentation. It would appear that the contractors will use whatever technique provides the best payback on a particular job. If a technique does not pay, contractors will not use it. Section IV of this report addresses factors to be considered in making these decisions.

SUMMARY

On the basis of the literature review and case analysis, the following conclusions have been drawn:

1. Existing PCC pavements may be recycled by breaking and crushing the material into aggregate, which may be used in any fashion in which virgin aggregate is used. Extensive field demonstrations have shown that the recycled material may be used for aggregate base, stabilized base, econocrete base, and new PCC pavement.
2. The aggregate specifications used are generally the same as those for virgin material. There appears to be no need to restrict the use of recycled material if it meets conventional aggregate specifications. However, some variance in mix design may be required.
3. Economic analysis at a specific site is extremely complex, as explained in a subsequent section. The following factors dramatically influence the costs and cannot be quantified in an artificial analysis:
 - a. The contractor's specific mix of equipment models, makes, capacities, etc.
 - b. Availability of the equipment; in other words, how much other work the contractor is involved in at a particular time.

- c. Options available to the contractor and their influence on suppliers of aggregate, cement, and other materials.
- d. Scheduling requirements imposed by the owner or operator in terms of facility down-time, availability, and schedules.
- e. Cost of disposing of the old concrete.

Assumptions must be made about these factors before an economic analysis can be performed.

4. In any PCC pavement rehabilitation project, recycling may clearly be cost-effective and should be offered as an option in virtually all contracts.

5. Stockpiling of PCC pavement or other salvageable material would enhance the cost-effectiveness of recycling if it were done on a routine basis prior to rehabilitation work. The time during which a pavement would be closed to users would thus be reduced because material would be available at any time for crushing and for use in trial mixes to assess the proper proportions and strength characteristics. It is recommended that all PCC removed during maintenance operations be treated as a valuable resource and stockpiled routinely. It is recognized that such a procedure presents some problems; nevertheless, the practice is justified.

SECTION IV

COST-BENEFIT COMPARISONS

INTRODUCTION

The prices incorporated into contractors' bids are determined by means of a process that varies with the individual contractor. Certain aspects of the process are common and probably account for the similarity frequently found in bids submitted by various contractors. These aspects include the cost of fuel, materials, equipment operation, and labor. In contrast, other factors may account for substantial variances in bids. Such items include mobilization costs, profit margin, risk factors, and equipment inventory and availability. While these factors may account for differences in contractor bids, other considerations will produce a difference between bids and artificial analyses like that required in the present study. The environment in which construction materials are produced and sold comprises a marketplace. Prices in that marketplace are governed by supply and demand. The existence of an airfield construction contract will dramatically influence the balance and therefore the prices in such a marketplace. The point is that prevailing prices at any given time may not reflect accurately the prices that would be in effect for an airfield construction job at the site under consideration.

FACTORS INVOLVED IN ECONOMIC ANALYSIS

Several key elements that determine the attractiveness of PCC recycling on any specific job are discussed here. An attempt is also made to analyze three specific jobs. It is realized there may be differences between the real world costs and the costs used here.

In the economic evaluation of pavement projects, the primary factor that affects PCC recycling is the availability of new aggregate. In most of the cases reviewed, it was indicated that the availability of cheap new aggregate reduces the value of PCC recycling as an alternative. Long haul distances, however, usually sway the economic factors toward recycling. In order to

justify recycling, the cost of new aggregate delivered to the site, plus the cost of disposing of the old concrete, must be more than the cost of crushing the recycled PCC. Crushing costs include transportation, staging, and set-up costs, as well as operating expenses.

Aggregate quality greatly influences the selection of the procedure to be used. If the existing aggregate sources are of marginal quality, the recycling of an existing pavement may be more attractive. Conversely, if the existing pavement is badly deteriorated because of an alkali-aggregate reaction or some other deleterious circumstance, the use of new aggregate may be economically more advantageous. The quality of aggregate to be used may also be determined by the intended end use of the recycled PCC and the nature of the specifications for that material. Performance-oriented specifications encourage the contractor to use high-quality materials. The use of recycled materials as base or stabilized base reduces the level of concern about the quality of the aggregate.

Disposal of the displaced pavement is an important factor, particularly in urban areas. Dump fees combined with long haul distances to the dump site could make the conventional pavement replacement method very costly. In many cases the dump fees are not borne by the contractor because the contracting authority provides a dump site. In such cases the costs involved are those related to removal, hauling, and such dump site expenses as the cost of burying the material. The size of material that a particular dump site will accept also affects the costs of breaking and removal.

Crushing costs are another factor in the economic analysis. Concrete crushing is a hard rock application and therefore requires a jaw crusher for primary and roll or cone crushers for secondary crushing. The crushing plant must be portable in order to minimize haul distances. Also required are screening decks, feeders, conveyors, and stacking conveyors. Electromagnets for extracting reinforcing steel may or may not be required. Equipment specifically suited to this application is available in the United States. Estimates obtained during this study indicate that the 1981 cost of this type of plant is more than \$1 million.

Another cost related to crushing is the expense of moving the equipment, setting up, and staging. In the case of a contractor who is involved in more than one construction job, the availability of the equipment must also be considered.

The ease with which concrete may be crushed depends in part on the nature and amount of reinforcing steel it contains. Many airfield pavements contain little or no reinforcing and thus are relatively easy to break, remove, and crush. Crushing heavily reinforced pavements is more costly.

At civilian airports the construction work is usually subject to tight scheduling so that a satisfactory level of air carrier operations can be maintained. Stiff penalties for failure to meet schedules are usually included in the contracts. Recycling alternatives are more sensitive than conventional alternatives to scheduling because of the need to close an area to users in order to remove and crush the existing material before the production and placing of new pavement can begin. Tight scheduling may reduce the attractiveness of the recycling alternative.

The factors outlined above are considered the most important in evaluating the economic attractiveness of recycling PCC pavements. Others also have an influence, although they are considered of secondary importance: availability of space to set up crushing operations, differences between the cement requirements for conventional and recycled-aggregate concrete, experience of the contractors involved, and contract specifications for the performance of the recycled material.

The economic factors related to recycling PCC pavements are shown in Table 7. The high and low cost estimates were developed by examining a number of jobs. It is recognized that significant variations may occur in any specific contract. However, these values are considered reasonable for the purposes of this study.

TABLE 7. ECONOMIC FACTORS CONSIDERED IN COMPARING ALTERNATIVES.

	Minimum	Maximum
<u>Recycling:</u>		
Crusher Mobilization/Demobilization (M), \$	15,000	30,000
Crusher Operation (O), \$/h	350	500
Production Rates (P), metric ton/h (ton/hr)	136 (150)	272 (250)
Proportion of Coarse Aggregate, P_c	0.5	0.7
Proportion of New Fine Aggregate, P_n	0.6	0.8
Distance to Crusher (DC), km (mi)	0.18 (0.5)	8.0 (5.0)
<u>Conventional:</u>		
New Aggregate at Source:		
1 inch to No. 4 (CA), \$/metric ton (\$/ton)	2.80 (2.50)	8.00 (7.25)
Fine Aggregate (FA), \$/metric ton (\$/ton)	1.10 (1.00)	5.80 (5.25)
Disposal Costs (DP), \$/metric ton (\$/ton)	1.10 (1.00)	6.60 (6.00)
Amount of Waste Concrete, metric tons (tons)	9,070 (10,000)	43,350 (50,000)
Distance to Disposal Site (DD), km (mi)	4.8 (3.0)	32 (20)
<u>Other Factors:</u>		
Amount of Concrete Required (R), metric tons (tons)	9,070 (10,000)	90,700 (100,000)
Hauling Costs (H), \$/metric ton-km (\$/ton-mi)	0.0685 (0.10)	0.1370 (0.20)
Hauling Distance (DS), km (mi)	8 (5)	120 (75)

COST MODELS

A model for comparing the cost of recycled aggregate with that of conventional material was formulated. The model consists of two equations that express the cost of aggregates if recycling is used (C_r) and the cost if new materials are obtained (C_c).

$$C_r = A \left\{ \left[P_c - P_r P_f \right] \left[\frac{O}{P} + (DC \cdot H) \right] + P_n P_f \left[FA + (DS \cdot H) \right] \right\} + M$$

$$C_c = A \left\{ P_c \left[CA + (DS \cdot H) \right] + P_f \left[FA + (DS \cdot H) \right] \right\} + W \left[DP + (DD \cdot H) \right]$$

The symbols are those used in Table 7 and a few others defined as follows:

A = amount of aggregate required, metric tons (tons)

P_f = proportion of fine aggregate = $(1 - P_c)$

P_r = proportion of fine aggregate obtained from recycling
 $= (1 - P_n)$

W = amount of waste concrete produced, based on the total amount of aggregate required

The following assumptions were made in developing these two equations:

1. The cost of the additional cement in a recycled mixture is offset by the value of the additional aggregate produced and the value of the reinforcement salvaged from the existing pavement.
2. Once the materials are stockpiled, concrete production costs are unaltered by the type of aggregate used.
3. No significant amount of waste concrete will be produced if the existing concrete is recycled.
4. Breaking and removal costs are assumed equal for both methods.

In Figure 3, recycling and conventional material supply at various haul distances for two different required amounts are compared. The data generated are shown in Table 8. The models can be used to evaluate relative costs and sensitivity to the variables of interest.

The cost models were applied to data obtained for some actual jobs, identified here as cases 1 through 3. The data are presented in Table 9.

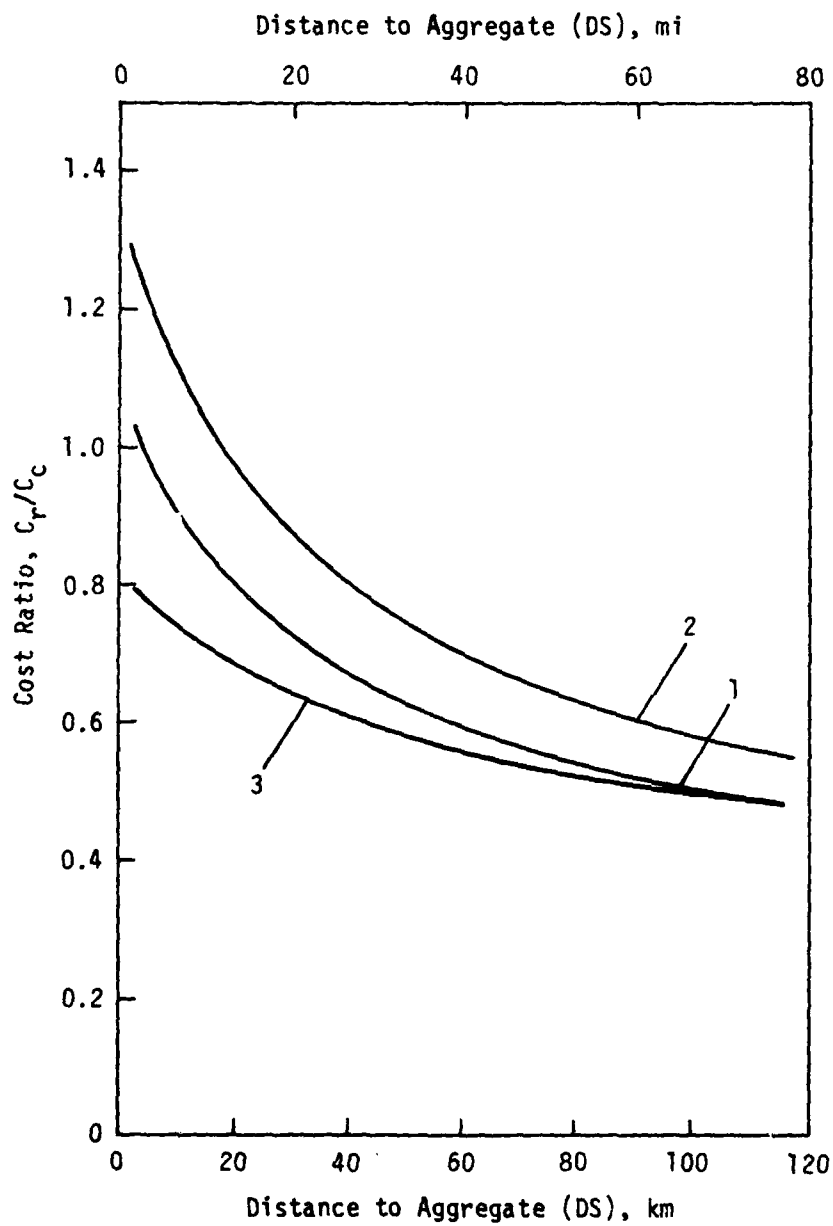


Figure 3. Cost Ratio for Various Distances for Examples Shown in Table 8.

TABLE 8. COST RATIO FOR VARIOUS HAUL DISTANCES.

DS, km (mi)	Cost Ratios (C_r/C_c)		
	Example 1	Example 2	Example 3
1.6 (1)	1.03	1.29	0.79
8.0 (5)	0.93	1.16	0.75
16.1 (10)	0.84	1.03	0.71
32.2 (20)	0.72	0.87	0.64
80.5 (50)	0.55	0.64	0.53

Note: The following values are held constant:

$M = \$30,000$
 $O = \$500/h$
 $P = 136 \text{ metric ton/h (150 ton/h)}$
 $DC = 1.6 \text{ km (1 mi)}$
 $H = \$0.103/\text{metric ton-km } (\$0.15/\text{ton-mi})$
 $Df = 0$
 $DD = 12.9 \text{ km (8 mi)}$
 $CA = \$3.18 \text{ metric ton } (\$3.50/\text{ton})$
 $FA = \$1.36 \text{ metric ton } (\$1.50/\text{ton})$
 $P_c = 0.6$
 $P_n^c = 0.75$

Case 1: $A = 27,216 \text{ metric tons (30,000 tons)}$
 Case 2: $A = 13,608 \text{ metric tons (15,000 tons)}$
 Case 3: $A = \text{same as 2; } DP = \$3.30/\text{metric ton } (\$3.00/\text{ton})$

TABLE 9. COST DATA FOR CASES REVIEWED

Variable	Case 1	Case 2	Case 3
A, metric tons (tons)	38,646 (42,600)	27,125 (29,900)	58,060 (64,000)
M, \$	30,000	25,000	30,000
O, \$/h	400	450	400
P, metric ton/h (ton/h)	181 (200)	136 (150)	181 (200)
DC, km (mi)	0.8 (0.5)	0.8 (0.5)	1.6 (1.0)
FA, \$/metric ton (\$/ton)	1.65 (1.50)	1.65 (1.50)	1.65 (1.50)
H_r , \$/metric ton-km (\$/ton-mi)	0.103 (0.15)	0.103 (0.15)	0.137 (0.20)
DS, km (mi)	129 (80)	24 (15)	4.8 (3)
DP, ^a \$/metric ton (\$/ton)	0 ---	0 (0) 1.1 (1)	1.1 (1) ---
W, metric tons (tons)	0.8 A	0.8 A	0.8 A
DD, km (mi)	6.4 (4)	3.2 (2)	16.1 (10)
CA, ^b \$/metric ton (\$/ton)	3.86 (3.50) ---	3.86 (3.50) ---	3.86 (3.50) 2.76 (2.50)
H_c , \$/metric ton-km (\$/ton-mi)	0.069 (0.10)	0.069 (0.10)	0.069 (0.10)
Results:	Case 1	Case 2	Case 3
$P_c = 0.6$	for all cases	for DP = 0	for CA = 3.86 (3.50)
$P_n = 0.75$			
C_r			
C_c	\$215,736	\$120,979	\$169,520
C_r/C_c	\$469,452	\$130,364	\$294,400
	0.46	0.93	0.58
		for DP = 1.1 (1)	for CA = 2.76 (2.50)
C_r		\$120,979	\$169,520
C_c		\$154,284	\$168,960
C_r/C_c		0.78	1.00

^aFor case 2, two values of DP were evaluated.^bFor case 3, two values of CA were evaluated.

The cost models indicate that recycling offers advantages in the first case. Note the long haul distance in case 1. The real-world job resulted in the use of recycling in this case. The model calculations for case 2 show almost an equal cost for both methods. This case featured a lower total requirement for materials. It also involved an area where contractors were not familiar with recycling and an existing pavement that exhibited evidence of alkali-reactive aggregates. The result was the use of new materials. The waste concrete was dumped into a landfill provided by the contracting authority. Notice the influence of a \$1.1/metric ton (\$1.00/ton) dump fee on the ratio. In this case it is doubtful that the contractor would have used recycling anyway. Case 3 involves a relatively large job, a very short haul distance, and some penalty for dumping waste concrete. A decision not to recycle was made because of very tight time limits and high penalties for delays.

The models used are capable of providing reasonable indications of the economic advantage of recycling a PCC pavement. It is essential that some work be done to establish costs of individual items. However, other factors often exert a determining influence on the outcome. These factors are usually not the type that can be included in a cost model of the sort presented here.

SUMMARY

Cost factors that influence the decision whether to provide aggregate by recycling existing PCC or by purchasing new aggregate were identified. On the basis of those factors responsible for the difference between the two methods, cost models were used to evaluate comparative costs. The evaluation of data from three actual sites indicates that haul distance and aggregate price are critical factors in cost comparisons. Such factors as aggregate quality, scheduling, and contractor experience are very important, but they cannot be included in the cost models.

The cases studied indicate that contractors make the best economic decisions under prevailing conditions. If the Air Force finds it desirable to

develop recycling experience or to conserve resources, it will probably have to require recycling. Each job involving the rehabilitation of PCC pavement should be carefully evaluated to determine how Air Force pavement needs may be best served. It is clear that without some field experience, most contractors do not select recycling. Therefore, it is reasonable to expect that required recycling will prove to be the best way to get the technology started.

SECTION V TECHNOLOGICAL DEFICIENCIES

EQUIPMENT

Breaking and Removal

The tasks required in PCC recycling are illustrated in Figure 2. Specific equipment is used for each task. Some of the equipment used on the projects examined in the course of this study reflect significant developmental work by contractors. This is particularly true for the tasks of breaking and removal. Conventional equipment does not produce acceptable results in terms of size, separation of concrete and steel, or rate of production. Special diesel-powered pile-driving hammers have become the most satisfactory devices for breaking the existing PCC pavement. For lightly reinforced pavements, this specialized equipment is not required. A second specialized piece of equipment is a large tooth, called a rhino horn, used for raking the concrete into a pile and breaking up the reinforcing material to simplify the task of loading the broken pavement. These tools, however, were developed for reinforced highway pavements and may offer no clear advantage in airfield pavement work.

Case studies indicate that breaking and removal remain substantial tasks. Innovations that could simplify these tasks would therefore improve the cost-benefit ratio for PCC recycling. One contractor is currently attempting to develop a technique for lifting, breaking, and loading the existing pavement in a single, continuous operation.* This particular work is proprietary, and no details are available for publication. Research should be done on how concrete may be most efficiently broken. In the course of the literature review, no technique with a production rate competitive with that of the diesel piledriver was identified. The investigation of rapid concrete breaking is an area requiring a study of fundamental fracture mechanisms in PCC pavement.

*Conversation with Deems Pfaff, Pfaff Construction Company, Apple Valley, Minnesota, September 28, 1981.

It is concluded that technological innovations in concrete breaking could result in a substantial change in the cost-benefit ratio of PCC recycling. Such innovations appear to be dependent on equipment development and on a better understanding of the fundamental fracture mechanisms in PCC.

Loading and Hauling

Conventional loading equipment was employed on most jobs documented in the technical literature. It has been recommended that open-bottom loading buckets be used to reduce the amount of fine material that is mixed with the broken PCC. Similarly, conventional dump trucks have traditionally been used for hauling. Contractors recommend lining dump bodies with wood or rubber materials to reduce damage and noise.

The most significant improvement that could be made in loading and hauling would be to completely eliminate them from the recycling process and to crush the material on site. At present, the crushing plant is set up at a given site, and the material to be processed is delivered to the plant. It would be feasible to assemble a crushing plant that would be capable of traveling along the existing pavement alignment, picking up the broken PCC, and crushing and discharging the material. This approach could be applied most effectively to a mixed-in-place base.

Another way to eliminate loading and hauling would be to move the material to the plant on a conveyor system. In the case of airfields, the distances involved would be reasonable for such a concept. However, it should be pointed out that while all paving contractors have loaders and dump trucks, few own several miles of conveyors. Clearly the contractors will ultimately decide on the equipment to be used for any particular job.

Although there are opportunities for equipment development and innovation, these activities are not considered appropriate research areas for AFESC. Therefore, technological improvements in the equipment used for recycling PCC were not considered further.

MATERIAL PROPERTIES

In all cases in which PCC recycling has been used on airfield pavements, the recycled material has been used as unbound or stabilized base. Recycled PCC has not been used as aggregate in new PCC because of a lack of experience, and a resulting lack of confidence, in designing the concrete mixture. On three recent major highway projects, the existing pavement was recycled as aggregate for the new PCC pavement. Each project involved support in the form of laboratory testing that provided data on which concrete pavement mix designs could be based. Until the use of recycling has been demonstrated in more major projects, designers will not understand the material properties well enough to provide proper designs. It is assumed that greater cost-benefit advantages would be realized if the recycled material were incorporated in new PCC rather than in the base layers. Therefore, the development of methods to evaluate an existing pavement for use as aggregate in new PCC pavement is needed.

The use of concrete deteriorated by freeze-thaw damage or the presence of alkali-reactive aggregates has been discouraged. However, when such aggregates are used as virgin materials, procedures exist for reducing the deterioration. For example, freeze-thaw-susceptible materials perform better if the maximum size is reduced, and alkali-reactive aggregates cause less trouble when flyash is used as part of the cement. The concrete technology literature offers alternatives that should be evaluated so that the most cost-effective design may be obtained. A comprehensive mix design evaluation of the existing PCC should be made. Admixtures used for various purposes in PCC mixtures should be evaluated for any advantages they may offer to mixes made with recycled aggregates.

CONTRACTING AND SPECIFICATIONS

The lack of contract alternatives that permit the recycling of existing pavement is a serious technological deficiency. Material specifications should be performance-based, and no special consideration should be given to recycled aggregate materials. Existing specifications for concrete, cement-treated base, econocrete base, and granular base are satisfactory for routine use when these materials contain aggregate made from old concrete.

SUMMARY

The recycling of existing PCC involves little new technology. It is instead a slightly different way of performing tasks that have been a part of pavement work for many years. Two areas are open for improvements that may impact the application of recycling to airfield pavements. First, equipment development may reduce the cost of specific tasks. Second, thorough and efficient procedures should be developed for evaluating existing pavements and designing mixtures for recycling them in new pavements. While the first of these is not within the areas normally investigated by AFESC, the second does seem an appropriate topic for further research. The required work is more fully described in Section VI and Appendix C.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Recycled PCC can be used in new pavement construction as aggregate for base or new PCC pavement.
2. Evidence of deterioration in the existing concrete is not sufficient reason to negate the use of recycling. Proper mix designs will provide satisfactory new concrete produced from old concrete exhibiting either freeze-thaw deterioration or alkali reactivity.
3. Technological advances in the equipment used to break and remove existing PCC and the development of crushing equipment for on-site use could improve the cost-effectiveness of PCC recycling.
4. The development of procedures for designing mixes and evaluating their performance through laboratory testing should be the subject of research in the near future.

RECOMMENDATIONS

1. Incorporate PCC recycling as a requirement on an airfield pavement construction project in order to gain experience and develop the technology.
2. Investigate the feasibility of stockpiling old PCC on Air Force bases for subsequent use as aggregate material in pavement construction.
3. Develop procedures for evaluating existing materials in the course of designing concrete mixtures and for designing mixtures in such a way as to mitigate freeze-thaw susceptibility and alkali reactivity.
4. On all jobs involving recycling PCC as an alternative, compile a data base in order to identify specific conditions important to the contractor's decision about recycling. Data on the economic factors identified in this report should be obtained and evaluated.

Research areas recommended for consideration are discussed in Appendix C.

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APPENDIX A ESTIMATED AGGREGATE PRODUCTION FROM AN EXISTING PAVEMENT

The following example is presented to illustrate the potential aggregate production from an existing pavement.

EXISTING PAVEMENT

Length: 3048 m (10,000 ft)
Width: 46 m (150 ft)
Thickness: 0.41 m (1.33 ft)
Volume: 57,000 m³ (2 x 10⁶ ft³)
Density: 2323 kg/m³ (145 lb/ft³)
Weight: 1.32 x 10⁵ metric tons (1.45 x 10⁵ tons)
Material Losses: Loading/Hauling--5 percent
Crushing--10 percent
Material Produced: 1.12 x 10⁵ metric tons (1.24 x 10⁵ tons)

AGGREGATE REQUIRED FOR CONCRETE REPLACEMENT

Concrete Required: Volume: 57,000 m³ (2 x 10⁶ ft³)
Weight: 1.32 x 10⁵ metric tons (1.45 x 10⁵ tons)

Recycled Aggregate to be used, percent by weight	Aggregate Required, metric tons (tons)	Recycled Aggregate available, percent by weight
80	1.05 x 10 ⁵ (1.16 x 10 ⁵)	106
70	9.22 x 10 ⁴ (1.02 x 10 ⁵)	121
60	7.90 x 10 ⁴ (8.70 x 10 ⁴)	141

APPENDIX B
PCC RECYCLING SPECIFICATIONS

IOWA PCC RECYCLING SPECIFICATION*

1.0 Description.

Recycled concrete pavement shall consist of Portland Cement Concrete (PCC) of the type and class specified in the contract. Aggregate used for the concrete will be recycled Portland Cement Concrete which has been crushed and sized. Additional fine aggregate may be added to the mixture, if needed, to provide the desired consistency and workability.

2.0 Types of Pavement.

2.1 Plain jointed pavement -- refers to Portland Cement Concrete Pavement with joints at a prescribed spacing, but without any reinforcing bars, except tie bars at longitudinal joints.

2.2 Reinforced jointed pavement -- refers to a jointed Portland Cement Concrete pavement constructed with reinforcing steel that has been inserted to control crack width.

2.3 CRCP -- refers to Portland Cement Concrete Pavement that has been constructed without joints and is heavily reinforced.

2.4 Prestressed concrete pavement -- refers to Portland Cement Concrete Pavement that has been post-tensioned or prestressed, and may or may not contain reinforcement.

3.0 Methods of Placement.

The recycled concrete pavement may be placed in the conventional form method or by slip-forming. The construction requirements for each of these methods of placement are as detailed in the specifications for concrete pavement. Irregularly shaped areas of either type of pavement may be formed and finished by hand methods. Reinforced bridge sections should be placed in accordance with the details and limits shown on the plans.

*The material presented here is taken directly from Huisman, Charles L., and Britson, Ralph A., "Recycled Portland Cement Concrete 'Specifications and Quality Control,'" in *National Seminar on PCC Pavement Recycling and Rehabilitation*, Transportation Research Board, Washington, D.C., September 27-30, 1981, pp. 137-140.

4.0 Materials.

All materials used in the pavement shall meet the requirements of AASHTO Standard Specifications, except the aggregate derived from crushing the existing pavement. The existing concrete pavement which is to be crushed and used as an aggregate in the new pavement must be thoroughly evaluated by the Contracting Authority to determine if it is suitable for its intended use. Type I Portland Cement shall be used unless otherwise stipulated in the contract documents.

5.0 Removal of Old Pavement.

All Portland Cement Concrete Pavement, as identified on the plans, is to be removed and salvaged as described herein, unless specifically excluded by the plans.

5.1 The existing Portland Cement Concrete shall be fractured on location with mechanical breakers having the capacity to fracture the pavement into pieces with the largest dimension not to exceed approximately 18 inches. With CRCP and joint reinforced concrete pavement, more aggressive breakage is desirable in order that crushing productivity is maintained and removal of embedded reinforcing steel is facilitated. The broken material shall be removed and transported to the mixing site using conventional procedures and equipment as approved by the Engineer.

5.2 Where asphaltic concrete resurfacing is present, the asphaltic concrete shall be removed before the Portland Cement Concrete is removed. The asphaltic concrete to be removed may be buried in the fill or stockpiled and salvaged for other uses as directed by the Contracting Authority.

5.3 It is intended that all of the asphaltic concrete be removed. However, isolated areas of adhering asphaltic concrete up to one inch in thickness will be considered acceptable.

5.4 During removal of the existing Portland Cement Concrete Pavement, care must be taken to assure minimum contamination of the salvaged concrete with underlying subbase material or the soil.

6.0 Crushing and Stockpiling.

The salvaged pavement shall be crushed and stockpiled at the site designated on the plans.

6.1 The salvaged product is to be crushed to maximum size, approximately one and one-half inch.

6.2 The crushed material shall be separated by screening over a 3/8-inch screen and the two products stockpiled separately in order to minimize segregation.

6.3 Stockpiling shall be done in accordance with the standard stockpiling specifications or as designated by the Engineer. Processing equipment shall include a means by which excessive fines can be controlled, so that the maximum material passing the No. 200 sieve in the total product does not exceed 5 percent.

6.4 Washing the finished product is not considered necessary; however, certain weather and site conditions during removal or crushing may necessitate washing.

6.5 Reinforcing steel, if any, removed from the existing pavement shall become the property of the Contractor and shall be disposed of off the project.

7.0 Mix Proportions.

The objective of the mix design is to utilize the crushed concrete in such a way as to obtain a satisfactory Portland Cement Concrete Pavement.

7.1 Crushed concrete in the processed form may be suitable for use without the addition of virgin aggregates; however, finishing and workability will generally be enhanced by adding natural fine aggregate in amounts of approximately 25 percent.

7.2 Addition of natural coarse aggregate is not considered necessary unless there is a need for it to improve workability or because of quantity shortages.

7.3 Trial mixes shall be made using the crushed concrete as aggregate, and test specimens will be made for evaluating the mixture. Crushed concrete for trial mixes will generally have to be laboratory produced. This is to be done prior to preparing the mix design specification. Samples of the pavement to be recycled should be obtained and sufficient quantities crushed to make the necessary trial mixes and test specimens for proper evaluation.

7.4 Normal procedure is to proportion the mix so that coarse and fine crushed concrete may be consumed in the same ratio that they are produced; however, it may be necessary to add a sufficient amount of natural fine aggregate to produce acceptable workability.

7.5 The minimum cement factor will be determined by the level of strength desired and will normally be similar to that required for conventional concrete pavement mixtures.

8.0 Specific Gravity.

Mix design shall be by absolute volume, which requires that the specific gravity of the materials used be determined.

9.0 Water and Consistency.

The quantity of mixing water used shall be that which will produce acceptable workability and uniform consistency.

9.1 Except as specifically modified by the Engineer, the slump, measured in accordance with AASHTO T-117, shall not be less than 1/2 inch or more than 3 inches for machine finished fixed-form pavement, 2 inches for machine finished slip-form pavement, or 4 inches for hand-finished pavement.

9.2 If it is found impossible to produce concrete having the required consistency without exceeding the maximum allowable water-cement ratio specified, the cement content shall be increased as directed by the Engineer so that the maximum water-cement ratio will not be exceeded.

9.3 The design water-cement ratio shall be determined in the laboratory using the materials which are to be used in the project.

10.0 Entrained Air.

Air entrainment shall be accomplished by the addition of an approved air-entraining admixture.

10.1 The intended air content of the finished concrete is 6.5 percent with a maximum variation of ± 1.5 percent.

10.2 If it is determined in the laboratory that the air in the crushed concrete may contain entrained air which would register on the plastic air meter, it may be necessary to use higher than normal air in order to be certain that the new mortar has sufficient air.

11.0 Durability.

Freeze-thaw durability of recycled concrete should be evaluated in accordance with ASTM C-666, Method B, modified to provide a 90-day moist cure period. Other tests which would provide equivalent durability information may be used. Durability factors from ASTM C-666, Method B, as modified herein, are considered acceptable if they are 80 or above.

12.0 Admixtures.

When authorized by the Engineer, the same admixtures used in conventional Portland Cement Concrete shall be used in recycled concrete. An approved water-reducing admixture shall be required.

13.0 Equipment General.

The Contractor shall provide sufficient equipment to perform all operations necessary to complete the work. Equipment shall meet the requirements of the Contracting Authority.

14.0 Proportioning and Mixing Equipment.

Equipment and operation of equipment for proportioning and mixing concrete materials shall comply with the requirements of the Contracting Authority.

15.0 Finishing.

Finishing of concrete pavement shall be in compliance with the Contracting Authority's requirements.

16.0 Curing and Protection of Pavement.

After finishing operations have been completed, the pavement shall be cured and protected in accordance with the requirements of the Contracting Authority. The curing and protection operations shall be the same as those required for conventional Portland Cement Concrete Pavement.

17.0 Pavement Joints.

Location, spacing, and design of contraction, expansion, and longitudinal joints shall comply with the Contracting Authority's requirements for the installation of such joints.

18.0 Filling Joints.

Unless otherwise provided, before any portion of the pavement is opened to the Contractor's forces or to the general traffic, expansion, longitudinal, and transverse joints shall be filled with the appropriate joint filler material as approved by the Contracting Authority.

19.0 Measurement and Payment.

19.1 Breaking, removal, and hauling--when the contract provides for removal of old pavement and hauling to a designated area for crushing, the area of pavement removed will be computed in square yards from measurement of the width from edge to edge, or back of curb, if any, and the lineal distance on the pavement surface along the roadbed. Payment for this item will be at the contract price per square yard. Disposal of reinforcing steel, if any, shall be considered incidental to removal of the old pavement and will not be measured or paid for separately.

19.2 Crushing and stockpiling -- the quantity of material going through the crushing plant and into the finished stockpile shall be paid for at the contract price per ton.

19.3. Natural fine aggregate -- if natural sand is used as an additive in the concrete, the actual quantity of this material used, measured in tons, shall be paid for at the contract price per ton.

19.4 Placing Recycled Portland Cement Concrete Pavement -- the total quantity of Portland Cement Concrete Pavement placed, measured in square yards, shall be paid for at the price per square yard and in accordance with the Contracting Authority's normal practice of making payment for Portland Cement Concrete Pavement in-place.

EDENS EXPRESSWAY PROJECT SPECIFICATION*

Porous Granular Embankment. This item shall consist of furnishing, transporting, and placing porous granular material. This material is intended to be used only as a bridging layer over soft and unstable areas of noncohesive soil and for placement under water. It is also intended for cohesive soil areas too wet to modify with lime as determined by the Engineer.

Lime modification, as specified elsewhere in these Special Provisions, shall be used to stabilize all the remaining areas of unstable soil conditions. Porous Granular Embankment material shall be of a reasonable uniform gradation from coarse to fine and shall conform to Article 704.07 and the applicable portions of Section 209 of the Standard Specifications with the following modifications.

1. For depths of undercut 6 inches or less, use capping aggregate CA-6.
2. For depths greater than 6 inches, use the following gradation except for the top 3 inches, which shall be Capping Aggregate.
 - a. Crushed stone, crushed blast furnace slag, and crushed P.C. concrete.

<u>Sieve Size</u>	<u>Percent Passing</u>
3"	90 ± 10
2"	40 ± 25
#200	5 ± 5

- a. For undercuts greater than 16 inches this sieve size may be increased to 6 inches.

*The material presented here is taken directly from Dierkes, John J., Jr., "Urban Recycling of Portland Cement Concrete Pavement, Edens Expressway, Chicago, Illinois," in *National Seminar on PCC Pavement Recycling and Rehabilitation*, Transportation Research Board, Washington, D.C., September 27-30, 1981, pp. 169-172.

- b. Gravel, crushed gravel, and pit run gravel.

<u>Sieve Size</u>	<u>Percent Passing</u>
3"	90 ± 10
2"	60 ± 25
#4	40 ± 20
#200	5 ± 5

- a. For undercuts greater than 16 inches this sieve size may be increased to 6 inches.

- c. Reclaimed bituminous concrete.

<u>Sieve Size</u>	<u>Percent Passing</u>
3"	90 ± 10
#200	5 ± 5

It is intended that this granular material be placed in one-foot lifts or as directed by the Engineer. The depth of undercut shall be as directed by the Engineer. Rolling the top of the replacement material with a minimum 350 PLI (pounds per lineal inch) total applied force vibratory roller or equivalent, as approved and directed by the Engineer, should be sufficient to obtain the desired keying or interlock and necessary compaction of the coarse aggregate. The Engineer will visually determine that adequate keying has been obtained. To aid in fine grading this coarse aggregate, three inches of Capping Aggregate will be utilized as the last lift in meeting the recommended thickness of Porous Granular Embankment.

Capping Aggregate. The aggregate to perform this function shall have a gradation of CA-6 and shall conform with Article 704.05 of the Standard Specifications. Rolling the top of this aggregate with a minimum of 350 PLI (pounds per lineal inch) total applied force vibratory roller or equivalent, as approved and directed by the Engineer, should be sufficient to obtain the desired keying and necessary compaction. The Engineer will visually determine that adequate keying and compaction have been obtained.

Method of Measurement and Basis of Payment. This work shall be measured in accordance with Article 209.04 of the Standard Specifications and paid for at the contract unit price per cubic yard for Porous Granular Embankment.

NCHRP 224 GUIDE SPECIFICATION*

1.0 Description.

This work shall consist of removing and crushing portland cement concrete, mixing with new aggregates, admixtures (as required), and portland cement, and placing, finishing, and curing the recycled portland cement concrete to the lines, grades, and dimensions shown on the plans and/or specified in these special provisions.

2.0 Materials.

2.1 Recycled Aggregate: The recycled aggregate shall be obtained by crushing the old portland cement concrete removed from the roadway. The old concrete shall exhibit no signs of chemical reactivity from D-cracking and shall be free of non-PC concrete material (such as asphaltic concrete or reinforcing steel). Where asphaltic concrete (AC) overlays have been used the AC layer shall be removed and kept separate from the PC. The old PC may be broken by any acceptable means, such as a tractor mounted jackhammer for punching holes in the pavement. Then a backhoe or other device can be used to pick up the segments and load them on trucks. If reinforcement is present it must be cut to separate the pieces of concrete. In order to preclude the creation of excessive fines in the recycled PC coarse aggregate from the subbase, the small pieces of rubble created during the break-up and removal operation shall not be used.

2.2 New Aggregate: The new aggregate shall consist of gravel, crushed gravel, crushed stone, air-cooled blast furnace slag, natural sand, manufactured sand, or a combination of the above and shall conform to ASTM Specification C-33, except gradation.

2.3 Portland Cement: Type I or Type II portland cement as specified in ASTM C-150 shall be used.

2.4 Admixture: Water reducing and air entraining materials are required for some mixtures. These materials shall conform to ASTM Specifications C-260 and C-494.

2.5 Fly Ash: When possible, fly ash may be used. The fly ash shall meet the provisions of ASTM C-618.

*The material presented here is taken directly from Epps, J. A., Little, D. N., Holmgren, R. J., and Terrel, R. L., *Guidelines for Recycling Pavement Materials*, Report No. 224, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., September 1980.

2.6 Recycled Portland Cement Concrete: This material shall contain recycled aggregates, new aggregate (as required), portland cement, fly ash (as required), and admixtures (as required). The final coarse aggregate, whether blended or not, shall meet the following requirements:

1. Gradation (ASTM C136)	<u>Percent Passing</u>
2 in (50 mm)	100
1-1/2 in (37.5 mm)	95 to 100
3/4 in (19 mm)	35 to 70
3/8 in (9.5 mm)	10 to 30
No. 4 (4.75 mm)	0 to 5
	<u>Maximum Allowable (%)</u>
2. Clay lumps and friable particles (ASTM C-142)	3.0
3. Material finer than No. 200 (ASTM C-117)	2.0
4. Abrasion loss (ASTM C-131)	50

The final fine aggregate shall consist of natural sand, manufactured sand, or a combination thereof. Unless otherwise stated on the plans, the fine aggregate shall meet the following requirements:

1. Gradation (ASTM C-136)	<u>Percent Passing</u>
3/8 in (9.5 mm)	100
No. 4 (2.36 mm)	95 to 100
No. 8 (2.36 mm)	80 to 100
No. 16 (1.18 mm)	50 to 85
No. 30 (600 μ m)	25 to 60
No. 50 (300 μ m)	10 to 30
No. 100 (150 μ m)	
	<u>Maximum Allowable (%)</u>
2. Clay lumps and friable particles (ASTM C-142)	3.0
3. Material finer than No. 200 (ASTM C-151)	5.0
4. Insoluble residue (ASTM D-3042)	30.0

3.0 Mixture Design.

The concrete shall be designed to have a minimum 28-day compressive strength of 3000 lb/in² when tested in accordance with ASTM C-39, or a minimum 28-day flexural strength of 500 lb/in² when tested in accordance with ASTM C-78. These minimums shall be based on an average of at least 3 specimens per test with the provision that a maximum of 1 in 10 specimens may fall below the minimum without penalty. For durability a minimum total portland cement plus fly ash content of 564 lb/yd³ shall be utilized. Furthermore at least 423 lb of portland cement per yd³ shall be used. Mixture designs shall follow ACI method 211-1-74 or a method approved by the engineer. When specified on the plans the mixture shall be evaluated in accordance with one or more of the following methods.

- | | |
|-------------------------------|---------------------|
| 1. Splitting Tensile Strength | ASTM C-496 |
| 2. Abrasion Resistance | ASTM C-418 |
| 3. Freeze-Thaw Resistance | ASTM C-666, Proc. A |
| 4. Drying Shrinkage | ASTM C-157 |
| 5. Alkali Reactivity | ASTM C-227 |
| 6. Time of Set | ASTM C-403 |

4.0 Equipment.

As many as necessary of the following named pieces of equipment shall be used to complete the specified work: rippers, pulverizers, impact hammers, steel cutters, crushers, proportioning and mixing equipment, placing and finishing equipment, hand tools, and other miscellaneous tools. Other equipment may be used in addition to, or in lieu of, the specified equipment when approved by the engineer.

5.0 Construction.

5.1 Removal and Crushing: All existing portland cement concrete shall be removed and crushed except as noted on the plans. All removed and crushed pavement shall be the property of the contractor.

- a. If asphaltic resurfacing is present, the asphaltic concrete shall be removed before the portland cement concrete is crushed, and each shall be crushed separately. It is intended that all of the asphaltic concrete be removed from the portland cement concrete. Isolated areas of adhering asphaltic concrete up to one inch in thickness will be considered acceptable, including patches of asphaltic concrete.
- b. Reinforcing steel shall be removed from the existing pavement prior to or during the crushing operation and shall be disposed of by the contractor.
- c. The contractor shall remove the pavement in a manner which does not develop a large amount of fines in the pavement material and which excludes subgrade and subbase material to the maximum extent practicable.
- d. The pavement material shall be crushed to pass a 1-1/2-inch sieve. Processing equipment shall include a screen by which excessive fines in the product can be controlled by removal of fines passing the No. 8 screen. Control will be as directed by the engineer, and his target will be 5 percent passing the No. 200 sieve. Aggregate washing will not be required.
- e. Any excess material and fines removed during processing shall be disposed of as shown on the plans.

5.2 Proportioning and Mixing: Proportioning and mixing shall be performed with standard equipment as approved by the engineer. Procedures shall conform to ACI method 316-74 or as approved by the engineer.

5.3 Placing, Finishing, and Curing: Placing and finishing shall be performed with standard equipment as approved by the engineer. Curing compounds shall be utilized as approved by the engineer. Procedures shall conform to ACI method 316-74 or as approved by the engineer.

6.0 Measurement.

6.1 Recycled Aggregate: Total number of square yards of old portland cement concrete and asphalt cement removed and crushed in stockpiles.

6.2 Portland Cement and Fly Ash: Total number of tons of material incorporated into the job.

6.3 Recycled Portland Cement Concrete: The area (square yards) of portland cement concrete resurfacing constructed of the mix proportions and thickness specified. The item shall include all new aggregate, portland cement, admixtures, proportioning, mixing, hauling, placing, finishing, and curing activities.

6.4 Recycled Aggregate--Salvage Value: Total number of tons of removed and crushed pavement materials not utilized on job. With this bid the contractor is the owner of the excess recycled aggregate. The salvage value bid by the contractor will be subtracted from the total bid price if the bid price is positive or added if the bid price is negative.

7.0. Basis of Payment.

The quantities discussed above shall be paid for at the contract unit price bid for each item. Payment shall be in full compensation for finishing, hauling and placing materials for mixing, placing, consolidation, finishing, and curing and for all labor and use of equipment, tools, and incidentals necessary to complete the work in accordance with these specifications.

APPENDIX C

RESEARCH PLAN

The two research programs outlined below cover the research areas that are most important with respect to the implementation of PCC recycling in airfield pavement construction.

RECYCLED AGGREGATE AND CONCRETE PROPERTIES

When existing PCC pavements are crushed and graded for use as aggregate in new PCC, several characteristics of the aggregate are significantly different from those of conventional aggregates. The crushed pavement is highly angular; consequently, a uniform mix is more difficult to obtain than when conventional aggregate is used. The technical literature addresses this problem and suggests that a higher proportion of cement and some natural fine aggregate be used in the mix to improve its workability. However, the more important aspects of accelerated set, shrinkage control, and freeze-thaw durability have not been adequately studied. A mix in which recycled concrete is used as aggregate makes a rich-angular aggregate concrete, as opposed to the lean-rounded aggregate concrete normally encountered in airfield pavements. The effect of these fundamental differences on performance is unknown. It is known, however, that most PCC pavement failure is related to environmental response rather than to loading. The environmental durability of recycled aggregate concrete has not been documented. Another characteristic of concrete-rich mixtures is surface scaling. A harsh, rich mix is likely to have poor surface characteristics when the techniques normally employed to finish airfield paving are used. Finally, the use of existing concretes exhibiting alkali-reactive aggregates must be evaluated. Many pavements deteriorate because of the volume changes produced when reactive silica in the aggregate contacts the alkaline materials in portland cements. The chemical-reaction products occupy more volume than the ingredients, and they usually cause surface scaling and edge cracking. In the current state of the art, mix designs are modified to reduce the effect of these adverse chemical reactions when natural aggregates containing reactive silica are used. Testing is needed to evaluate this approach as a means of producing satisfactory concrete from recycled-concrete aggregate.

The research effort described above is a necessary step toward enabling field engineers to develop confidence in using recycled-aggregate concrete in airfield paving jobs. It would include the identification of at least two sites where an existing PCC pavement may be used as a source of material for laboratory concrete mixes. The material should be of an age and condition to be considered for replacement. One pavement should exhibit alkali-reactive aggregate damage, and the other should show no evidence of this sort of deterioration. A quantity of the material would be removed and crushed in a full-scale crusher to provide materials to be evaluated. The crushed material would be stockpiled at the NMERI facility for further use as described below.

Standard concrete aggregate specification testing would be performed on the materials. The crushed materials would be compared with the normal aggregate available at each site. Mix designs for concrete of airfield pavement quality would be prepared. Procedures peculiar to the use of recycled concrete as aggregate, such as using natural sand for a portion of the fine aggregate, would be incorporated. The performance of the material would be evaluated in the laboratory by means of flexural strength, compressive strength, freeze-thaw durability, and volume change tests. A test would be devised to evaluate the susceptibility of these materials to finishing by machines commonly employed in airfield paving work. Material performance would be related to the results of similar tests on specimens of conventional concrete for the sites under study.

The results of the study are intended to reveal whether recycled-aggregate concrete exhibits a performance similar to that of conventional concrete mixtures. If so, it would be assumed that normal design thicknesses could be employed. If inferior or superior performance is indicated, however, an alteration of the designs may be in order. These findings could significantly influence the economics of PCC recycling. Table C-1 outlines resource requirements for the project.

TABLE C-1. RECYCLED AGGREGATE AND CONCRETE
PROPERTIES PROJECT.

Time Allotted: 30 months

Personnel Requirements:

Professional--4.0 man-years

Technical--4.5 man-years

Support--1.5 man-years

Budget: \$400,500

PCC RECYCLING FIELD TRIAL

After data have been developed indicating that conventional design methods are acceptable for designing recycled PCC mixes, a field trial should be conducted. The objective would be to provide an opportunity to select and apply specifications peculiar to PCC recycling and to evaluate their utility in a construction program. The experience gained would be documented to provide a guide for all future applications of the technology.

Candidate Air Force installations would be selected on the basis of the type and condition of the existing pavement and the need to rehabilitate it. The NMERI staff would survey the bases and recommend several sites from which the Air Force project officer could make a selection. The NMERI staff would then develop a sampling plan and obtain the materials to be used in developing the mix designs. Testing of the materials would be performed at the NMERI facility.

When the testing had been completed, the NMERI staff would present a briefing at which the concrete mix design, the specifications, the quality control program, and a performance monitoring scheme for the facility would be outlined. This information would be vital to the proper documentation of the project and would enable the Air Force to obtain maximum benefit from the program. The quality control effort is extremely important because it will document the actual construction materials placed; their variation; and the influence, if any, of construction problems on material quality. As the

performance is monitored, the quality control data base will also yield valuable information about the correlation of test results with actual performance.

When this project had been completed, all work would be documented in a technical report intended to serve as a reference for the design and development of future Air Force recycling jobs. Additional activities should also be included to enhance the overall value of the project. These would include a visit to the construction site by base engineers who may be involved in similar projects. It would be helpful if a short course on concrete pavement technology were presented in the course of this visit. Table C-2 outlines resource and time requirements for the field trial project.

TABLE C-2. PCC RECYCLING FIELD TRIAL PROJECT.

Time Allotted: 18 months

Personnel Requirements:

Professional--2 man-years

Technical--1 man-year

Support--1 man-year

Budget: \$190,500

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