154

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 154

RECYCLING OF PORTLAND CEMENT CONCRETE PAVEMENTS

TRANSPORTATION RESEARCH BOARD
National Research Council

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RECYCLING OF PORTLAND CEMENT CONCRETE PAVEMENTS

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. DECEMBER 1989

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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NCHRP SYNTHESIS 154

Project 20-5 FY 1985 (Topic 17-06)
ISSN 0547-5570
ISBN 0-309-04901-6
Library of Congress Catalog Card No. 89-51544

Price: $8.00

Subject Areas
Energy and Environment
Pavement Design and Performance
Cement and Concrete
Construction

Mode
Highway Transportation

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff Transportation Research Board

This synthesis will be of interest to pavement designers, construction engineers, and others interested in economical methods for reconstructing portland cement concrete (PCC) pavements. Information is provided on the processes and procedures used by a number of states in using recycled PCC pavement as aggregate in reconstructed concrete pavement.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Since 1975 a number of state highway agencies have reconstructed concrete pavements using the old PCC as aggregate in the new pavement. This report of the Transportation Research Board describes the processes used on various projects in several states, giving details of construction procedures, as well as test results on various properties of the recycled aggregates and the resultant concrete.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Robert E. Skinner, Jr., Director for Special Projects. The Principal Investigators responsible for conduct of the synthesis were Herbert A. Pennock and Martin T. Pietrucha, Special Projects Engineers. This synthesis was edited by Judith Klein.

Special appreciation is expressed to William A. Yrjanson, Director of Engineering, American Concrete Pavement Association, who was responsible for the collection of the data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Ray Hurst, Highway Engineer, Federal Highway Administration; Edward J. Kehl, Construction Engineer, Bureau of Maintenance, Illinois Department of Transportation; O. J. Lane, Testing Engineer, Iowa Department of Transportation; Roger Larson, Research Engineer, Federal Highway Administration; Aramis Lopez, Jr., Pavement Division, Federal Highway Administration; and Leo P. Warren, Chief of Physical Testing and Inspection, Minnesota Department of Transportation.

William G. Gunderman, Engineer of Materials and Construction, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

RECYCLING OF PORTLAND CEMENT CONCRETE PAVEMENT

SUMMARY

Recycling portland cement concrete (PCC) pavement and reusing the aggregates for construction of pavements or their structural elements has developed into a cost-effective rehabilitation option.

Several developments in the past 10 years have made recycling more economical for all types of PCC pavements. These include:

- Development of improved equipment for breaking all types of PCC pavements, from plain to continuously reinforced, in preparation for crushing operations.
- Development of methods of steel removal to minimize hand labor.
- Modification of crushing equipment to handle steel reinforcement.

Recycling of PCC pavements in the United States is proceeding at an accelerating rate. In a growing number of areas of the United States, it is becoming increasingly advantageous to recycle concrete. The conservation of materials, the problem of solid-waste disposal, and the reduction in construction costs all enter into the increased interest in recycling of old PCC pavements.

Laboratory studies have been conducted by several state departments of transportation and federal agencies to determine the suitability of recycled aggregate for use in building new PCC pavements.

These studies have found that the use of recycled aggregate will produce strong, durable concrete suitable for PCC pavements in all areas of the United States. The coarse aggregate produced has no significant effect on mixture proportions or workability compared with the control mixtures made with conventional aggregates. The recycled fine aggregate [material passing the 4.75-mm (No. 4) sieve] is normally not used in a mixture because of its particle shape and water demand. When recycled fines are used, they are generally limited to about 30 percent of the fine-aggregate (sand) portion of the mixture.

Construction of concrete pavements using D-cracked concrete pavement as a source of aggregate has been accomplished on a number of projects. The coarse aggregate produced is crushed to ¾-in. top size, which substantially reduces the D-cracking potential of concrete made with these aggregates.

Wyoming was the first state to recycle pavements showing distress from alkali-silica reaction and to use the recycled aggregate to build a new PCC pavement. Aggregates in the Pine Bluffs area contain traces of volcanic material. Use of these results in an alkali-silica reaction causing severe distress in the form of map cracking of the pavement

surface. Long-term tests were conducted to determine if low-alkali cement and a suitable fly ash would control the expansion to tolerable limits. These tests have shown positive results.

Recycling of PCC pavements has been accomplished on major urban freeways. The Edens Expressway in the Chicago area was completely reconstructed with recycled concrete for the open-graded base and subbase layers in the pavement structure. The Lodge Freeway in Detroit, Michigan, was completely reconstructed in 1987 in less than six months, with the recycled pavement being used as coarse aggregate in the new pavement.

Recycling projects in seven states (Michigan, Minnesota, Iowa, North Dakota, Wisconsin, Wyoming, and Oklahoma) are reviewed, along with the pertinent findings on these projects.

Airport pavement recycling is increasing as old pavements are replaced to meet the needs of heavier aircraft. The primary use of the recycled aggregates has been for cement-treated base course for a new PCC pavement, with some used for lean-concrete base, open-graded drainage layer (coarse aggregate), and for new PCC pavement. When recycled aggregates are used for cement-treated base, the material is usually crushed to ¾-in. to 1-in. top size, with the total crushed product used in making the cement-treated base.

Recycling of PCC pavements is an option that should be considered wherever a concrete pavement is to be reconstructed. Developments in equipment for breaking, removal, and crushing have made the recycling of all types of concrete pavements economically possible. Recycling of PCC pavements conserves natural-aggregate supplies and provides a high-quality source of aggregate at the job site.

The aggregate particles produced by crushing concrete have good particle shape, high absorptions, and low specific gravity compared with conventional mineral aggregates. Research by a number of agencies has shown an increase in freeze-thaw resistance of concrete made from recycled aggregates when compared with concrete made from some normal conventional aggregates. In addition, the durability of concrete made with aggregate subject to D-cracking can be substantially improved by recycling.

CHAPTER ONE

INTRODUCTION

This synthesis is concerned with the recycling of existing portland cement concrete (PCC) pavement and the reuse of the recycled aggregate in constructing new PCC pavements or other elements of a pavement structure.

Recycling of PCC pavements in the United States is increasing. In a growing number of areas, it is becoming advantageous to recycle old concrete. The conservation of materials, the problem of solid-waste disposal, and the reduction in construction costs all enter into the increased interest in recycling old PCC pavement and concrete rubble.

With greater vehicle volumes and heavier vehicle weights on the U.S. highway system, pavement distress is accelerating. There is a tremendous challenge facing the United States to preserve its highway network by rehabilitating these roads to restore their serviceability. There are a number of rehabilitation strategies that can be selected based on the condition of the existing pavement. In the case of PCC pavements, the rehabilitation may involve:

- Concrete pavement restoration, which could involve full-depth and partial-depth patching, slab stabilization, diamond grinding, joint and crack resealing, and drainage and shoulder repair.
- Resurfacing.
- Reconstruction and/or recycling.

The selection of the rehabilitation strategy should involve a number of decisions based on data collected by an in-depth survey of the existing pavement. Information needed for an adequate evaluation includes: distress types (severity and amount); design of the pavement; materials and soil properties; past and future traffic volumes and characteristics; cores from selected joints or cracks; surface profile measurements; deflection testing; and sampling of the subgrade and base below the pavement to determine their conditions. The most cost-effective rehabilitation strategy can then be selected based on life-cycle costs.

When reconstruction of a PCC pavement is selected as a rehabilitation strategy, recycling of the PCC pavement and reuse of the aggregates produced should be considered based on such factors as cost and availability of local aggregates, suitability of recycled aggregates for the intended use, disposal costs, and environmental considerations.

WHY RECYCLE?

There is a need for high-quality construction materials, such as aggregate, to provide the structures and transportation facilities for a growing society. However, existing supplies of natural aggregate are being depleted in the United States. In many areas, there is no local aggregate that meets present-day quality standards. In some areas the remaining natural-aggregate sources are inaccessible or expensive to use. Often the material is buried deep in the earth or too distant from markets to offer a desirable return on investment. There is a need to develop replacement sources of aggregate in the areas where it is in short supply. Existing PCC pavement represents a readily available supply of aggregate that can be recycled for various uses.

Given the current concern about the environment, disposal of rubble and other construction waste materials by dumping or burial is becoming a less attractive and more expensive option. This is particularly true in urban areas. How to dispose of the massive quantities of concrete waste generated in these areas is a difficult problem. For years, these wastes were sent to landfills. Today, however, the need for fill is small, especially in highly developed metropolitan centers, where landfills can take only a small portion of the waste generated to make way for new construction.

Reconstruction of urban streets and expressways also creates massive disposal problems. However, recycling can help to alleviate some of these problems. Recycling can have tremendous benefits for the environment, and contractors can save money in material acquisition and disposal costs. There is also the potential for cost savings in many areas where aggregates are not locally available. In some areas of the United States, aggregates are hauled over 200 miles, with a 50- to 70-mile haul not uncommon. With the haul costs for construction materials increasing, recycling will become attractive in more areas.

For the reasons stated above, state and federal agencies and others are actively encouraging the recycling of PCC pavements when it is economically feasible. The Federal Highway Administration (FHWA) has been active in promoting demonstration projects on the recycling of PCC pavements. These projects are intended to assist in developing the technology and determining the feasibility of recycling old PCC pavements.

HISTORY OF RECYCLING OF PORTLAND CEMENT CONCRETE

Whenever a new technology is introduced, it is usually viewed with some uncertainty. Concrete-recycling technology has certainly had its share of skeptics. Among the frequently held reservations were: Would the recycled material make good aggregate? Would it be economically feasible? How is the steel removed from the pavement in a cost-effective manner? How are the concrete mixtures proportioned using recycled coarse and fine aggregates? What strengths can be obtained? These questions were answered through the innovation of contractors and equipment manufacturers and through studies by state and federal agencies.

A joint research project (*1*) by the Texas State Department of Highways and the Texas Transportation Institute included a survey on litter disposal and use of waste materials. The survey indicated that:

> very few states were giving consideration to the reuse of existing road-bed materials for rehabilitation and reconstruction uses other than for unstabilized base courses. The normal disposal of asphalt concrete or portland cement concrete seem to have been in landfills or for riprap in drainage ditches. While the riprap idea has merit, the disposal of these materials in landfill areas is particularly questionable today, due to both the need to conserve our valuable resources and the relatively high cost of providing new construction materials.

This practice has changed substantially in the past 10 years, with growing concern for the conservation of natural resources and energy and environmental and cost considerations. The renewed interest in the recycling of street, highway, and airport pavements has substantially increased the number of commercial recycling operations in urban areas.

The projects constructed to date have used recycled concrete aggregates for new PCC pavements, econocrete (lean-concrete) bases (highways and airports), shoulder concrete, porous granular fill, unstabilized base courses, asphalt pavements, porous concrete shoulders, cement-treated base courses, and open-graded drainage layers under new PCC pavements.

Recycled PCC aggregate was used as an unstabilized base for flexible pavement construction in Texas on I-35 in 1972. On U.S. Route 60 in Texas, recycled PCC aggregate was used for new asphalt pavement in 1974.

Louisiana used recycled PCC aggregate on a project on I-20 east of Monroe. The recycled aggregate was used in the binder and base course and not in the surface course. It was reported that because of the high absorption of PCC aggregate, the asphalt requirements were about 1.5 percent more than for conventional aggregate. Workability problems were solved during the job. Louisiana has also used recycled PCC aggregate in new PCC pavement construction.

Florida used recycled PCC aggregate for flexible pavement construction on a project on I-10 in northwest Florida. Illinois used recycled PCC aggregate for an asphalt binder course on an Interstate route.

LABORATORY STUDIES

In the materials research area, a number of studies were conducted in the 1970s by the Army Corps of Engineers Waterways Experiment Station (*2–4*), the Iowa Department of Transportation (*5*), Massachusetts Institute of Technology (*6*), the Minnesota Department of Transportation (MinnDOT), Michigan Department of Transportation (MDOT), and the FHWA. These studies were conducted to determine the suitability of recycled aggregate and the economic feasibility of recycling. Other studies have been made since that time, and the following is a summary of some of the findings from all of these studies:

- The coarse-aggregate particles produced by crushing the concrete have good particle shape, high absorptions, and low specific gravity compared with conventional mineral aggregates.
- The use of crushed concrete as a coarse aggregate had no significant effect on mixture proportions or workability of the mixtures compared with the mixtures using conventional aggregates.
- When crushed concrete was also used as fine aggregate, the mixture was less workable and required more cement because of water demand. It was found that substitution of a natural sand for all or a portion of the fine aggregate was required to produce a workable concrete.
- Research has shown an increase in freeze-thaw (*2, 3, 7*) resistance of concrete made from recycled aggregates compared with concrete made from some conventional aggregates.
- The durability of concrete made with aggregate taken from concrete that was subject to D-cracking can be substantially improved by recycling. (D-cracking is a form of pavement distress caused by poor-quality aggregates that absorb moisture and deteriorate through freeze-thaw action.) Freeze-thaw testing should be performed to determine if the recycled aggregate will make durable concrete.
- The use of recycled aggregate did not have any significant effect on the volume response of specimens to temperature and moisture effects.
- Aggregate recycled from low-strength concrete is not detrimental to the compressive strength of concrete mixtures that contain this aggregate.
- The use of water-reducing admixtures is effective in increasing strengths of concrete mixtures that contain recycled concrete as aggregate. Air-entraining admixtures and fly ash are used to provide durability and improve the workability of the concrete made from recycled aggregates.

EUROPEAN EXPERIENCE

In Europe after World War II, there were massive waste material-recycling programs that turned building rubble into new concrete construction. However, as soon as the rebuilding boom was over, the recycling programs were generally abandoned. In recent years there has been renewed interest in recycling in Europe.

During the summers of 1976 and 1977, two roadways of a freeway north of Paris underwent extensive rehabilitation. The work involved removal of the existing outer two lanes of a three-lane concrete roadbed, removal of a cement-treated base, and stabilization of the underlying foundation soils. Reconstruction involved the recycling of the old concrete pavement for use in a new lean-concrete base layer and in a porous concrete shoulder. The entire 8.53 km (5.3 miles) of reconstruction of the southbound lanes was completed in seven weeks. This pavement carries the heaviest traffic in France—150,000 vehicles per day, of which more than 20 percent are trucks.

The pavement was broken up with two machines that drop a 7-ton weight from a height of 7 ft, hitting the slab every 16 in. Average production was 12,000 yd^2/day. The recycled-concrete aggregate was mixed with 269 lb/yd^3 of cement and 118 lb/yd^3 of fly ash to make the lean-concrete base. The base and pavement were placed with a slipform paver. The porous shoulders were constructed of recycled aggregate with no material sized below 0.2 in. and with 253 lb/yd^3 of cement. The porous shoulders were placed with a small paver equipped with a vibratory compactor.

CHAPTER TWO

SELECTED FIELD PROJECTS (1975 TO 1980)

IOWA DEPARTMENT OF TRANSPORTATION (IDOT)

U.S. 75—Lyon County, Iowa

Iowa's first recycling project began in 1976 on U.S. 75 in Lyon County, Iowa. The existing roadway was a PCC pavement that was nominally 7 in. thick with a thickness of 10 in. at the edges. The pavement was 18 to 20 ft wide, paved in 1934 and 1936, with gravel used as a coarse aggregate. It had been widened with 10 in. of portland cement concrete in 1958 and resurfaced with 3 in. of asphalt concrete (AC) in 1963.

There were two objectives for this recycling project:

- Determine if the AC surfacing could be removed, the existing PCC pavement broken, removed, crushed to a size less than 1½ in., proportioned through a conventional central-mix proportioning plant with the addition of concrete sand, and placed with a conventional slipform paver.
- Determine if a two-course, composite pavement, each course of different mixture proportions, could be placed monolithically with conventional slipform equipment after being proportioned and mixed in a conventional central-mix plant.

The project was completed with no major problems, and the objectives were met satisfactorily. The project was so successful that the following year IDOT proceeded with two reconstruction projects in which the old recycled pavement was used as the source of aggregate for the new pavement.

The aggregate materials used in the initial project were crushed portland cement concrete, crushed portland cement concrete and asphalt concrete combined, and natural sand. A Type I cement was used with admixtures consisting of an air-entraining agent and a water reducer.

The old pavement was removed by a pneumatic hammer mounted on the rear of a backhoe/loader. The hammer punched holes in the old pavement every 2 to 3 ft. This created weak points so that the old concrete slab could be broken more easily. The existing 3-in. asphalt pavement was then removed with the backhoe. The surface was cleaned with a loader bucket, which essentially completed the removal of the asphalt resurfacing. After the asphalt surface was removed, the backhoe picked up the slabs, which were in 2- to 3-ft-square sections, and loaded them into dump trucks for transport to the crushing site. A hydraulically operated shear cut free the slabs that were tied together by the reinforcing steel. Reinforcing steel consisted of four longitudinal bars, located 9 in. on each side of the pavement centerline and at both edges. Transverse ⅝-in. bars, 11 ft long at 3-ft centers placed alternately on either side of the centerline, were also present, as were dowel bars at joints.

The old pavement had been placed directly on the subgrade soil, and only a very small amount of the subgrade soil stuck to the slabs as they were removed in dry-weather conditions. During wet weather more of the subgrade material tended to adhere to the old pavement. The contractor tried to limit the removal operations to dry-weather conditions. By taking care, the backhoe operator was able to load the broken concrete with a minimum of subgrade material.

By crushing the gravel aggregate concrete to a maximum size of 1½ in., 24 percent of the recycled portland cement concrete and 22 percent of the portland cement concrete-asphalt combination passed the 4.75-mm (No. 4) sieve. The specific gravities of the recycled aggregate were lower than those of the parent materials but absorption was higher.

The crushed material was not separated on the initial project, and it contained particles from 1½ in. to material passing the 75-μm (No. 200) sieve. Some segregation did occur in the stockpile (Figure 1), which caused mixing problems, and the crushed product was difficult to batch. The feed through the bin gates was inconsistent, causing difficulties in setting the automatic gate.

To remedy the segregation problem, future projects required splitting the crushed product on the 9.5-mm (⅜-in.) sieve. It was thought that by providing the crushed aggregate in both coarse and fine fractions, the mixture proportions would be easier to control. Separating the crushed product would also facilitate mixture proportioning. An economical and workable mixture design can be made by using a three-aggregate mixture of recycled coarse aggregate, concrete sand, and recycled fine aggregate.

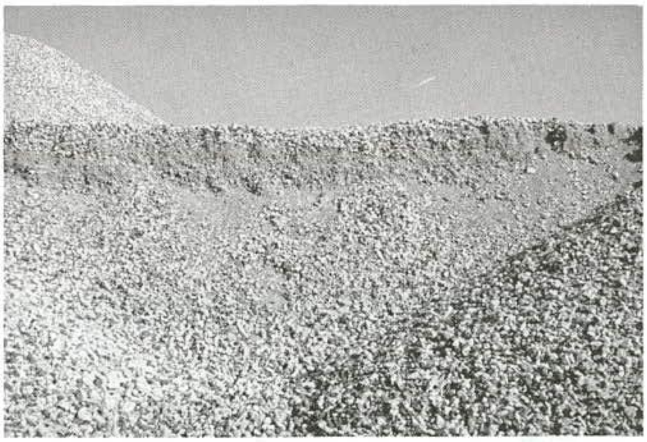

FIGURE 1 Segregation in stockpiled materials.

TABLE 1
CONCRETE MIXTURES

Material	Quantity (lb/yd³)
Mix "A": 35% crushed aggr., 65% fine aggr.	
Cement	564
Water	305
Air	
Aggr. (crushed PCC)[a]	1244
Fine Aggr. (sand)	1589
w/c = 0.54 (Max. w/c = 0.613)	
Mix "B": 50% crushed aggr., 50% fine aggr.	
Cement	564
Water	277
Air	
Aggr. (crushed PCC)[a]	1822
Fine Aggr. (sand)	1033
w/c = 0.49 (Max. w/c = 0.556)	
Mix "C": Crushed AC & PCC (Lower Course of Composite Section)	
Cement	470
Water	254
Air	
Crushed Aggregateb	2885
w/c = 0.54 (Max. w/c = 0.613)	
Mix "C3": 85% AC & PCC & 15% Sand (Lower Course of Composite Section)	
Cement	470
Water	254
Air	
Crushed AC & PCC[b]	2452
Aggregate (Sand)	474
w/c = 0.54 (Max. w/c = 0.613)	

[a] Approximately 24% of crushed PC concrete will pass 4.75 mm (No. 4) screen.

[b] Approximately 22% of crushed AC & PC concrete will pass 4.75 mm (No. 4) screen.

Quantities based on following specific gravities:
Cement 3.14; fine aggr. (sand) 2.68; crushed PCC 2.457; crushed AC & PCC 2.445

The mixtures used on this project are shown in Table 1. The A and B mixtures were used on a 9-in. full-depth section, whereas the C and C3 mixtures were used as a lower course of a composite pavement consisting of 7 in. of C or C3 mixture with a monolithically cast A mixture.

Concrete Strength and Durability

Table 2 lists the average compressive and flexural strengths at 28 days. Concrete made from recycled PCC aggregate appears to have excellent flexural strength properties, which are important in the load-carrying capacity of pavements.

In the laboratory, durability testing was performed on concrete specimens made from recycled material from the project. Under Iowa Standard Specifications for coarse-aggregate durability, test specimens using the aggregate in question must exhibit a durability factor of at least 80 when tested according to ASTM C 666, Procedure B, and moist-room cured for 90 days. Test results at 300 cycles are shown in Table 2, which indicates that the durability factor for the recycled PCC mixture is satisfactory, whereas the combined PCC and asphalt mixture had a durability factor of 79.

I-680—Pottawattamie County, Iowa

Iowa recycled another PCC pavement in 1977 based upon the success of the 1976 Lyon County project. This project was 3 miles of I-680 in Pottawattamie County. The old pavement, constructed in 1952 with a good-quality crushed limestone coarse aggregate, was in good condition, exhibiting essentially no distress when it was recycled. The crushed PCC aggregate was used with natural sand in the 4-in. econocrete base and the 6-in. PCC shoulders on one lane of I-680. The stockpiled broken concrete stored over the winter presented some problems in crushing and screening because of absorption of moisture.

Iowa Route 2—Taylor & Page County

Another recycling project in southwest Iowa was constructed in 1978, with completion in 1979. The materials for this project were crushed in 1977. The project was approximately 16 miles in length, beginning near Clarinda and extending east to near Bedford, Iowa.

The old pavement was constructed in 1929 with Platte River sand-gravel aggregate from Oreapolis, Nebraska, used. The slab thickness varied from 7 in. in the middle to 10 in. at the outer edges. The pavement was 18 ft wide with 3-in. curb on all but about 3 miles of the 16-mile project. In 1964 all curbed sections were resurfaced with AC for curb elimination.

The old pavement was in generally good condition. There was some surface check cracking, which is typical, to varying degrees, of the feldspathic Platte River material. This surface cracking had little adverse effect on the pavement except in a few localized areas. Twenty-three 4-in.-diameter cores were taken from the old pavement. The average strength of those cores was 6535 psi. The reason for reconstruction was to widen the roadway and correct alignment.

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

Shattering of the asphalt resurfacing was the first operation in the removal. This was accomplished with a special pavement breaker (Figure 2). The pavement breaker was fabricated using a new diesel pile-driving hammer mounted on the running gear of a motor grader and towed with an end loader. This was the first use of this type of breaker on a recycling project.

TABLE 2
CONCRETE STRENGTH AND DURABILITY

Strength Tests

	Mixture	psi		Mixture	psi
Concrete Compression 28 day - Average Results	A	4431	Modulus of Rupture 28 day - Average Results (center-point loading)	A	799
	B	4292		B	811
	C	2250		C	585
	C3	2290		C3	560

Durability Tests

Mixture	Cement (lb/yd³)	Aggregate Type	Aggregate Proportion	Sand Added	Durability[a] Factor
1	564	Cr. PCC	60-40	633	88
2	564	Cr. PCC	50-50	1043	94
3	470	Cr. AC & PC	66-34	486	79

[a]Durability Factor - 300 cycle, ASTM C 666, Procedure B.

The diesel hammer was adjusted to produce the right amount of energy when coordinated with the forward speed (1 mph to 3 mph) to fracture the overlay with minimal damage to the underlying slab. After the fracturing, a motor grader equipped with three ripper teeth removed the asphalt from the PCC slab. A rubber-tired front-end loader was used to remove the loosened material and scrape free any adhering material. The final operation was brooming to remove the fine material.

FIGURE 2 Pavement breaker using diesel pile-driving hammer.

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

A rubber-tired hydraulic excavator equipped with a ripper tooth (referred to as a rhino horn) (Figure 3) was used to dislodge and remove part of the reinforcing steel. To avoid punching the concrete rubble into the base, the equipment was operated from the excavated shoulder area.

FIGURE 3 Hydraulic excavator with ripper tooth to remove steel.

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

The concrete rubble was then loaded with a track-mounted front-end loader for transport to the crushing site. Loading of rubble was very important because the contract required recovery of at least 80 percent of the old concrete slab. It was necessary to avoid incorporating earth subgrade into the rubble, which would have caused problems in producing a crushed product with not more than 5 percent passing the 75-μm (No. 200) sieve. The concrete was stockpiled for crushing at two sites that had been leased by IDOT. Crushing the concrete rubble presented some problems not encountered in quarrying operations. First, a scalper (grizzly) was used ahead of the primary jaw crusher to remove mud balls and other fines. This was effective in alleviating the problems of meeting the 75-μm (No. 200) sieve specification.

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

Primary crushing reduced the concrete to approximately 3-in.-size material. The crushed product was further processed in the secondary crusher and separated into 1½-in.- to ⅜-in.-size material and material less than ⅜ in. The fines were removed from the material less than ⅜ in. at the secondary crusher. (After scalping of fines before primary crushing this was no longer necessary.) The crushed products were stockpiled by a conveyor belt with radial movement capability.

The crushing operations produced approximately 65 percent coarse and 35 percent fine aggregate fractions. Approximately 90 percent of the concrete (54,000 tons) was salvaged from the roadway. Washing of the aggregates was not required on any of the Iowa recycling projects.

The two earlier IDOT recycling projects had demonstrated that some natural sand was necessary to produce a workable mixture. On this project, 934 lb of natural sand was added to 637 lb of recycled fines (material less than ⅜ in.).

Durability of the concrete made with recycled aggregate was tested by ASTM C 666, Method B (freezing in air, thawing in water). Concrete-abrasion tests conducted on both recycled-aggregate concrete and concrete made with virgin aggregate showed very similar wear characteristics.

The specific gravity of the crushed coarse and fine aggregate on this project was 2.35, or somewhat lower than that reported on other projects and tests. This can be explained by the higher mortar content of concrete, which contained the Platte River sand-gravel having essentially a ⅜-in.-maximum-size material.

The typical grading of the crushed concrete is shown in Table 3. Mixture proportions for this project are shown in Table 4. The flexural strength, air content, and density are shown in Table 5.

It was estimated by IDOT that a savings of more than $115,000 was realized on this project by recycling and reusing the aggregate in construction of a new concrete pavement. The estimated savings was based on reduction in aggregate costs and haul road repair costs.

TABLE 3
TYPICAL GRADATION OF CRUSHED CONCRETE

Sieve Size	Percent Passing
Coarse Fraction	
38.1 mm (1 1/2 in.)	100
25.0 mm (1 in.)	72
19.0 mm (3/4 in.)	39
12.5 mm (1/2 in.)	21
9.5 mm (3/8 in.)	9.3
4.75 mm (No. 4)	2.9
2.36 mm (No. 8)	2.0
75 μm (No. 200)	0.7
Clay lumps	0.2
Fine Fraction	
19.0 mm (3/8 in.)	100
4.75 mm (No. 4)	76
2.36 mm (No. 8)	51
1.18 mm (No. 16)	30
600 μm (No. 30)	16
300 μm (No. 50)	8.0
150 μm (No. 100)	3.5
75 μm (No. 200)	2.0

MINNESOTA DEPARTMENT OF TRANSPORTATION

Recycling D-Cracked Pavement

Construction on the first major concrete-recycling project in the United States to use a D-cracked concrete pavement (Figure 4) as a source of aggregate for a new PCC pavement was accomplished in 1980 (*8*). The project was developed through extensive research and testing by MinnDOT and involved recycling of

TABLE 4
MIXTURE PROPORTIONS

Material	Approximate Dry Quantities (lb/yd³)
Cement	626
Water	
Air	
Crushed Concrete, Coarse	1083
Crushed Concrete, Fine	637
Natural Sand	934
Design water-cement ratio: 0.48	

Quantities based on following specific gravities:
Cement 3.14; fine aggr. (sand) 2.65; coarse crushed PCC 2.35; fine crushed PCC 2.35
An approved water-reducing admixture was required.

TABLE 5
FLEXURAL STRENGTH, AIR CONTENT, AND DENSITY OF CONCRETE

Slump (in.)	Air Content (%)	Modulus of Rupture (centerpoint loading)		Density (lb/ft³)
		7 Day	14 Day	
1.65	6.8	718	778	
1.46	6.9	745	809	135.8
1.47	7.0	771	843	

16 miles of U.S. 59 from Worthington to Fulda in southern Minnesota.

The original pavement was constructed in 1955 using a gravel coarse aggregate with approximately 60 percent limestone particles susceptible to D-cracking. After about 25 years of service, the pavement exhibited distress, primarily in the form of D-cracking.

The rehabilitation of this section of highway involved the recycling of the pavement into coarse aggregate for a new PCC pavement and the use of material passing the 4.75-mm (No. 4) sieve as stabilizer in the existing granular base.

Laboratory Research

Laboratory research and field performance have shown that crushing a potential D-cracking aggregate to a smaller size substantially reduces the D-cracking potential of concrete made with the aggregates. With this in mind, MinnDOT specified crushing the concrete to ¾-in. top size, with 95 to 100 percent passing the 19.0-mm (¾-in.) sieve and 0 to 5 percent passing the 4.75-mm (No. 4) sieve.

Although no intermediate grading requirements were specified, grading tests run during the aggregate-processing operation indicate that a uniform and clean material was being produced. Initial testing of the recycled aggregate revealed that the materials passing the 75-μm (No. 200) sieve were not deleterious, so washing was not required.

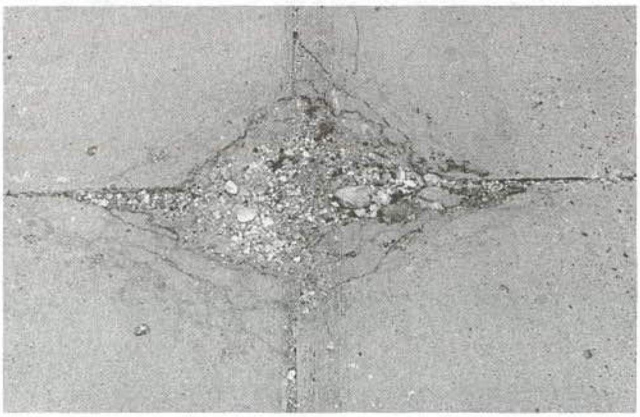

FIGURE 4 D-cracked PCC pavement.

The core strength of the original pavement was in the range of 5000 to 5500 psi and the air content about 4.5 percent.

The material passing the 4.75-mm (No. 4) sieve was very angular and the trial mixture using this material increased water demand substantially to obtain workability. For this reason, MinnDOT engineers decided to use a natural sand with the recycled coarse aggregate.

The trial mixture investigations included the use of fly ash as a replacement for cement. Three mixtures were investigated: one containing no fly ash, a 10 percent fly ash replacement by weight for cement, and a 20 percent fly ash replacement for a 15 percent cement reduction. It was the intent to use the fly ash as a plasticizer, thereby reducing the water demand.

Freeze-thaw durability testing was performed in accordance with ASTM C 666, Method B modified. The concrete with the 20 percent fly ash replacement showed a greatly reduced potential for D-cracking. The mixture proportions used on the project are shown in Table 6.

Recycling Operation

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

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

The concrete was picked up with a backhoe equipped with a special oversize bucket to aid in rapid filling of the bucket. A dozer equipped with long teeth pushed the concrete to the backhoe for pickup, and the concrete pavement was removed at the rate of 1500 ft to 2500 ft/day. A 36-in.-×-48-in. primary crusher was used with a 54-in. cone crusher. A 1-in. scalping screen was

TABLE 6
CONCRETE MIXTURE PROPORTIONS

Material	Quantity (lb/yd³)
Cement	465
Fly Ash	109
Water	255
Sand	1,198
Recycled Coarse Aggregate (Sp. Gr. - 2.38) Absorption - 4.5%	1,632
Assumed Air	5.5%

installed in front of the primary crusher to remove granular base and other fine material. Present specifications require a scalping screen.

The paving operation proceeded without any problems with the materials or the mixture. The control of entrained air was not a problem. Flexural strength at 14 days averaged approximately 700 psi by the center-point loading test method. Pavement smoothness as measured by the roughometer averaged about 70, indicating a very smooth pavement.

Cost Savings

It is estimated by MinnDOT that a savings of $725,000 was realized by recycling this project. The savings include disposal costs of concrete pavement and cost of aggregate for concrete.

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

CALIFORNIA ECONOCRETE BASE

The first use of recycled concrete in an econocrete base for a new concrete pavement was in California in 1975. The contractor used a mixture of crushed or recycled concrete and asphalt pavement. A crusher was set up on vacant property and contractors were invited to dump concrete or asphalt pavement. They were charged a $5/ton dumping fee. The materials were crushed to a maximum size of $1\frac{1}{2}$ in. Reinforcing bars and other undesirable materials were removed by hand from the conveyor belt following primary crushing. The lean-mixture concrete using the mixture of recycled concrete and asphalt pavement required 8 percent cement. A central-mix plant with $7\frac{1}{2}$-yd^3 mixing drums was used and the mixed concrete was hauled to the site in belly dumps. The base was placed 0.4 ft thick and 50 ft wide by a slipform paver. The same paver was later used to slipform the 48-ft-wide concrete pavement on the base. The average 28-day compressive strength on cores from the lean-concrete base was 730 psi.

ILLINOIS DEPARTMENT OF TRANSPORTATION

Edens Expressway—Chicago

In the north suburbs of Chicago, the Illinois Department of Transportation reconstructed a major urban freeway, the Edens Expressway (I-94), a six-lane divided highway carrying 130,000 vehicles per day, of which 10 percent are trucks. The 10-in. reinforced-concrete pavement had been resurfaced with 3 in. of asphalt. The pavement was in considerable distress, which was caused by the 100-ft contraction joint spacing. Serious infiltration at the joints had resulted in blowups and large joint spalls caused by compression failures.

The rehabilitation work involved removal and replacement of all existing pavement, removal and replacement of the existing crushed stone base, and removal and replacement of the subgrade in many locations. The contract also called for widening and redecking 14 mainline bridges, lowering the grades at underpasses to provide a minimum of 14 ft 6 in. clearance, improving and modifying the drainage, correcting superelevations, installing new and improved lighting systems, adding full-width shoulders on both bridges and pavement, and constructing a permanent concrete safety barrier in the median.

Construction Sequence

In 1978, a temporary asphalt lane was added on the west side of the southbound lanes to provide for four lanes of traffic—two lanes in each direction separated by a precast median barrier. This allowed traffic to be removed from the northbound roadway so that work could proceed on removal and replacement of the northbound pavement, including subgrade correction and repaving with 10 in. of continuously reinforced concrete pavement (CRCP) (Figure 5).

Because of the potential shortage of trucks, the long haul distance required for disposal of materials, and the restricted disposal sites, the contractor chose to recycle the concrete pavement. The recycled material could be used in the structural section of the pavement. Traffic congestion was a deterrent to economical hauling. Although the nearest aggregate source was only 18 miles from the job site, it was a 3-hr trip to the quarry and back. With recycling on the project, most of the hauling was done on the job site. Also, because the project schedule called for 24-hr operation, a large part of the hauling was accomplished at night during light traffic hours. It was estimated that one truck on a job site haul for recycling could do the work of six trucks on off-site disposal.

Approximately 1,000,000 yd^3 of surplus earth had to be hauled to disposal areas. During the night-shift operations the trucks could recycle in about half the time of daytime hauling. Disposal of earth is much easier than disposal of broken concrete with mesh protruding. Most fill areas will not accept this material.

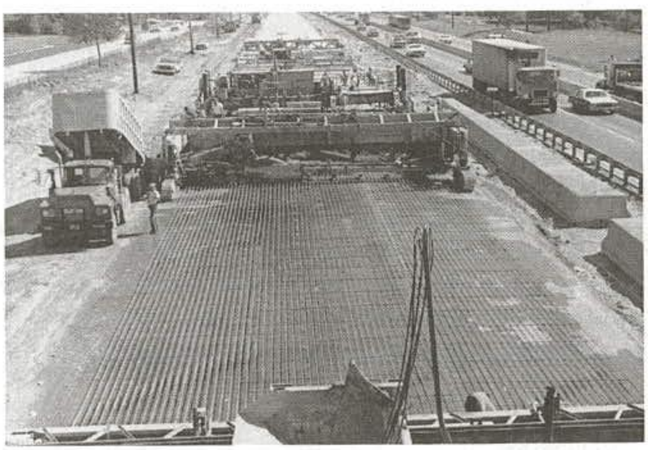

FIGURE 5 Construction of 10-in. continuously reinforced concrete pavement.

This is also the first major recycling project in which a dowel-mesh pavement was recycled. Three hundred fifty thousand tons of the original pavement were crushed and recycled on site, producing two useful products. Approximately 85 percent was graded for use as porous granular embankment, specified for backfilling undercuts, and the remainder was used as an Illinois CA-6 aggregate, which was specified as a 3-in. lift under the new stabilized base.

Recycling Operation

The 15-mile expressway was broken and loaded out in about 50 days for the northbound lanes in 1979 and the same time period in the southbound lanes in 1980. The 10-in. mesh-reinforced pavement was pulverized by two large mobile diesel hammers (15,000 ft-lb of impact), which had been fabricated by the contractor for this project. This equipment fractures the old slab into pieces 3 ft or less at a rate of 6000 yd^2 for each breaker during the 12-hr work shift. The 3-in. asphalt overlay was removed before breaking. It was found that if a $\frac{1}{2}$-in. layer of asphalt was left intact on the pavement, the effectiveness of the hammer was reduced 30 percent; $\frac{1}{4}$ in. or less of material on the concrete was not detrimental to breaking.

A smaller drop hammer (1350-lb weight, 10-ft lift) was used in areas of shallow utilities with less than 2 ft of cover. The catch basin and manhole areas were broken before the diesel hammers did the major breaking.

After breaking, the shattered concrete was dozed into piles before being loaded into semitrailer trucks and transported to the crushing sites. A portion of the steel mesh was broken by the diesel hammers, but the major portion of the mesh was broken by the dozers pushing the broken concrete into piles on the existing broken pavement. The steel mesh was removed with electromagnets operating above the conveyor belts along with hand picking. Some of the longer wires were removed by hand at the crusher site. All crushing was accomplished in the cloverleaf area of major intersections. Because of the limited space, a careful balance between the incoming and outgoing material was required.

Savings

This project is an excellent example of reuse of pavement materials into a new pavement structure. A considerable savings in energy and costs resulted from the recycling of the old PCC pavement on this project. Recycling eliminated the cost of disposal of 350,000 tons of pavement rubble and provided material for the porous granular backfill and a granular base material. It is estimated that 200,000 gallons of diesel fuel was saved by recycling this pavement. This project also illustrates the feasibility of complete reconstruction of a heavily traveled urban expressway. The contract specified a completion date of October 31, 1979 for the northbound roadway and October 31, 1980 for the southbound roadway. The contract also had an incentive-disincentive clause with regard to completion time for 1979 and 1980 work of $56,000/day. This amount would be assessed the contractor for late completion beyond October 31, 1979 on the northbound roadway and late completion beyond October 31, 1980 on the southbound roadway.

Unlike other projects in which very tight completion schedules are specified, the incentive pay was not computed from the project-completion date. Incentive pay for early completion was specified to be computed from the end of September rather than the end of October. The project was completed on schedule.

CHAPTER THREE

SELECTED FIELD PROJECTS (1981 TO 1986)

Recycling of PCC pavements has been accelerating since 1980. Following is a summary of PCC recycling operations in the seven states (Michigan, Wisconsin, Iowa, Minnesota, North Dakota, Wyoming, and Oklahoma) in which the majority of PCC recycling has been done.

MICHIGAN DEPARTMENT OF TRANSPORTATION

Michigan has been one of the most active states in the reconstruction of its Interstate system by recycling of old PCC pavement into aggregates for new-pavement construction with more than 425 lane miles (3,000,000 yd^2) of recycled aggregate pavements. Table 7 lists recycling projects built through 1987.

Reviews of the projects are presented by McCarthy (*9*) and by McCarthy and McCreery (*10*). These papers present a review of 14 major concrete-recycling projects scheduled to be completed in Michigan from 1982 through 1986 and include criteria for design, life-cycle costing, construction methods, equipment, and use of materials. The projects totaled more than $90 million in construction costs and were constructed on I-94, I-75, and I-96.

Background

The first recycling project in Michigan was built in 1982 on 1 mile of Garfield Road in Macomb County. The broken concrete was processed through a crushing plant and used as the coarse aggregate in the new pavement. In 1983 and 1984, MDOT awarded four major Interstate recycling projects on I-94 and I-75, with a total construction cost of about $25 million. In 1985,

TABLE 7
CONCRETE RECYCLING PROJECTS IN MICHIGAN

Year	Route	Location	Length, Configuration	Concrete Shoulders
1981	street	City of Wyoming, suburb of Grand Rapids	1 mi, 4-lane arterial	no
1982	Garfield Road	Macomb County	1.2 mi, 55 ft. wide	no
1983	I-94	Kalamazoo County, near Battle Creek	5.7 mi, dual 24 ft.	yes
1984	I-94	Van Buren County, E. of Hartford Interchange	8.96 mi, dual 24 ft.	yes
	I-75	Wayne and Monroe counties, S. of Detroit	6.7 mi, dual 36 ft.	yes
	I-75	Monroe County, S. of Detroit, NB only	6 mi, single 36 ft.	yes
1985	I-94	Calhoun County to Jackson County line	6.3 mi, dual 24 ft.	yes
	I-94	Kalamazoo County, near Galesburg	8.7 mi, dual 24 ft.	yes
1986	I-94	Calhoun County, E. of 11 Mile Road	5.7 mi, dual 24 ft.	yes
	I-96	Ionia County, W. of Lansing	7.7 mi, dual 24 ft.	no
	I-96	Ionia County, near Portland	10.49 mi EB, 24 ft. 5.46 mi WB, 24 ft.	no
	I-94	Van Buren County near Paw Paw	5 mi, dual 24 ft.	yes
	I-94	Washtenah County, Harris Rd. vicinity	2.31 mi, dual 24 ft. into dual 36 ft.	yes
1987	I-94	Calhoun County E. of old U.S. 27	4.4 mi, dual 24 ft.	yes
	I-75	Monroe County Ohio Line, NB only	6.3 mi, single 36 ft.	yes
	I-94	Van Buren County W. of Paw Paw	5.8 mi, dual 24 ft.	yes
	U.S. 10	Wayne County, Lodge Freeway to I-75, Detroit	8.7 mi, dual 36 ft.	yes
	I-96	Ionia and Kent counties	8.2 mi, dual 24 ft.	no

two more projects on I-94, totaling approximately $20 million, were placed under contract. In 1986, five more major recycling projects were placed under contract, totaling some $44 million. On these projects coarse aggregate for the new concrete pavement was produced from the broken concrete. A portion of the recycled fines was permitted in the concrete mixtures. The Michigan recycling projects through 1985 contained specification requirements that the old pavement be recycled into coarse aggregate for the new pavement. This was required to obtain the 5 percent additional federal aid allowed by FHWA as an incentive for innovative procedures. In 1986, when FHWA no longer granted this incentive, MDOT did not require recycling but made the use of the recycled aggregates for concrete or for open-graded drainage course optional with the contractor. On all projects since that time, the contractors have chosen to use the recycling option and produce aggregate for the concrete pavement and open-graded drainage courses.

By 1983, the MDOT research engineers believed that sufficient laboratory and field work had been done to indicate that good-quality concrete could be obtained using recycled aggregates. The major problem was to develop specifications and production methods for economically and reliably getting the desired product. Therefore, one of the criteria in selecting candidate projects was size—a project large enough to warrant a contractor using the best equipment and methods available.

The department's first project in 1983 was a 5.7-mile section of I-94 near Battle Creek. This dual 24-ft roadway section was originally constructed in 1958. The original design provided for transverse joints with dowel-bar load transfer constructed at 99-ft intervals. The pavement was 9 in. thick and reinforced with welded mesh and expanded metal. Transverse joint problems, including blowups, were numerous and classic manifestations of D-cracking were also widespread. There were some bituminous patches existing along the centerline and at transverse cracks and joints.

Total average daily traffic (ADT) for both directions in 1980 was 28,000, with 23 percent of the vehicles classed as commercial.

Standard specifications were used for controlling the work except for use of recycled aggregates. The specified compressive strength was 3500 psi at 28 days for the pavement and 3000 psi at 28 days for the concrete shoulders.

Because the tests made on the original virgin coarse aggregate had shown it to have poor durability and the existing slabs were D-cracked, the MDOT Testing and Research Laboratory decided to reduce the allowable maximum size of the recycled coarse aggregate.

The recycled coarse aggregate was required to have 95 to 100 percent passing the 19.0-mm ($\frac{3}{4}$-in.) sieve rather than the 90 to 100 percent passing the 25.0-mm (1-in.) sieve specified for virgin aggregate. After crushing, a high percentage of the virgin aggregate particles in the recycled coarse aggregate are reduced to less than $\frac{1}{2}$ in. because most of the recycled aggregate particles of this size are composed of mortar and aggregate. More recent projects have specified 100 percent passing the 38.1-mm ($1\frac{1}{2}$-in.) sieve and 90 to 100 percent passing the 25.0-mm (1-in.) sieve when good-quality aggregates were used in the pavement being recycled.

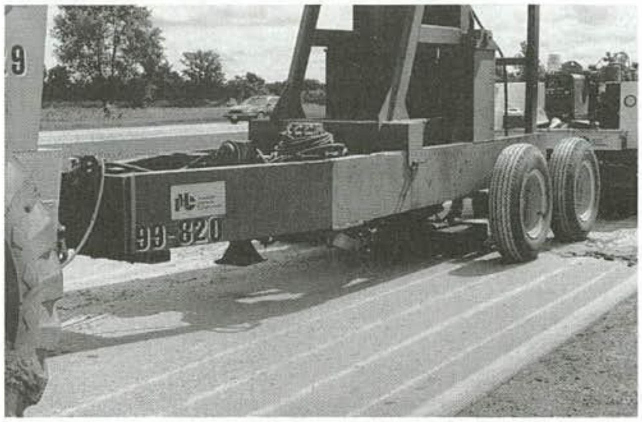

FIGURE 6 Breaker with 4-ft-square impact plate with steel bars.

Pavement Design

Since 1984, pavements built with recycled aggregates have included a 4-in. open-graded base course under the new pavement with an edge drain or other type of collection system. The new pavements on the Interstate routes are designed 10 in. thick, with mesh reinforcement and doweled joints at 41 ft. Tied concrete shoulders are also included. The mesh reinforcement used in the 41-ft panels is the same size as that used in the 99-ft panels being recycled. Epoxy-coated dowels are also used.

Recycling Operations

Improvements were made in equipment for breaking, steel removal, and cracking the heavily reinforced mesh pavements. In 1986, most of the contractors used a 30,000-ft-lb diesel pile hammer with a 4-ft-square impact plate for breaking the pavement (Figure 6). Four square steel bars were welded to the bottom of the plate and leave a pattern as shown in this photo. The breaker was towed by a separate power unit.

Following the breaking operation, contractors used different methods for removing and transporting the broken concrete to the crushing site. One method involves the use of a backhoe with a rhino horn attachment (Figure 7) that is used to lift the broken

FIGURE 7 Backhoe with rhino horn used to lift and windrow broken concrete.

FIGURE 8 Loading concrete with front-end loader. Note clean pickup of concrete.

FIGURE 9 Stockpile of broken concrete.

concrete, separate the pieces, and windrow the material for loading by a front-end loader. The backhoe works off the top of the broken concrete, and any section of pavement too large for the primary crusher is broken by the rhino horn.

The combination of the 30,000-ft-lb breaker and the use of the rhino horn permits removal of the pavement without any steel cutting at the roadway. All steel is removed at the crushing site by self-cleaning electromagnetic belts and by handpicking.

A front-end loader is used to load the broken concrete into trucks (Figure 8). Note the clean pickup from the granular base. Because of the damage that can occur to dump boxes from hauling large pieces of concrete, some of the truckers use a semicircular steel insert inside the boxes for protection. The stockpile of broken concrete is shown in Figure 9.

Contractors have used two different types of crushing systems to produce aggregate from PCC pavements. The most common is a primary jaw crusher with a secondary roll or cone crusher. It has been the experience on some Michigan projects that the primary jaw crusher and secondary roll crusher produce about 80 to 82 percent coarse aggregate meeting Michigan 6A modified specifications, which call for 100 percent passing the 38.1-mm (1½-in.) sieve, 90 to 100 percent passing the 25.0-mm (1-in.) sieve, and 0 to 10 percent passing the 4.75-mm (No. 4) sieve.

The impact crusher results in a much higher percentage of fines. On a recycling project south of Detroit on I-75, the crushing operation resulted in 65 percent coarse aggregate and 35 percent fine aggregate. A backhoe was used to pick up and load the broken concrete, which could have resulted in more fines being carried to the crushing plant than would a front-end loader operation.

Mixture Design and Strength

Tables 8, 9, and 10 give information on the concrete mixture designs used on two recycling projects in 1985 on I-94, one near Albion and the other near Kalamazoo, Michigan (*11*). The fine aggregate used at Albion was 70 percent natural sand and 30 percent recycled material, whereas at Kalamazoo 100 percent natural sand was used.

Table 8 gives the grading of the recycled aggregates used on these projects. The specifications required that the loss by wash could not exceed 4 percent for the blended crushed fine aggregate and the natural-sand fine aggregate. The concrete mixture proportions for these projects are given in Table 9.

TABLE 8
STATISTICAL ANALYSIS OF AGGREGATE GRADING USED IN THE 1985 RECYCLED CONCRETE PROJECTS

	IR 13083-20992 I-94 near Abion							IR 39022-20736 EB I-94 near Kalamazoo		
Material	Crushed Coarse Aggregate			Crushed Fine Aggregate				Crushed Coarse Aggr.		
Sieve	38.1 mm (1 1/2")	25.0 mm (1")	4.75 mm (No. 4)	12.5 mm (1/2")	9.5 mm (3/8")	4.75 mm (No. 4)	75 μm (No. 200)	38.1 mm (1 1/2")	25.0 mm (1")	4.75 mm (No. 4)
Spec. (% Passing)	100	90-100	0-10	100	95-100	90-100	Loss by wash	100	90-100	0-10
N	96	96	96	25	25	25	25	117	117	117
Average	100	89.9	4.3	100	100	95.2	8.2	100	95.1	5.0
Std. Dev.	0	4.8	2.5	0	0	1.7	1.2	0	3.2	2.9
Range		80-99	1-15	100	100	92-99	5.8-10		84-100	1-12

TABLE 9

CONCRETE PROPORTIONING FOR 1985 MICHIGAN RECYCLING PROJECTS

Material	Albion	Kalamazoo
Cement	480 lb	480 lb
Fly Ash	72 lb	72 lb
Recycled Coarse Aggregate	100%	100%
Recycled Fine Aggregate	30%[a]	- -
Natural Sand (2NS)	70%	100%

[a]30% of the fine aggregate portion of the mixture. Air-entraining and water-reducing admixtures are also used.

The strength test results from a sampling of the roadway concrete at approximately 2-mile intervals are given in Table 10. These tests were performed by the MDOT Materials and Technology Laboratory.

Coring of Pavement

The Michigan Department of Transportation determines the thickness of the pavement and the depth of steel reinforcement by drilling 6-in.-diameter cores. Some of these cores are tested for compressive strength for informational purposes (Table 11).

Use of Recycled Aggregate

Based on the grading characteristics of crushed concrete (80 percent coarse and 20 percent fine aggregate) and allowing for a 10 percent loss, the resulting crushed recycled aggregate will provide enough coarse aggregate from a 9-in. pavement, 24 ft wide, to construct a new 10-in. pavement with concrete shoulders of 10 ft and 4 ft. This assumes a 60 percent coarse-aggregate, 40 percent fine-aggregate combination in the mixture.

TABLE 11

COMPRESSIVE STRENGTHS OF RECYCLED CONCRETE PAVEMENT CORES

I-94 near Albion	EB I-94 near Kalamazoo
N = 23 cores	N = 22 cores
Average = 3828 psi	Average = 4907 psi
Std. Dev. = 499 psi	Std. Dev. = 447 psi
Range = 3010-4570 psi	Range = 4120-5470 psi

The natural sand, water, cement, fly ash, and air-entrainment in the concrete mixture all contribute to the volume of a recycled aggregate mixture, thus resulting in enough coarse aggregate to build thicker pavements and shoulders, or for other uses such as an open-graded drainage course. Michigan has permitted the use of recycled coarse aggregate for open-graded drainage courses. The use of recycled fines is not permitted in drainage layers because some of the cementitious materials in the fines go into solution as water percolates through the material and a precipitate forms in the drainage structure or on the geotextile fabric used to wrap the drain.

Cost Savings

When recycling has been performed in rural areas of Michigan on I-94, it is estimated that a savings of 50 to 65 percent in coarse-aggregate costs is realized. Coarse-aggregate costs are $7 to $9/ton at the job site, depending on haul distance.

Recent Experience

Recently problems have occurred on some jointed reinforced-concrete pavements constructed with recycled aggregates. Intermediate cracks in 41-ft slabs were found to be spalling and faulting. It is believed that the recycled aggregate was too small (< ¾ in.) to provide aggregate interlock at the intermediate

TABLE 10

COMPRESSIVE STRENGTH TEST RESULTS

			7-Day Cure		28-Day Cure		90-Day Cure	
	Entrained Air (%)	Slump (in.)	Modulus of Rupture (psi)	Compressive Strength (psi)	Modulus of Rupture (psi)	Compressive Strength (psi)	Modulus of Rupture (psi)	Compressive Strength (psi)
I-94 Near Albion (100% cr. C.A.; 30% cr. F.A.; 70% 2NS sand; fly ash)								
N	5.	5.	10.	10.	10.	10.	10.	10.
Average	6.1	2.0	606	3463	722	4514	782	5655
Std. Dev.	0.8	0.8	48	295	43	411	37	563
EB I-94 Near Kalamazoo (100% cr. C.A.; 100% 2NS sand; fly ash)								
N	4.	4.	8.	8.	8.	8.	8.	7.
Average	6.0	1.25	646	4175	719	5176	777	6066
Std. Dev.	0.3	0.3	41	181	33	220	56	317

cracks and the slab reinforcement was not designed to provide load transfer. In addition, much of the recycled aggregate was heavily mortared, which may have contributed to the lack of aggregate interlock. Although investigation of the problem is continuing, caution should be exercised when using recycled aggregate in jointed reinforced-concrete pavement. It is recommended that a plain pavement with doweled joints be used when recycled aggrgates are used to construct PCC pavements for heavy traffic routes. Joint spacings of 15 to 18 ft are recommended for these pavements.

Traffic Control

With the exception of one project on I-75, in which traffic was diverted to another state trunk line, all reconstruction work on rural Interstates has been performed on closed roadway sections while the other roadway carried two-way traffic.

Precast concrete median barriers are used to help guide traffic at the crossovers. Throughout the remainder of the project an asphalt barrier curb, 4 in. high and 18 in. wide, is placed at the roadway centerline to separate traffic (Figure 10). Plastic reflecterized tubes spaced at 100 ft are placed in a base buried in the barrier. This is a very effective method of separating traffic and substantially reduces the replacement of tubes damaged by traffic.

MICHIGAN URBAN PROJECT—DETROIT

In 1986 and 1987 Michigan reconstructed the John C. Lodge Freeway (U.S. Route 10) in Detroit. The project involved complete reconstruction of an 8.7-mile section of the six-lane freeway. Built in 1956, the Lodge Freeway has been one of the busiest thoroughfares in and out of downtown Detroit, with 120,000 vehicles per day in 1987.

The first phase of the work in 1986 involved widening the roadway by cutting back the side slopes on the depressed highway and constructing retaining walls, barrier walls, and a temporary shoulder. This phase of the work was done under traffic. The second phase of the work, in 1987, involved removal of the existing pavement and reconstruction of both roadways, each

FIGURE 10 Barrier curb with reflectorized tubes used to separate traffic.

FIGURE 11 Reconstructed northbound roadway of Lodge Freeway.

of which had three and four lanes of pavement with concrete shoulders (Figure 11).

The work involved recycling the old concrete pavement as coarse aggregate for the new pavement and placing 463,000 yd^2 of new 10-in. pavement, 101,000 yd^2 of concrete shoulders, and 16,000 lin ft of barrier walls. Recycling of the old concrete produced 200,000 tons of coarse aggregate and 67,000 tons of fine aggregate. The recycled fines were not used in the concrete for the new pavement.

During reconstruction, the northbound roadway was closed first and traffic detoured to other freeways and surface streets. When the northbound roadway was completed it was opened to traffic and southbound traffic was detoured to alternative routes.

Guillotine breakers (Figure 12) were used on this project. The breaker has a 6.3-ton dropweight, which can generate 12,000 to 120,000 ft-lb of energy, depending on the drop height. Because of the weak subgrade, a backhoe that could operate on the broken pavement was used to pick up and load the broken concrete.

A jaw crusher reduced the broken concrete to 3- to 4-in. top size, followed by a cone crusher to further reduce the recycled concrete to $\frac{3}{4}$-in. top size. All steel was removed at the crushing site (Figure 13) by electromagnets and handpicking. The steel mesh was essentially clean of adhering concrete (Figure 14).

Concrete Mixture

The concrete mixture had 451 lb of cement, 113 lb of fly ash, recycled coarse aggregate, and natural sand as a fine aggregate. Recycled fines were not used in the mixture. The strength of the concrete averaged 721 psi in flexure at seven days by centerpoint loading.

Accelerated Construction Schedule

To accelerate construction of this project, the contract allowed only three months for complete removal and reconstruction of each roadway. An incentive and disincentive clause of $30,000/day for early or late completion was included in the contract.

FIGURE 12 Guillotine type of breaker used on Lodge Freeway project.

The project was completed ahead of schedule for both roadways, resulting in a substantial bonus to the contractors and return of the freeway to full use in a very short period of time.

MICHIGAN LABORATORY INVESTIGATION OF RECYCLED PCC AGGREGATE

Fergus (*7*) conducted extensive research on the use of recycled PCC aggregate for construction of new pavements. More details of this research are contained in the Appendix.

FIGURE 13 Crushing equipment used on Lodge Freeway project.

FIGURE 14 Steel mesh cleanup of adhering concrete.

Purpose and Procedures

The principal purpose of Fergus's work was to investigate the feasibility of crushing an existing PCC pavement and using the resulting aggregate in a concrete mixture for a new PCC pavement.

The experimental procedures used for this work attempted to incorporate the complete range of variables found in crushing and using recycled concrete. The basic research procedure was to obtain sufficient amounts of concrete from an existing pavement to perform comprehensive experiments. Material for the standard experiments was obtained from pavement slab sections that had been removed from a highway during a reconstruction project. The slab material was crushed at a commercial crushing plant, with further processing at the laboratory. In addition, pavement cores were obtained from various highway locations for correlation experiments.

Seventy experimental tests related to the determination of aggregate properties were completed. Three hundred eighty tests for the determination of concrete properties were completed. All laboratory tests were accomplished in accordance with ASTM standards or procedures used by MDOT.

Aggregate Properties

The weighted bulk specific gravity and percent absorption of recycled PCC coarse aggregate are shown in the Appendix. The results show a progressive decrease in bulk specific gravity and an increase in absorption as particle size decreases. The bulk specific gravity decreased from 2.52 for material retained on the 25.0-mm (1-in.) sieve to 2.23 for the material passing the 19.5-mm ($\frac{3}{8}$-in.) and retained on the 4.75-mm (No. 4) sieve, with a weighted average of 2.31. The absorption increased from 2.54 for the material retained on the 25.0-mm (1-in.) sieve to 6.50 for the material passing the 19.5-mm ($\frac{3}{8}$-in.) and retained on the 4.75-mm (No. 4) sieve, with a weighted average of 5.00. Visual examination of the aggregates of each sieve size indicates that the top-size material contains a larger proportion of crushed natural aggregate than that retained on the smaller sizes. The aggregates retained on the 4.75-mm (No. 4) sieve were mostly crushed mortar particles.

The percent soundness loss (ASTM C 88 using magnesium sulfate) for the recycled coarse aggregates used in this study varied from 0.4 to 2.0. Soundness loss is not specified in the current Michigan specification; before 1973 a maximum loss of 12.0 was specified.

The percent soundness loss for the recycled fine aggregates used in this study varied from 7.53 to 8.31. Absorption of fine aggregate made from recycled aggregate concrete (re-recycled) was 11.79 percent.

The bulk specific gravity of the recycled fine aggregate varied from 2.15 to 2.23. The specific gravity of the re-recycled fine aggregate was 2.00.

The extremely high absorption and low specific gravities of re-recycled aggregate are assumed to result from the fact that the aggregate particles were mainly crushed mortar and contained progressively higher percentages of entrained air.

Durability

Coarse aggregates produced by crushing portland cement concrete were superior to the control natural gravel in those tests designed to evaluate the effect of aggregate properties with respect to freeze-thaw durability of concrete. Recycled PCC fine-aggregate properties were essentially comparable to the durability properties of the control natural sand.

Salt Content of Recycled Pavement

Michigan uses rock salt as a deicing agent for highways, and there was some concern that detrimental amounts of sodium chloride may have penetrated the concrete used for recycling. Test methods used by MDOT to determine the salt content in bridge-deck concrete were used to determine the amount of salt.

The salt content of recycled PCC aggregates from the sources tested varied from 1.03 to 1.89 lb/yd^3, well under the Michigan limit of 4 lb/yd^3.

Durability of Recycled Aggregate Concrete

Test specimens were exposed to 300 freeze-thaw cycles in accordance with procedure in ASTM C 666-77. Tests were started at 14 days of age.

The durability factors for concrete made with the recycled aggregates were exceptionally high, in the range of 95 to 100 plus. The Young's dynamic modulus of elasticity and Poisson's ratio are within the normal range for saturated concrete.

One of the interesting aspects of this research was the experiment involving the recycling of recycled portland cement concrete. Test results for both aggregate and concrete properties indicate that the re-recycled aggregate was high in quality and durability. Therefore, one may project that existing PCC pavements, in addition to providing an aggregate source for the future, will continue to generate an adequate supply of aggregates for pavement replacement after once being recycled.

WISCONSIN DEPARTMENT OF TRANSPORTATION

The first concrete-recycling project in Wisconsin was in 1983 on a 13.5-mile section of the westbound roadway of Interstate 94 near Menomonie. The recycled aggregate was used to construct an 11-in. concrete pavement and demonstrated the practicality of the concrete-recycling process. In 1984, the eastbound section of this roadway was recycled. Also in 1984, both roadways of a 32-mile section of Interstates 90 and 94 north of Madison were reconstructed with recycled concrete, with additional lanes added to provide six traffic lanes.

Table 12 gives some data on Wisconsin recycling projects from 1983 to 1985. These projects also involved the construction of approximately 106 lane miles of PCC shoulders. Recycling eliminated the need for disposal of the concrete.

TABLE 12

PORTLAND CEMENT CONCRETE RECYCLING IN WISCONSIN

Year	No. of Projects	12-ft Lane Miles Pavt. Placement Using Recycled Concrete	Concrete Removed (s.y.)	Aggregate Conserved (tons)
1983	1	27	192,000	67,900
1984	10	139	992,000	351,400
1985	2	52	363,000	128,000
Totals	13	218	1,547,000	547,300

Rehabilitation of Interstates 90 and 94

A 32-mile segment of Interstates 90 and 94 in Wisconsin was rehabilitated in 1984. The work included the addition of two new lanes and the replacement of the existing four lanes of reinforced-concrete pavement with a 10-in. CRCP (Figure 15) and 6-in. nonreinforced-concrete shoulders. All the reinforcing steel used in the CRCP was epoxy coated and placed on bar chairs. This work was completed under heavy traffic in one construction season. Twenty bridges were also widened and rehabilitated, adding to the complexity of the project.

FIGURE 15 Ten-in. CRCP used for new pavement in Wisconsin.

A 2½-in. bonded concrete overlay was selected in lieu of concrete replacement on a 4-mile section of the project. The bonded overlay was placed on an existing 8-in. section of 23-year-old CRCP.

Project Background

This segment of Wisconsin's Interstate highway system is an important recreational and commercial route, originally opened to traffic in October 1961. The original pavement consisted of mesh- and dowel-reinforced concrete, except for a 4.2-mile section of CRCP. The mesh and dowel pavement was 9 in. thick, with joints at 80 ft. The CRCP was 8 in. thick, reinforced with No. 5 bars spaced at 6 in., set on transverse steel and bar chairs. The steel represented 0.65 percent of the pavement cross section.

This section of roadway carries 30,000 vehicles/day, with more than 30 percent trucks. One-way truck traffic consists of more than 4500/day, with a high percentage of tractor/semi-trailer trucks (85 percent of current truck volume). Traffic volume increased dramatically on summer weekends to typical peaks of 45,000 vehicles/day. The contracts were written to permit a lane closure around certain work sites during weekdays, but two lanes of traffic in both directions were mandatory during weekends and holidays.

Two lanes of traffic were maintained in each direction for peak travel times throughout the construction period, including the bridge-rehabilitation operations. In addition, all interchanges were kept open. As a result, the traveling public experienced only minor inconvenience during construction.

The project was divided into eight contracts of $5 million to $8 million each, which included traffic control, grading, structures, and paving. In addition, there was a marking and signing contract and two other bridge contracts. Approximately 25 contractors and subcontractors were responsible for the work under these 11 contracts. Nearly 200 lane miles of Interstate highway were reconstructed using more than 200,000 yd^3 of concrete recycled into aggregate for the new pavement. This is the largest project in the United States to use recycled concrete as a coarse aggregate in new pavement.

The removal and disposal of the old concrete on a project of this size in an environmentally acceptable manner was of concern to the Wisconsin Department of Transportation. The success of the recycling project in 1983 convinced the DOT engineers that recycling was a feasible option for this project even though good aggregate deposits are readily available in the project area. The use of recycled aggregate was specified for this work.

Durability of Recycled Concrete

Preliminary laboratory investigation was made to assure that concrete pavements using recycled aggregate would have adequate strength and durability for long-term performance. Tests made on concrete specimens cast with recycled materials indicated that the recycled concrete would be as durable as concrete made with natural aggregates. Many of the recycled mixtures tested exhibited better durability than concrete with all-natural materials. Table 13 gives some of the test results on recycled broken concrete pavement blended with natural concrete aggregates. Table 14 gives test reults from another section of the I-94 recycling.

Breaking and Removing Concrete

The equipment used for breaking the concrete was either the diesel hammer (Figure 16) or resonant breaker (Figure 17), with the majority of the breaking done using the diesel hammer.

After pavement breaking, the reinforcement was removed by dragging the broken concrete with a ripper or rhino horn mounted on a track dozer, or extraction forks on a backhoe. This method of dislodging the broken pavement pieces to aid the removal process caused some base course disruption, thus increasing the amount of base course picked up with the salvaged concrete pavement. This operation was supplemented by extensive hand labor to remove the steel reinforcement still adhering to the concrete (Figure 18). Generally, any mesh removed by this type of operation is disposed of as waste material.

Following removal of the major portion of the reinforcement, the broken pavement was loaded for transportation to the crushing site. The use of rubber-tired loaders instead of steel-track loaders minimizes the amount of base pickup. The turning of track loaders causes disruption in the base, resulting in an excessive amount of base course picked up in the removal operation.

Although a small amount of base course will be removed during concrete-salvaging operations, it should be held to a minimum. Base course contributes an excess of unusable fines, especially material passing the 75-μm (No. 200) sieve, which must be removed during the crushing/processing operation.

The broken pavement is then transported to the crushing area, to be processed into ¾-in.- and 1½-in.-top-size aggregate. The same materials gradings are specified as are used in concrete pavements composed of all-natural aggregate (Table 15).

The standard primary and secondary jaw crushers with both wet- and dry-screening operations have been used on these projects. There has been no significant difference in production rates between the two processes. The choice of wet or dry operation has been made by each contractor. Those who have selected the wet screening have done so because they believe they get a more efficient screening operation. Those who have selected the dry screening have not had problems with that process. Both processes have thus far provided aggregate that meets the Wisconsin DOT material specifications, so the DOT has not indicated a preference for one process.

After primary crushing, a magnetic metal extractor is used to separate the steel. This device does an excellent job, and only a minimal amount of steel ends up in the coarse-aggregate piles. The final processing of aggregate is similar to any other crushing operation.

Table 16 gives the typical coarse-aggregate properties of recycled and natural aggregates based on tests performed by the Wisconsin DOT materials laboratory.

Chloride Content of Concrete

Tests were conducted by Wisconsin DOT on samples of concrete from pavements with various years of service. Typically

TABLE 13
TEST RESULTS FOR RECYCLED PAVEMENT IN WISCONSIN (JACKSON COUNTY)

Grading of Materials (% passing)

Sieve	Coarse Aggregate: Natural Aggregate No. 1	Coarse Aggregate: Natural Aggregate No. 2	Coarse Aggregate: Recycled Concrete	Fine Aggregate: Natural Sand	Fine Aggregate: Recycled Fines
38.1 mm (1 1/2")	-	100	100		
25.0 mm (1")	100	44	75		
19.0 mm (3/4")	99	7	49		
12.5 mm (1/2")	36	1	32		
9.5 mm (3/8")	9	---	24		
4.75 mm (No.4)	1	---	14	97	100
2.36 mm (No. 8)				87	74
1.18 mm (No. 16)				76	53
600 μm (No. 30)				46	32
300 μm (No. 50)				15	18
150 μm (No. 100)				3	9
75 μm (No. 200)				1.4	3.9
Fineness Modulus				2.76	3.14

Properties of Materials

	Natural Aggregate: Coarse Aggr.	Natural Aggregate: Fine Aggr.	Recycled Concrete (material ret. on 4.75 mm - No. 4)
Wear, %	20	-	45
Soundness Loss, %	0.6	-	1.5
Specific Gravity	2.60	2.60	2.26
Absorption, %	1.57	0.71	5.55
Colormetric Test, Plate	-	#1	-
Chloride Content, lb/yd^3	-	-	0.46

Properties of Concrete

	Mix A	Mix B	Mix C
Coarse Aggregate	100% Recyc.	75% Recyc. 25% Natural	50% Recyc. 50% Natural
Fine Aggregate	80% Natural 20% Recyc.	80% Natural 20% Recyc.	80% Natural 20% Recyc.
Average Specific Gravity	2.36	2.41	2.46
Grade A, AE, Agg/yd^3, lb	2716	2774	2831
Fine Agg. % of total	45	43	40
Net Water, gal/sk	3.95	3.92	3.80
Slump, in.	2	2	2
Air Agent, /100#	1.5	1.5	1.5
Net Air, %	5.0	5.1	4.5
Density, lb/ft^3	139.6	140.8	144.4

Compressive Strength Test Results (psi)

	Mix A	Mix B	Mix C
7-Day	4250	3980	3990
28-Day	5180	4930	5150
90-Day	6060	5810	5630

Durability (300 cycles, ASTM C 666, Procedure B)

	Mix A	Mix B	Mix C
% loss/gain	+2.0	+1.6	+0.8

Maximum allowable loss after 300 cycles is 40% of original modulus of elasticity.

All coarse aggregate was separated on the individual concrete sieves and recombined to the middle of the Standard Specification gradation requirements.

TABLE 14

TEST RESULTS FOR RECYCLED PAVEMENT IN WISCONSIN (DUNN COUNTY)

Grading of Aggregates (% passing)

Sieve	Crushed Concrete As Received	Crushed Concrete As Used	Fine Aggregate Crushed Fines	Fine Aggregate Natural Sand
25.0 mm (1")	100	---		
19.0 mm (3/4")	84	100		
12.5 mm (1/2")	50	67		
9.5 mm (3/8")	35	34		
4.75 mm (No.4)	20	0	100	100
2.36 mm (No. 8)			76	82
1.18 mm (No. 16)			60	69
600 μm (No. 30)			40	53
300 μm (No. 50)			24	25
150 μm (No. 100)			14	5
75 μm (No. 200)			9.2	2.2

Properties of Materials

	Crushed Concrete	Natural Sand
Loss in Wear Test, %	37	-
Loss in Soundness Test, %	13.4	-
Specific Gravity	2.38	2.65
Absorption, %	4.31	0.75
Calcium Chloride, lb/yd³		
Retained on No. 4	3.90	-
Passing No. 4	0.52	-
Grade	A-AE	A-FA-AE
C.A. Recycled Pav't, lb/yd³	1706	1681
F.A. Natural Sand, lb/yd³	1137	1120
Fly Ash, lb/yd³	-	75
Air Agent, oz/100 lb	1.5	1.5
Water, gal/sk	4.4	4.7
Slump, in.	2 1/2	2 1/2
Air Content, %	6.9	6.1
Compressive Strength (psi)		
7-day	3800	3930
28-day	5190	5480
90-day	5840	6390
Durability (300 cycles, ASTM C 666 Procedure B)		
% Loss	1.3%	2.1%

Maximum amount of loss after 300 cycles is 40% of the original modulus of elasticity.

Materials: Coarse Aggregate -- Crushed pavement retained on No. 4 sieve
Fine Aggregate -- local igneous and dolomitic sand
Fly ash -- ASTM C 618, Class F

the concrete contains 4 to 5 lb of chloride/yd^3 of concrete. Tests of processed material and calculations made with typical batch proportions indicate that chloride in a recycled concrete attributable to the recycled coarse aggregate would be $1\frac{1}{2}$ to 2 lb/yd^3. Virgin aggregate sources would have approximately 1 lb/yd^3 chloride in new concrete mixes.

FIGURE 16 Diesel hammer breaker.

Summary of Aggregate Characteristics

Properties for natural processed gravel and crushed concrete pavement differ somewhat when evaluated as coarse aggregate

FIGURE 17 Vibrating beam resonant breaker.

FIGURE 18 Concrete adhering to steel reinforcement.

TABLE 16

TYPICAL COARSE AGGREGATE PROPERTIES OF RECYCLED PAVING CONCRETE AND NATURAL AGGREGATES (WISCONSIN DOT MATERIALS LAB 1982 - 1985)

	Recycled Paving Concrete	Natural Aggregates
Specific Gravity	2.2 - 2.4	2.6 - 27
Absorption (%)	4.3 - 5.9	0.5 - 1.6
Loss in L.A. Wear Test (%) (50 max.)	20 - 45	20 - 30
Loss in Soundness Test (%) (12 max.)	0.1 - 2.5	0.5 - 2.8

for concrete pavement. Qualitatively, the crushed concrete pavement is comparable to virgin material. Differences to note are that recycled material is lighter, has higher absorption, and contains more than twice as much chloride as the naturally occurring material.

The recycled coarse aggregate has an absorption of 4 to 5 percent and the recycled fines have an absorption in the neighborhood of 8 percent. Recycled fines were not used on the projects constructed before 1985. The soundness loss for recycled coarse aggregate is usually less than 3 percent.

Some Observations by Wisconsin DOT on Concrete Pavement Recycling

Wisconsin reports that it has not had problems maintaining the desired air contents. Compressive strength has been equal to or greater than that typically expected from mixtures using virgin aggregate.

Wisconsin reports that when recycling concrete pavement, the coarse aggregate produced will equal approximately 70 percent of the volume of the original pavement. About 20 percent will be lost as fines passing the 4.75-mm (No. 4) sieve, and about 10 percent is lost during removal and processing operations. The department expects that this loss will be reduced as contractors become more experienced and as equipment and methods improve. The loss would also be less if reinforcing was not present in salvaged pavement. Paving operations needed no alterations to accommodate the recycled mix.

Materials handling, batching, and mixing of the recycled materials was done just as it would be when using virgin aggregates. In order to maintain workability at the paver, it was necessary to add more water and start with a batch of greater slump. This is attributed to the higher absorption value for the recycled aggregates and the fact that those aggregates were dry when batched. Significant reduction in slump occurred between the mixer and the paver, as the dry aggregate absorbed mix water.

The appearance of the plastic concrete and the hardened concrete pavement is no different whether it consists of virgin or recycled aggregates. Compressive-strength testing and evaluation of freeze-thaw durability were used to evaluate concrete quality. Tests indicate that both properties are comparable to those in concrete made with all virgin aggregates. Control cores taken from projects verify the good compressive strength obtained with the recycled aggregate mix.

Recycling was specified in the contract on the initial concrete-recycling projects. This was done to advance recycling technology and gain experience and to minimize a potentially sensitive disposal problem. In analyzing the bid prices received and feedback from contractors, it is evident that recycling is cost-effective for some projects and not for others. Wisconsin is now making it optional with the contractor on reconstruction projects as to whether the PCC pavement is recycled for aggregate or hauled to a landfill site.

Some additional observations:

- Proportioning materials with recycled PCC as coarse aggregate is no different from normal practice.

TABLE 15

CONCRETE AGGREGATE SIZE AND GRADING[a]

	Percent Passing		
	Coarse Aggregate		
Sieve Size	Size No. 1	Size No. 2	Fine Aggregate
50 mm (2 in.)	---	100	
38.1 mm (1 1/2 in.)	---	90 - 100	
25.0 mm (1 in.)	100	20 - 55	
19.0 mm (3/4 in.)	90 - 100	0 -15	
9.5 mm (3/8 in.)	20 - 55	0 - 5	100
4.75 mm (No. 4)	0 - 10	---	90 -100
2.36 mm (No. 8)	0 - 5	---	---
1.18 mm (No. 16)	---	---	45 - 80
300 μm (No. 50)	---	---	10 - 30
150 μm (No. 100)	---	---	2 - 10

[a]Source: Wis. DOT Standard Specifications for Road and Bridge Construction.

• Workability of recycled concrete has been satisfactory.

• The proportion of fine aggregate (natural sand) for recycled mixes has ranged from 40 to 44 percent on Wisconsin paving projects.

• Compressive-strength tests of concrete produced by the washed and unwashed processes have not conclusively proved the benefit of washing.

• Control of concrete slump can be a problem because variation in aggregate moisture is greater (higher absorption).

• Wisconsin DOT has used recycled PCC with fly ash and with water-reducing admixtures.

• Control of the air content of the mortar is comparable to that of other concrete mixtures. Air-content tests of the plastic concrete were corrected for air voids in the recycled coarse aggregate (aggregate-correction factor). This will permit measurement of the air content of the *new* mortar portion of the recycled mixture.

• Concrete made with recycled PCC aggregate will have slightly lower density because the specific gravity of the recycled concrete is lower than that of natural aggregates.

• Compressive strength of recycled concrete will probably be higher than that of concrete made with the natural aggregates common in Wisconsin.

• Durability, as measured by freeze-thaw testing of beams, is comparable for recycled-aggregate concrete and natural-aggregate concrete.

• So far no old concrete pavements have been rejected as a source of concrete aggregate.

IOWA DEPARTMENT OF TRANSPORTATION

Iowa has had a number of recycling projects in addition to those covered earlier in this synthesis. Some of these projects are listed in Table 17 and described below.

I-35 in Story County

A CRCP (Figure 19) constructed with a D-cracking aggregate was recycled and used as base for a new plain concrete pavement with doweled joints. The existing full-depth asphalt shoulders were left in place. Milling of the shoulder surface was done to provide a satisfactory track line for the slipform paver. A subdrain system was installed to provide drainage for the trenched section.

FIGURE 19 Recycling of CRCP.

TABLE 17

CONCRETE RECYCLING PROJECTS IN IOWA

Year	Route	County	Length
1976	U.S. 75	Lyon	
1977	I-680	Pottawattamie	3 miles
1978-79	Iowa Route 2	Taylor & Page	16 miles
1983	I-35	Story	
1985	I-80	Powershick	
1986	I-80	Pottawattamie	
1985	County Road E	Greene	2.37 miles
1986	County routes	Greene	4.3 miles
1987	I-80	Iowa	
1987	County routes	Greene	

I-80 in Poweshiek County

An existing dowel-mesh pavement with 76.5-ft joint spacing was recycled and used as base for a new plain concrete pavement with dowel joints. The old pavement was constructed with D-cracking aggregate.

I-80 in Pottawattamie County

An existing dowel-mesh pavement showing severe distress from D-cracking was recycled and used as a base for a new plain concrete pavement with doweled joints. Two projects were constructed in 1985 and 1986.

Greene County, Iowa

Greene County, Iowa, has a 212-mile network of PCC pavements serving an agriculturally based population. In 1984 the county engineer and his staff began to develop a long-term plan for preservation of their pavements. The older roadways did not meet today's geometric standards for the paved farm-to-market system. Shoulders were too narrow, drainage structures were failing, and horizontal and vertical alignments were sometimes unsafe.

Recycling of existing PCC pavement was considered as a method of reconstruction, and a project was proposed to remove and crush existing pavement, grade and drain the roadway to current standards, and construct a new PCC pavement using crushed concrete as the primary source of aggregate. This method would conserve dwindling supplies of virgin aggregates and eliminate the necessity to provide waste areas for old concrete.

During the winter of 1984–1985, Greene County designed the first major recycling project for a farm-to-market roadway in Iowa, County Road E-18, beginning at Paton and extending 2.37 miles west. The original pavement was constructed in 1955. The 1955 standard design specified PCC pavement 5 in. thick by 20 ft wide, with earth shoulders 4 ft wide. The coarse aggregate was durable river gravel.

The 1985 reconstruction contract specified removing and crushing old pavement, regrading the roadway, installing concrete culverts, and constructing 7-in.-thick-by-22-ft-wide PCC pavement with 6-ft-wide earth shoulders. The cost of total reconstruction was $200,000/mile. Recycling and paving totaled $140,000/mile.

In 1986 the county let a contract for pavement removal, crushing, grading, and drainage on projects totaling 4.3 miles. The original pavements near Payton and Dana were constructed in 1955, 1956, and 1959. The county engineer separated the grading and paving contracts to allow the new grade to settle one winter.

Greene County let contracts in March 1987 for 7-in. PCC pavement that specified use of recycled concrete. The total cost of recycling and paving was $134,000/mile.

The county engineer estimates that 95 percent of the old concrete was reusable as fine and coarse aggregate for concrete. Sufficient material was produced from 1 mile of old pavement to supply aggregate for 2 miles of reconstructed pavement using some natural sand in the recycled mixture. Materials not incorporated in the pavement are used for roadstone, driveway surfacing, or granular shoulders. The county engineer estimates the market value of the excess material at $10/ton.

Greene County has adopted its recycling program for the next five-year planning period. Five or 6 miles of reconstructed pavement using recycled-concrete aggregate will be constructed each year.

MINNESOTA DEPARTMENT OF TRANSPORTATION

Minnesota has constructed additional recycling projects since constructing the recycling project on U.S. 59 that was covered earlier in this synthesis. Recycling and reuse of the material from reconstruction of PCC pavements is at the option of the contractor, provided MinnDOT determines that the aggregates used in building the pavement came from an approved source. Table 18 is a partial list of recycling projects that have been constructed.

Three recycling projects have been completed on I-94 in the Fergus Falls to Evansville area. The additional projects were to be constructed in 1988. The pavement is crushed to a grading with 100 percent passing the 25.0-mm (1-in.) sieve, 95 to 100 percent passing the 19.0-mm (¾-in.) sieve, and 0 to 5 percent passing the 4.75-mm (No. 4) sieve. Minnesota does not use the recycled fines in the concrete for new PCC pavement but requires the use of a natural sand. About 65 percent coarse aggregate is produced in crushing this pavement to the grading specified.

The recycled coarse aggregate was used to construct a new 11-in. reinforced PCC pavement with skewed doweled joints at a 27-ft spacing. The pavement is built 27 ft wide, with the edge stripe 3 ft from the outside pavement edge.

On one 11.2-mile project, it was reported that recycling a 9-in.-thick, 24-ft-wide pavement supplied enough coarse aggregate to build an 11-in.-thick, 27-ft-wide pavement, with about 5000 tons of aggregate remaining.

Minnesota has recycled several projects on Interstate highways, U.S. routes, and state routes. The recycled coarse aggregate has been used essentially in new PCC pavement construction when the old pavement was constructed from an approved source. Pavements showing distress from D-cracking have been recycled into new PCC pavement when durability testing indicates that a durable concrete can be produced.

The sources of glacial gravel determine its susceptibility to D-cracking. The Keewatin glaciation that affected the quality of Minnesota aggregates was centered in Manitoba and Saskatchewan and moved down through western Minnesota into southern Minnesota. It carried some carbonate rock, which is associated with D-cracking. When the carbonate rock content of the glacial gravel is 30 percent or less, D-cracking is not a problem.

The first recycling project in Minnesota on TH-59 north of Worthington contained a glacial gravel of about 55 to 60 percent carbonate particles and evidenced D-cracking. This pavement was 25 years old and was crushed to ¾-in. top size for use in constructing a new PCC pavement. Fly ash was used in the concrete mixture using the recycled coarse aggregate because it was shown by testing to improve the durability of these materials. Minnesota determines the acceptability of recycled aggregate based on freeze-thaw testing using ASTM C 666, Method B modified.

NORTH DAKOTA STATE HIGHWAY DEPARTMENT

North Dakota has completed eight recycling projects on I-94 and I-29 through 1988. North Dakota's first PCC pavement-recycling project was let to contract in July of 1983. Two more concrete pavement-recycling projects were let in September of 1983 and in April of 1984. All three projects involved recycling on North Dakota's Interstate system. The projects have a combined length of 36 miles and involve the recycling of CRCP and jointed concrete pavements (*12*).

North Dakota's first three PCC-recycling projects are summarized in Table 19. The concrete pavement on all three projects showed signs of D-cracking, ranging from moderate to severe. Because tests have shown that crushing a potential D-cracking aggregate to a small size will reduce the D-cracking potential of this aggregate, the North Dakota Highway Department decided that these pavements would be prime candidates for recycling.

The existing pavements were 25, 13, and 26 years old when they were recycled. The performance of the aggregates in these pavements will be improved by recycling, and North Dakota assumes that the new pavement constructed with recycled aggregate will have a service life of at least 25 years.

Since these first three projects, North Dakota has had additional recycling projects on I-94 near New Salem, Medina, Jamestown, Valley City, and Hillsboro.

North Dakota lists the following advantages to removal and recycling of concrete pavements:

- Coarse concrete aggregate is readily obtainable on the project from the old pavement.
- A waste-disposal site does not have to be obtained for the old concrete.
- Substandard geometrics can many times be improved after the pavement has been removed.
- Subgrade problems can be corrected.
- Vertical clearances under overhead structures can be increased.
- Recycling provides a completely new long-lasting roadway.

TABLE 18
CONCRETE RECYCLING PROJECTS IN MINNESOTA

Route	Year	Location	Project Length	Square Yards	Use
U.S. 59	1980	Worthington North	16 mi	229,170	Aggregate for new PCC pavmt.
U.S. 212	1982	West-Central	6.2 mi		Backfill and shoulder agg.
T.H. 15	1982-1983	Martin Co.	11.5 mi	134,780	Agg. for new PCC pavement
T.H. 15	1983		8 mi	95,490	Agg. for bituminous base course for flexible pavement
I-90	1983	Austin area	5.5 mi		Severely D-cracked pvmt. material wasted or used in fill
I-90	1984	Minnesota state line to Beaver Creek			Agg. for new PCC pavement
I-94 W/B	1986	Evansville	11 mi		Agg. for new PCC pavement
I-94 E/B	1987	Fergus Falls	9 mi		Agg. for new PCC pavement
I-94 W/B	1988	Fergus Falls	6.5 mi		Agg. for new PCC pavement
I-94 E/B	1988	Brandon	12 mi		Agg. for new PCC pavement
T.H. 60	1988	Mountain Lake	10 mi		Agg. for new PCC pavement
U.S. 52		Olmstead County			Agg. for new PCC pavement

• Future traffic disruptions caused by pavement maintenance are reduced.

Construction Sequence

The construction sequence on the three initial jobs was as follows: The earthen inslopes of the roadway were bladed away from the bituminous shoulder surfacing before any surfacing was removed. Before the concrete pavement was broken, the contractor removed the bituminous shoulder surfacing material and hauled it to a stockpile site. This was done for two reasons: (a) The potential to contaminate the broken concrete with bituminous material was eliminated and (b) removing the shoulder material first eliminated the lateral support it provided to the concrete slab, and thus made breaking of the concrete easier.

Breaking and Removing Concrete Pavement

Breaking of the concrete was accomplished with three different machines: (a) whip hammer, (b) diesel-driven pile hammer, and (c) resonant pavement breaker.

The whip hammer is a hydraulic hammer mounted on the back of a truck. The hammer-like breaker delivers an impact to the pavement much as a carpenter's hammer does. This machine broke the pavement into relatively large pieces (more than 12 in. in size). Good production for this machine on 10-in. plain, nonreinforced concrete was 1600 yd^2/12-hr day. This machine was used by one contractor to break 10-in. pavement along the edge of the slab because it could work adjacent to a 10-in. drop-off, whereas other equipment could not.

The second type of pavement breaker used was a diesel-driven pile hammer mounted on wheels. The hammer was pulled by a

TABLE 19
NORTH DAKOTA'S FIRST THREE PCC RECYCLING PROJECTS

Project	Location	Length (Miles)	Original Pavement Type	Original Pavement Thickness (In.)	Age When Recycled (Years)
1	I-94 N.D. 30 to Cleveland	12.2	Jointed	10	25
2	I-29 Hillsboro N. & S.	10.7	CRCP	8	13
3	I-94 Eckelson to N.D. 1 South	13.2	Jointed	10	26

dozer. Four passes per 12-ft lane would break the slab into about 2-ft pieces.

The third type of pavement breaker used was the resonant pavement breaker, a relatively new type of pavement-breaking machine at the time this work was under way. The resonant pavement breaker employs vibratory motion to deliver breaking impact to the pavement. The heart of the machine is a 6½-in.-by-18-in.-by 12½-ft-long forged steel beam. Attached to the beam is a 7-in.-wide breaking shoe. The beam is put into vibration with hydraulically driven eccentric weights. The shoe delivers 44 impacts/sec to the concrete pavement. This machine breaks the concrete into small pieces, about 6 in. in size and smaller. This machine broke up to ½ mile of 24-ft-wide, 10-in. nonreinforced concrete pavement/12-hr day. The contractor would start on the outside edge of the pavement and work his way to the centerline, making one pass for about every 8 in. of pavement width. This was done to increase production by providing room for transverse displacement of the broken concrete chunks.

The resonant pavement breaker would completely free most of the reinforcing steel and tie bars from the CRCP and leave them in a suspended condition in the broken slab. After the machine had broken the pavement, it was possible to dig down and pull out longitudinal joint tie bars by hand. Removal of the steel on the CRCP was accomplished with a backhoe equipped with a rhino horn. This tooth was pulled through the broken pavement to dislodge the reinforcing steel and to pull it up to the surface. The exposed reinforcing steel was cut into small lengths with three oxyacetylene torches and then loaded onto trucks. The salvaged reinforcing steel and tie bars became the property of the contractor.

The broken concrete pavement was picked up by two methods. One contractor used a front-end loader to remove the material from the roadbed and load it into end-dump trucks. With a skilled operator the concrete could be removed with very little contamination from the subgrade. A second contractor chose to use a backhoe with a 3-yd^3 bucket equipped with digging teeth to load trucks. A dozer was used with the backhoe to help pile the broken concrete for the backhoe. The dozer blade was equipped with teeth to help eliminate scooping up base material. This operation also provided uncontaminated salvaged concrete.

Processing Salvaged PCC

The broken concrete was stockpiled at the crushing plant. The basic crushing operation for all three projects was similar. The concrete chunks were first passed through a primary crusher, then screened, with the oversize material passing through a secondary crusher. Material from the secondary crusher was again screened and separated into coarse- and fine-aggregate stockpiles. On projects 1 and 3, a 42-in. primary jaw crusher was used to crush the concrete chunks down to about a 4-in. maximum size. The material was then screened on a double 6-ft-by-20-ft deck screen to remove material smaller than 1 in., and the oversized material was carried by conveyor to a 51-in.-diameter cone crusher. After passing through the cone crusher the material was then conveyed back to the deck screen to be rescreened and separated into coarse- and fine-aggregate stockpiles.

As the material was moved by conveyor belt between the primary crusher and the screening units, any reinforcing steel encountered was removed either by hand or by an electromagnetic belt.

TABLE 20
COARSE AGGREGATE GRADATION SIZE 4

Sieve Size	Percent Passing
25.0 mm (1 in.)	100
19.0 mm (3/4 in.)	90 - 100
9.5 mm (3/8 in.)	20 - 25
4.75 mm (No. 4)	0 - 10
2.36 mm (No. 8)	0 - 5
75 μm (No. 200)	0 - 1

Screened material was separated into two stockpiles: one for material smaller than the 4.75-mm (No. 4) sieve and the other for material larger than the 4.75-mm (No. 4) sieve but smaller than the 25.0-mm (1-in.) sieve. The crushing of the old pavement yielded about 60 to 65 percent coarse aggregate by volume and 35 to 40 percent fine aggregate. Design estimates for the amount of coarse aggregate that will be produced when concrete is crushed are now based on a 65/35 (coarse/fine) split minus an estimated percentage of material wasted in salvage and crushing operations and lost in yield and in stockpiling operations. These losses are estimated to be between 5 and 10 percent.

The crushing operation produced 210 to 275 tons of material an hour. According to specifications, the contractor has to adjust the crushing operation to maximize the amount of crushed material retained on the 4.75-mm (No. 4) sieve while still maintaining a North Dakota size 4 coarse-aggregate grading. The grading is given in Table 20.

The crushing operation produced from 1.5 to 3 percent of material passing the 75-μm (No. 200) sieve in the coarse aggregate. The contractor set up a spray bar arrangement on a conveyor belt to wash the crusher dust from the coarse aggregate to meet the requirement of only 1 percent passing the 75-μm (No. 200) sieve.

Mixture Design

A typical mixtue design for North Dakota's first recycling project is given in Table 21.

This mix substituted fly ash for 15 percent of the cement by weight and allowed the use of recycled fine aggregate in the

TABLE 21
ORIGINAL RECYCLED CONCRETE MIX DESIGN

Material	Quantity (lb/yd^3)
Cement (Type 1)	439
Fly Ash	78
Water	247
Virgin Fine Aggregate	584
Recycled Fine Aggregate	584
Recycled Coarse Aggregate	1753

concrete. Use of the very angular recycled fines produced a harsh mix that was difficult to finish. The recycled fines had an absorption of 7.2 percent, which made control of the water content very difficult. This resulted in concrete strengths that were very inconsistent. To overcome this problem the amount of recycled fines was reduced and finally eliminated in order to obtain higher and more consistent strength results.

The mixture design currently being used is shown in Table 22.

Subgrade Preparation

Removal of the pavement on all three projects revealed wet subgrades. Subgrade preparation bid items were set up on projects 1 and 3 to dry out the subgrade. The existing aggregate subbase was removed from the subgrade and windrowed with a motor grader before subgrade scarification began. The subgrade was then scarified with a disk to dry it out. Salvaged crushed concrete fines were also mixed into the subgrade to act as a drying agent in wet areas. Scarification depths ranged from 6 in. to 24 in., depending on the subgrade condition. The subgrade was then compacted to 90 percent of the maximum dry density as determined by AASHTO T 180. The existing aggregate subbase, which had been windrowed, was mixed with salvaged recycled fines to provide 4 in. of aggregate base upon which to pave.

On project 2, the subgrade, which was heavy clay-type soil, was also scarified with a disk to dry. The subgrade was then treated with lime and fly ash to provide a 6-in. lime-fly ash-treated base. Both the lime and the fly ash were applied at a rate of 3 percent by weight of the subgrade soil. In several areas the depth of the lime-fly ash-treated base had to be increased to several feet to stabilize the clay-type soils.

On project 2, the original 8-in. CRCP was laid over 2 in. of plant-mix bituminous base on top of 6 in. of lime-fly ash-treated subgrade. Originally it was planned to recycle the 2-in. bituminous base to provide a new bituminous base for the 9-in. recycled concrete pavement. The 2-in. bituminous base became very contaminated in the salvaging operation. A change order was subsequently issued to crush the salvaged bituminous material and blend it with the salvaged recycled fines in a 65/35 ratio (65 percent salvaged bituminous pavement and 35 percent recycled concrete fines). The blended material was laid to a depth of 5 in. on top of the lime-fly ash-treated subgrade. The blended material set up very well and provided a very good base on which to pave.

Paving Operation

Paving with the recycled-concrete aggregate proceeded like any normal slipform concrete-paving project. The concrete pavement on project 1 was produced with a conventional 9-yd^3 central-mix plant. An auto grader was used to fine grade the aggregate base. Recycled concrete was then supplied to a belt placer followed by a conventional slipform paver. An artificial-turf drag followed by a transverse tining machine was used to provide the surface texture necessary for a skid-resistant pavement. The last machine in the paving train applied a sprayed membrane-curing compound. Skewed transverse contraction joints were sawed into the pavement. The joints were sawed at a 6:1 skew with random repetitive spacings of 12, 13, 16, and 14 ft.

TABLE 22
RECYCLED CONCRETE MIX DESIGN

Material	Quantity (lb/yd^3)
Cement (Type I)	439
Fly Ash	78
Water	247
Virgin Fine Aggregate	1191
Recycled Coarse Aggregate	1786

Costs

A substantial savings is realized when recycled aggregate is used instead of virgin aggregate (Table 23). The cost of virgin coarse aggregate ranged from $12 to $14/ton delivered to the plant site. The cost of removal of the old concrete pavement, estimated at about $2.50/yd^2 for 10-in. nonreinforced pavement, would be the same for both concrete replacement or recycling and thus can be ignored in the cost comparison of the two aggregates. Concrete-crushing costs, which would be charged only to the coarse aggregate produced, if crushed fines are not used in the mix, are estimated at about $4/ton of coarse aggregate. Assuming that crushing costs could run as high as $5 per ton, a conservative estimate of savings ranging from $7 to $10/ton is realized when recycled coarse aggregate is used. Using the mix design in Table 21 and the recycled pavement with PCC shoulders, the use of recycled coarse aggregate results in a savings of $35,000 to $50,000/mile of concrete pavement, when the cost of virgin aggregate is in the $12 to $14/ton range. Additional savings are realized in not having to dispose of the old concrete and eliminating the possibility of damaging haul roads used for aggregate delivery or waste concrete disposal.

Findings and Conclusions

North Dakota's findings and conclusions derived from projects 1 through 3 are summarized as follows:

- Recycling can be an economical solution to PCC pavement rehabilitation. The economics are determined by the availability of good-quality concrete aggregates.
- The crushing of concrete down to a 1-in. maximum size will yield about 60 to 65 percent by volume of coarse aggregate retained on the 4.75-mm (No. 4) sieve.
- The use of crushed concrete fines [material passing the 4.75-mm (No. 4) sieve] in a recycled mix is not recommended because the water demand is greatly increased, making it very difficult to control the water/cement ratio and to get consistent concrete strengths.
- The crushed concrete fines are very angular, and when used in the recycled mix, make finishing difficult.
- Crushed concrete fines are very absorbent and thus are a good material to use to help set up a wet subgrade.
- Crushed concrete fines mixed with crushed salvaged bituminous pavement and used as a base course set up very well and provide an excellent surface on which to pave.

TABLE 23
COST COMPARISONS OF RECYCLED AND VIRGIN AGGREGATE

	Recycled Aggregate		Virgin Aggregate	
			Fine Aggregate	Coarse Aggregate[a]
Project	Items	Bid Price	Bid Price	Bid Price
1	Removal, hauling, and crushing 10" PCC pavement	$2.10/yd²	$11.00/ton	$14.00/ton
2	Breaking, removal, hauling, and crushing 8" CRCP pavement	$4.37/yd²	$6.75/ton	$12.00/ton
3	Breaking, removal,hauling, and crushing 10" PCC pavement	$4.00/yd²	$11.00/ton	$13.00/ton

[a] Virgin coarse aggregate was used as there was not enough recycled coarse aggregate to pave the entire length of the projects because concrete shoulders were added to the typical section.

• Continuously reinforced concrete can be broken and nearly all reinforcing steel can be removed on the roadway before it is hauled to a stationary crusher.

• With skilled equipment operators, broken concrete pavement can be picked up on the subgrade with very little contamination.

In conclusion, the recycling of North Dakota's concrete pavements to date has been considered a success both functionally and economically. North Dakota plans to continue to recycle concrete pavements when major concrete pavement-rehabilitation projects are required.

WYOMING HIGHWAY DEPARTMENT

The Wyoming Highway Department has recycled several projects on I-80 and I-25, from Pine Bluffs in southeastern Wyoming to Green River in southwestern Wyoming (*13*). The recycled aggregates have been used in concrete mixtures to build new PCC pavements and shoulders.

The aggregates used to construct the pavements in the Pine Bluffs area contained traces of a rhyolitic volcanic material, resulting in an alkali-silica reaction causing severe distress in the form of map cracking at the surface (Figure 20), and delamination, resulting in potholes, spalling, and joint failure. The pavement was constructed in 1965. Wyoming was the first state to recycle pavements suffering from alkali-silica reaction.

FIGURE 20 Surface cracks caused by alkali-silica reaction.

Wyoming Highway Department personnel believe that recycling is a feasible rehabilitation option when the service life of an existing pavement cannot be economically extended by other restoration techniques. Recycling also offers many advantages, which include:

• Existing pavements represent a large supply of potentially good aggregates.

• Recycling eliminates many of the problems of waste disposal inherent in other repair techniques.

• Subgrade problems can be improved during a recycling project.

• Substandard geometrics can be improved during recycling.

• Vertical clearance and grade problems can be minimized and/or corrected during recycling.

• Drainage problems in the subgrade or base can be addressed during recycling.

• Significant energy savings can be obtained by recycling materials, especially in the areas of materials handling and materials production. Typically there is an energy savings of 8 to 15 percent between conventional and recycled concrete.

Economic considerations are the primary reason for recycling, although environmental benefits are derived as well. As remaining aggregate supplies become less accessible for convenient and economical use, recycling will conserve supplies of natural aggregate and reduce amounts of solid waste.

Observations of Wyoming's Highway Department

Recycled portland cement concrete is produced and handles much like conventional concrete. Recycled-concrete aggregates typically have higher absorptions, lower specific gravities, and higher abrasion ratings than natural aggregates and therefore adjustments are necessary in the mixture design stage. The inclusion of recycled fine aggregates in the mixture normally results in stiffer or harsher concrete characteristics and is therefore tempered by blending natural fines, increasing water and cement proportions, adding fly ash, and/or using a water-reducing admixture. Compressive and flexural strengths typically equal or exceed the existing pavement strengths because of the presence of more fractured faces in the aggregate and reproportioned cementitious components. There is some evidence that concrete made with recycled aggregates has improved durability and freeze-thaw resistance.

Recycling Pavements Showing Distress from Alkali-Silica Reaction

The first project was located in the Pine Bluffs area on I-80. This project, located in southeastern Wyoming, was 7.07 miles of divided Interstate highway.

The existing roadway consisted of parallel 24-ft-wide, 8-in.-thick PCC pavement on 6 in. of crushed base overlying a natural silty-loam subgrade. The roadway included 10.5-ft outside shoulders and 2.5-ft inside shoulders consisting of 2½-in.-thick plant-mix pavement on 11½ in. of crushed base.

The pavement was constructed with aggregate from local sources and had traces of a rhyolitic volcanic material. The pavement was suffering from severe distress, including extensive map cracking with resulting potholes, spalling, and joint failures. Maintenance had included isolated areas of AC overlays in the driving lanes and patching of potholes with asphalt material as a temporary measure to restore ride quality. These remedial measures soon failed because of reflective cracking and delamination. The average annual daily traffic (AADT) in 1984 for this section of Interstate 80 was 4360 vehicles, with approximately 33 percent of the traffic being trucks.

An evaluation of the existing pavement indicated the presence of a silica-type aggregate with reactive constituents soluble in alkali solutions. In the presence of a water-soluble alkali source, provided by the cement and moisture in the original pavement, these ingredients set in motion the factors necessary for an alkali-silica reaction. This reaction forms a gel that creates internal pressures in the concrete that are relieved through extensive cracking of the pavement. This deterioration was hastened by increasing traffic loadings experienced by this section of roadway in particular and Interstate 80 in general throughout Wyoming.

Recycling of the existing pavement into a thickened pavement was chosen as the most feasible technical and economic alternative and was chosen as the preferred rehabilitation approach.

The rehabilitation problem then centered on countering the reactive-aggregate problem in the existing pavement. Research and consultations with the Portland Cement Association (PCA), including a joint long-term study on reactive aggregate by the PCA and the Wyoming Highway Department, led to the following plan of action:

- After 20 years, it was assumed a significant amount of the reactiveness of the aggregate had been tied up.
- A low-alkali (< 0.60 percent as NaO) Type II cement would be used in the recycled concrete pavement.
- Coarse aggregate in the recycled PCC pavement would consist of recycled material larger than the 4.75-mm (No. 4) sieve blended with virgin limestone aggregate produced from a state quarry west of Cheyenne in an effort to temper reactive constituents of recycled material.
- A fly ash meeting the requirements of ASTM C 618 for reduction of expansion would be incorporated in the mixture design.

It was believed that the virgin coarse-aggregate blending would also increase flexural strengths and provide more aggregate interlocking at joints, thereby enhancing the structural effectiveness of the pavement. In addition, the fly ash would benefit workability and durability of the recycled PCC pavement.

Mixture Design

The preliminary mixture design was established as given in Table 24. A water-reducing admixture was also used. The virgin coarse aggregate had a Los Angeles "B" abrasion rating of 31.8 percent, whereas the recycled coarse aggregate had a rating of 38.3 percent. Specific gravity and absorption of the materials are given in Table 24.

The new pavement was paved 38 ft wide with a 24-ft mainline pavement and a 10-ft outside and 4-ft inside shoulder. The pavement was 10 in. thick on 4 in. of existing crushed-aggregate base. Transverse joints were skewed and at variable spacing of 14, 16, 13, and 12 ft.

A significant amount of testing was done by the Wyoming material laboratory during the mix design stage on three Class F fly ashes and one Class C fly ash to determine acceptability based on ASTM C 618, Table 2A requirements. The fly ashes were tested by the procedures outlined in ASTM C 441. It was found that only one of the fly ashes tested met the "Average Expansion—Job Mix" criteria outlined in Table 2A and that this fly ash also optimized the "Reduction in Mortar Expansion" values relative to the other fly ashes tested. This fly ash was specified in the construction job mix.

The recycled coarse aggregate was to be crushed to a 1-in. maximum size and split on the 4.75-mm (No. 4) sieve. The virgin coarse aggregate was specified to meet a No. 57 grading of 1-in. top size.

The concrete mixture used during construction was adjusted to increase the recycled coarse aggregate 22 lb/yd^3 and the virgin fine aggregate was increased 20 lb/yd^3 to adjust yield and balance the use of available materials. The net water requirement of the mixture was 237 lb/yd^3, with a water-to-cementitious-material (cement plus fly ash) ratio of 0.382 and a unit weight of 141.1 lb/ft^3 at a 5.5 percent air content.

The 28-day flexural strength averaged about 700 psi, the air content ranged from 5.3 to 5.6 percent, and slump was in the range of 1 to 1½ in.

Project I-80, Green River Marginal

This project, located in southwestern Wyoming, was 5.95 miles of divided Interstate highway fronting the city of Green River. The existing roadway consisted of parallel 24-ft-wide, 8-in.-thick PCC pavement on 8 in. of crushed base. The roadway had 10-ft outside shoulders and 2-ft inside shoulders consisting of 2 in. of plant-mix pavement on 14 in. of crushed base. The AADT in 1984 for this section of roadway was 13,745 vehicles, with a projected AADT of 23,200 in the year 2004. The recycled

TABLE 24
PRELIMINARY MIX DESIGN (WYOMING)

	Preliminary Mix Design (lb/yd³)	Specific Gravity	Absorption
Recycled coarse aggregate	1107	2.45	3.31%
Virgin coarse aggregate	601	2.65	0.83%
Recycled fine aggregate	253	2.36	6.45%
Virgin fine aggregate	882	2.63	0.76%
Fly ash	133		
Portland cement	488		

PCC pavement was designed using 2551 18-kip single-axle loads/day based on a design lane average daily truck traffic of 2345.

The roadway was constructed in 1967 on essentially new alignment using local materials. The pavement on this project was nearing the end of its design life. A series of defects and failures were developing that were only partially correctable by maintenance projects. Increased traffic, severe climatic conditions, and age had caused pavement distress in the form of isolated cracking, spalling, and faulting at the joints. The primary difference between this project and the Cheyenne-Pine Bluffs project was the absence of reactive aggregate in the existing pavement.

The decision was made to recycle and reconstruct this pavement as the most feasible alternative from an economic and technical standpoint. The virgin coarse aggregate was found to have a LAR "B" abrasion rating of 20 percent, whereas the recycled coarse aggregate had a rating of 39 percent. Specific gravities of the virgin material were approximately 2.6, and the recycled material typically ranged from 2.3 to 2.4. Absorptions of the recycled material typically were around 5.5 percent and 7.2 percent for coarse and fine aggregate, respectively.

The recycled coarse aggregate was graded to a 1-in. maximum size with 95 to 100 percent passing the 19.0-mm (¾-in.) sieve and 0 to 5 percent passing the 4.75-mm (No. 4) sieve. A minimum ¾-in. nominal crushing size was maintained on both coarse-aggregate materials.

Mixture Design

The preliminary mix design was established as follows:

Recycled coarse aggregate	1349 lb/yd³
Virgin coarse aggregate	254 lb/yd³
Recycled fine aggregate	233 lb/yd³
Virgin fine aggregate	898 lb/yd³
Fly ash	133 lb/yd³
Portland cement	488 lb/yd³

A water reducer was used in the mixture. The roadway section was 38 ft wide, with a 24-ft mainline pavement with a 10-ft outside and a 4-ft inside PCC shoulder.

The water-to-cementitious-material (cement plus fly ash) ratio on the job mix was 0.416. The seven-day flexural strengths typically exceeded 700 psi, and 28-day cylinders typically had compressive strengths exceeding 4000 psi. The net water requirement for the job mix was 258 lb/yd³. The unit weight of the mix was 135.9 lb/ft³.

Conclusions of the Wyoming Highway Department

The Wyoming PCC pavement-recycling projects proved to be highly successful from an economic, technical, and construction standpoint. It is apparent that recycling PCC pavement can currently save anywhere from $35,000 to $50,000/mile on two-lane PCC roadways and approximately 50 to 65 percent of the aggregate cost when compared with a conventional portland cement concrete.

As the economic and technical advantages of recycling become more apparent, and contractors and construction professionals become more familiar with its use, recycling PCC pavement will become an essential tool in future concrete pavement-rehabilitation strategies.

OKLAHOMA DEPARTMENT OF TRANSPORTATION

The first PCC recycling project in Oklahoma was a 7.75-mile section of I-40 east of Oklahoma City. This project was constructed in 1983 (*14*).

Project Description

The original pavement, constructed in 1961, was 9-in.-thick plain portland cement concrete with a 15-ft joint spacing. The only steel used was centerline tie bars 30 in. long on 30-in. centers. Both the 4-ft inside and the 10-ft outside shoulders were constructed of soil cement with a 1-in.-thick "chip & seal" wearing coarse. The roadway and shoulders both rested on a 6-in. soil-asphalt base, which in turn rested on 5 in. of select material. The original pavement was constructed with a limestone coarse aggregate with a maximum nominal size of 1.5 in. The pavement experienced moderate D-cracking after 22 years of service.

Rehabilitation

The project was first conceived as a breaking and seating of the existing PCC pavement and overlaying with AC. The original

15-ft.-long panels were to be mechanically fractured transversely at approximately the $\frac{1}{2}$ and $\frac{1}{4}$ points. The fractured pavement would then be cleared of loose, spalled concrete and rolled with a 50-ton, pneumatic-tired roller to seat the fractured pavement. An AC leveling course would be topped with 6 in. of hot-mix AC and an open-graded friction wearing course.

The alternative concrete design consisted of removing the existing 9-in. PCC pavement and replacing it with 10 in. of plain, undoweled PCC pavement while leaving the shoulders intact. The contractor had the option of using natural aggregate or recycled aggregate. Pay quantities included provisions for reconstruction of the 6-in. soil-asphalt base, if necessary. After the new pavement was placed, plans called for 1 in. of the shoulder to be cold milled and surfaced with 2 in. of hot-mix AC material. Drainage was not specified for either alternative.

The project was let to contract in July 1982. The low bidder chose to recycle the existing PCC pavement. The nearest source of natural aggregate was a quarry more than 50 miles away. The contract amount of $5.2 million to recycle the PCC pavement was $675,000 less than the crack and seat asphalt overlay alternative.

Removal and Crushing

A portable aggregate-crushing plant and a PCC batch plant were first placed in the median of the west half of the project and then moved to the east half of the project. In both cases, the eastbound lanes were constructed, then the westbound lanes. Traffic was detoured from the roadway being replaced to the adjacent roadway, with two-way movement.

Paved crossovers used portable concrete barriers to provide positive guidance. The ends of the barriers were protected by impact attenuators. Flexible delineator posts with rubber mat bases were placed on 200-ft centers to keep two-way traffic separated. Because the ADT exceeded 20,000 vehicles, maintenance forces had a never-ending job replacing the plastic delineator devices. On more recent projects in other states, an asphalt curb section 18 in. wide and 4 in. high with bases for delineator posts has been placed in the roadway centerline to separate traffic and protect the delineator posts.

Breaking the existing pavement was the first step in pavement removal. The contractor used two different breaking hammers, although both used diesel pile drivers that exerted 18,000 ft-lb of energy (Figure 21). Several different breaking patterns were tried. Starting at the centerline and alternately working toward the shoulders 18 in. at a time seemed to disturb the soil-cement shoulders the least.

When the pavement had been broken, a crawler loader lifted the rubble into the waiting bucket of a wheeled loader. The more maneuverable wheel loader then placed the rubble in the dump beds of waiting haul trucks. To reduce the amount of soil-asphalt picked up by the loader, the crawler made two passes on the rubble with a ripper to dislodge the broken concretes. Even more efficient production resulted when a backhoe used a ripper tooth (a rhino horn) in place of a bucket. The backhoe worked between the loaders, providing a continuous supply of loosened rubble.

The broken rubble was delivered to a standard crusher plant that uses hammer mills on both the primary and the secondary crushers. The small quantities of steel rebars were removed by a cross-belt magnet suspended over the conveyor belt between the crushers. Wire cages holding dowel bars, originally used as construction joints, were extracted by the front-end loader operator as he loaded the primary crusher bin. The plant was able to produce 43 to 45 percent (by weight) of the broken rubble as coarse aggregate. The hammer mills produced more fine materials than expected in the crushing process. These fines became the property of the crushing plant subcontractor.

The coarse aggregate met the size requirements; a typical analysis is given in Table 25. A typical analysis of the fines from the crusher operation is also given in Table 25. After the pavement in the first of the four sections of the project was crushed, an additional virgin aggregate was needed to finish paving those sections.

By change order, the grading was changed to the revised specification given in Table 25. The output of the crusher plant was improved to 55 to 60 percent coarse aggregate on the second section by replacing the secondary hammer mill with a triple roller crusher and the change in grading.

To reduce the potential for future D-cracking, the maximum nominal aggregate size allowed was $\frac{3}{4}$ in.

FIGURE 21 Diesel hammer breaker.

Mixture Design

In addition to reduction in aggregate top size, a fly ash was used in the mixture; 20 percent fly ash by weight replaced 15 percent of the cement as per Minnesota experience. The recycled-aggregate concrete was specified to meet Class A concrete standards, with a minimum seven-day strength of 3000 psi.

The mixture design for the project is given in Table 26. The recycled fine aggregate was not used in the mixture.

Compressive-strength tests in the laboratory showed that the recycled-aggregate mixture had an average strength of 3600 psi at seven days and the natural-aggregate mixture had an average strength of 3850 psi.

Pavement Construction

The contractor experienced an average 1.5-in.-lower subgrade than the job was designed for, and this presented a problem in restoring subgrade elevation in a trench, which is difficult work. The profile misfit after removal was caused by a combination of compaction by construction operations, thicker pavement than

TABLE 25
AGGREGATE GRADING (OKLAHOMA)

	Coarse Aggregate			Fines
Sieve Size	Percentage Passing	Specification	Revised Specification	Percentage Passing
25.0 mm (1 in.)	100.0	100	100	
19.0 mm (3/4 in.)	98.5	90 - 100	90 -100	
12.5 mm (1/2 in.)	46.5	20 - 55	25 - 60	100.0
9.5 mm (3/8 in.)	11.2	0 - 15	0 - 25	99.2
4.75 mm (No. 4)	1.5	0 - 5	0 - 10	78.8
2.36 mm (No. 8)			0 - 5	
2.00 mm (No. 10)				48.5
425 µm (No. 40)				19.4
180 µm (No. 80)				9.2
75 µm (No. 200)				4.5

designed, high shoulders from seal coats, and base material removed with the concrete.

To restore the grade and eliminate the need to mill the shoulders, an average of 3.5 in. of soil-asphalt was added to the base. This elevated the surface of the new 10-in. pavement a minimum of 2 in. above the uneven, worn shoulders. A pugmill was used on the site to produce 6560 yd^3 of soil asphalt. The material was placed, blended with the existing soil-asphalt base with a pulvermixer, and compacted. An autograder milled a precision grade before the concrete was placed. Excess soil-asphalt was stockpiled for use in the base of the next section.

After the soil-asphalt was made for the first section, it was found that by combining the fines from the crusher plant with the existing 6-in. soil-asphalt base, the necessary profile could be met, and sufficient base strength resulted. The remaining sections had fines instead of soil-asphalt blended into the base.

Paving Operations

Paving began on the first section in May 1983, with a slipform paver. The nonreinforced slab was 10 in. thick and 24 ft wide. The concrete was produced by an 8.5-yd^3, dual-drum central-batch plant (Figure 22). However, only 6 yd^3 of concrete were mixed at a time. The contractor used the outside shoulder as a haul road to the paving operation and wanted to minimize damage. Steel wedges protected the shoulder edge as loaded dump trucks turned off the shoulder onto the prepared base. The end-dump, single-unit trucks then backed to the slipform machine to deliver their loads of concrete.

Samples were taken as the concrete was delivered to the paver. Slump averaged 1.5 to 2 in. and air content was 4.6 percent. Test cylinders made of the recycled PCC yielded seven-day compressive strengths in the 3160 to 4580 psi range.

The concrete looked as good and handled as well with recycled aggregate as with natural aggregate. After the paving train placed the concrete, it was tined transversely for skid resistance. The last operation on the paving train was to spray the surface with a curing compound. Joints were sawed (skewed 4 ft. from perpendicular) every 15 ft, cleaned, and filled with silicone sealer. The shoulders were paved with an average of 2.7 in. of a dense-graded hot-mix AC.

TABLE 26
MIXTURE DESIGN

	Recycled Aggregate	Natural Aggregate
Portland cement (lb)	479	479
Fly ash	115	115
Entrained air (%)	5	5
Natural sand (lb)	1,130	1,206
Coarse aggregate	1,695	1,864
Water (gal)	30	30
Density (lb/ft^3)	136	145

FIGURE 22 Central-mix concrete plant and recycled-aggregate stockpile.

Observations

When the project was completed, about 3000 tons of coarse aggregate was left over. Recycling resulted in the conservation of 63,000 tons of virgin aggregate and a cost savings to the Oklahoma Department of Transportation of $675,000.

When recycling PCC pavements, the grading band should be adjusted to maximize the recovery of coarse aggregate. More coarse aggregate can be recovered when crushing to a larger top size, if feasible. With a 1-in. top size, a recovery of 55 to 65 percent can be expected, whereas with a 1½-in. top size, up to 80 percent can be recovered.

Subgrade conditions should be investigated before the design of a recycling project. The pavement base and subgrade conditions should be investigated throughout the project to develop an orderly plan for any corrective action needed. It is too late to deal with surprises when traffic has been detoured and there is pressure to complete the work. No drainage was installed in this "bathtub" section of roadway and some pumping is evident, which has resulted in about a $\frac{1}{10}$-in. fault at some joints.

Project I-35, Oklahoma City—Logan County

In April 1988, the Oklahoma DOT awarded a contract to reconstruct a 5.77-mile section of I-35 north of Edmond. The original dowel-mesh pavement with soil-cement shoulders was constructed in 1960. The contractor planned to recycle this pavement into a new 10-in. CRCP with PCC shoulders. Epoxy-coated steel will be used for the CRCP. A drainage system will also be installed during construction.

CHAPTER FOUR

AIRPORT PAVEMENT RECYCLING

Recycling of airport pavements has been proceeding at an accelerating pace in the past few years. Table 27 is a partial list of recycling projects at airports. Following is a description of some of these projects.

LOVE FIELD, DALLAS, TEXAS

At Love Field in 1964 a new 8800-ft. runway, parallel taxiway, high-speed turnoffs, hold apron, and an extension of an existing 4500-ft. runway were built of new 13-in. concrete. All of this pavement was placed on a 6-in. cement-treated subbase (CTSB). The contractor decided to use crushed concrete from old pavement on the site of the new runway as aggregate in the CTSB. The aggregate was 72 percent crushed concrete and 28 percent natural sand, and 4 percent cement by weight was added. A continuous-flow pugmill mixer was used. The mixed material was hauled in dump trucks and spread 7½ in. thick before being rolled and compacted with steel-wheeled, vibratory, and pneumatic-tired rollers.

JACKSONVILLE INTERNATIONAL AIRPORT, FLORIDA

Early in 1977, concrete recycling was used in construction of a new keel strip in a runway at the Jacksonville International Airport. Rather than overlay the entire runway, it was decided to recycle the existing concrete in the two center 25-ft-wide lanes (Figure 23). The 11-in. concrete was broken up by drop hammers, removed, and hauled to a crushing plant on the airport site. The concrete was crushed to 2-in. top size, separated on the 9.5-mm (⅜-in.) sieve, and stockpiled for use in a filter course and econocrete base.

TABLE 27
AIRPORT RECYCLING PROJECTS

Location	Job Size	Year	Use
Love Field, Dallas	8,800 R/W, T/W & Apron	1964	Cement-treated base for new PCC pavement
Jacksonville International Airport, Florida	R/W Keel - 50 ft	1977	6" lean concrete base & 6" open-graded drainage layer
FAA-ANG, Atlantic City	75,000 yd²		Cement-treated base for new 14" R/W PCC pavement and as agg. for outside lane of new R/W pavement
Oklahoma City, Will Rogers Airport	150,000 yd² terminal apron replacement - Removed 12" PCC		8" cement-treated base for 16" PCC pavement
Denver Stapleton Field	Remove 8,000 ft R/W - Asphalt and concrete - 47,000 yd² concrete		14" cement-treated base under new runway pavement
Atlanta Hartsfield Airport, Georgia	4th E/W Runway - 187,000 yd² removed from old terminal area - up to 16" thick reinforced with mesh		Cement-treated base for new PCC
Richmond, Virginia International Airport	Removed 75 ft of pavement on each side of 300 ft R/W		10" cement-treated base for new pavement
O'Hare Airport	157,000 - 120,000 yd² - 6" floor slabs on base		Used as cement-treated base for reconstructing parking apron & T/W

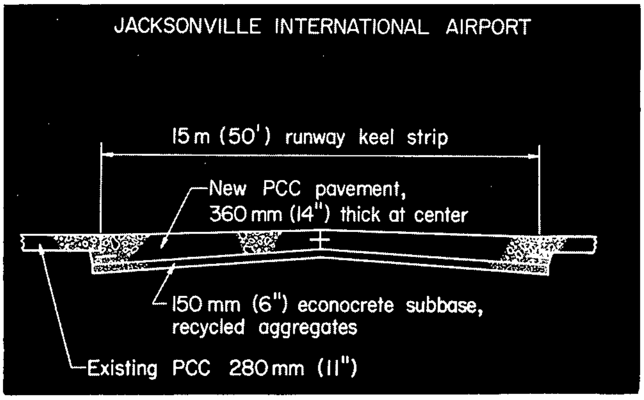

FIGURE 23 Center 50 ft of runway at Jacksonville International Airport was reconstructed.

After removal of the concrete, the old subbase and the subgrade were removed to a depth of 14 in. below the old grade. A filter fabric was placed on the subgrade and a 6-in. filter course of recycled coarse aggregate greater than $\frac{3}{8}$ in. was placed and compacted. On the filter course, a 6-in. layer of econocrete base was placed by a slipform paver. The lean concrete used the two sizes of recycled concrete as aggregate, with 250 lb of cement/yd^3, water, and a water-reducing admixture for greater workability. The lean concrete, which had a 28-day compressive strength of 1000 psi, was mixed in a 9-yd^3 central-mix plant and hauled by dump truck. Because the coarse aggregate for the new concrete had been hauled from Miami by rail, a distance of more than 300 miles, the economic gain from recycling the old pavement is obvious. Since this initial project, there have been three additional recycling projects at Jacksonville International Airport.

OKLAHOMA CITY, OKLAHOMA

This project involved reconstruction of an apron pavement staged so as to restrict gate closure to a minimum. The existing pavement was a 12-in. reinforced pavement with mesh and dowels. The project involved 150,000 yd^2 of pavement removal and recycling. The concrete was crushed to 1-in. top size, with all crushed material deposited in one stockpile.

The crushed product was used to construct an 8-in. cement-treated base with 5.6 percent cement. A new 16-in. PCC pavement was constructed on the cement-treated base.

FAA TECHNICAL CENTER AIRPORT

The Federal Aviation Administration's Technical Center Airport is used by the New Jersey Air National Guard and provides municipal service for Atlantic City, New Jersey. The project involved removal of a 7-in. PCC pavement built in the 1940s and the construction of a new 14-in. PCC runway 6000 ft long. The recycled material was used as a granular base under the runway, with a smaller amount used as aggregate for a portion of the new PCC runway pavement.

STAPLETON FIELD, DENVER, COLORADO

This project involved the reconstruction of an 8,000-ft runway in 65 working days. Part of the runway (47,000 yd^2) was PCC concrete and the remainder asphalt. The concrete pavement was broken by a diesel pile hammer and crushed for use in a cement-treated base. The asphalt was milled to various depths and left in place as a base for the new PCC pavement. The recycled PCC was used in the 14-in.-thick cement-treated base.

ATLANTA, GEORGIA

This project involved construction of the fourth east-west runway at Atlanta International Airport. Removal of 187,000 yd^2 of 16-in. reinforced-concrete pavement in and around the old terminal was involved. A diesel pile hammer breaker was used that delivered 30,750 ft-lb of force. The pavement was recycled and the aggregates used in a cement-treated base for the new pavements.

AIRPORT SUMMARY

These projects illustrate that the principal use of recycled aggregates from PCC pavement in airport construction has been as a cement-treated base or econocrete base. Some use has been made of recycled coarse aggregate in an open-graded drainage course. It is apparent that more use could be made of aggregates from recycled PCC pavement in concrete for new airport pavements. This could be particularly beneficial where high-quality aggregate is scarce and therefore costly.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions were developed from this study of recycling of PCC pavements:

- Recycling of PCC pavements is an option that should be considered whenever a concrete pavement is to be reconstructed.
- Developments in equipment for breaking, removal, and crushing have made the recycling of all types of concrete pavement, from heavily reinforced (continuously reinforced) dowel-mesh to plain PCC pavements, economically possible.
- Recycling of PCC pavements will conserve natural-aggregate supplies and provide a good-quality source of aggregate at the job site.
- Recycling of PCC pavements will solve the problem of disposing of huge quantities of rubble. This is particularly true in urban areas, where the disposal of concrete waste poses a difficult problem.
- There is the potential for savings in many areas of the United States. For example, recycling usually results in a savings in transportation costs. Recycling can be a tremendous benefit through savings in material and disposal costs. Conservation of energy through a reduction in haul distance can also be realized. For each proposed project, a cost analysis should be made that includes all potential savings as well as any increased costs.
- When PCC pavements are recycled, substandard geometrics can be improved, subgrade conditions can be strengthened or corrected, vertical clearance at bridges can be maintained or corrected, and drainage can be improved.
- The principal use of recycled PCC aggregate has been to construct new PCC pavements. Other uses include lean-concrete base (highways and airports), PCC shoulders, cement-treated base course, unstabilized base course, asphalt pavements, and open-graded drainage layers under PCC pavements.

Properties of Recycled PCC Aggregate and Concrete Made from These Aggregates

- The aggregate particles produced by crushing concrete have good particle shape, high absorptions, and low specific gravity compared with conventional mineral aggregates.
- The use of recycled *coarse* aggregate has no significant effect on mixture proportions or workability of the mixture compared with conventional concrete mixtures.
- When crushed concrete is used as fine aggregate, the mixture is less workable and requires more cement because of water demand. Most agencies do not use recycled fines in concrete mixtures, and if they are used they are are limited to a maximum of 30 percent of the fine-aggregate (sand) portion of the mixture.
- Research by a number of agencies has shown an increase in freeze-thaw resistance of concrete made from recycled aggregates compared with concrete made from some normal conventional aggregates. The durability of concrete made with aggregate subject to D-cracking can be substantially improved by recycling. Freeze-thaw testing (ASTM C 666) should be performed to determine if aggregate from D-cracked pavement will make durable concrete, because there are varying degrees of D-cracking potential in different aggregates.
- The salt content of recycled aggregate in Michigan varies from 1 to 1.9 lb/yd^3. Tests in Wisconsin of processed material and calculations made with typical batch proportions indicate that chloride in a recycled concrete attributable to the recycled coarse aggregate would be 1½ to 2 lb/yd^3.
- Freeze-thaw testing of concrete in Minnesota made with recycled D-cracking aggregate indicated a greatly reduced potential for D-cracking when fly ash was used in the mixture.
- The strength of concrete made with recycled aggregate can be equivalent to conventional concrete mixtures when natural sand or a limited amount of recycled fines is used in the mixture.
- Washing of coarse recycled aggregate is not considered necessary. When washing has been done, there was no conclusive evidence that the strength level was affected.

RECOMMENDATIONS

- When recycling PCC pavements, the grading band should be adjusted to maximize the recovery of coarse aggregate. More coarse aggregate can be recovered when crushed to a large size. With a 1-in. top size, a recovery of 55 to 65 percent can be expected, whereas with a 1½-in. top size, up to 80 percent can be recovered.
- Subgrade conditions should be investigated before a recycling project is designed. The pavement base and subgrade conditions should be investigated throughout the project to develop an orderly plan for any corrective action needed. It is too late to deal with surprises when traffic has been detoured and there is pressure to complete the work.
- Tests for soundness, specific gravity, etc. on recycled aggregate should be the same as those on natural aggregates.
- Additional research is needed to determine the use of recycled aggregates for open-graded drainage layer under pavements. Minnesota and Michigan have done some research to determine the suitability of recycled aggregate for drainage layers.

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APPENDIX

LABORATORY INVESTIGATION OF RECYCLED PORTLAND CEMENT CONCRETE AGGREGATE

The Michigan Department of Transportation conducted extensive research on the use of recycled PCC aggregate for construction of new pavements (7). Following are the results of some of this research.

PURPOSE

The principal purpose of the research was to investigate the feasibility of crushing an existing PCC pavement and using the resulting aggregate in a concrete mixture for a new PCC pavement.

The experimental procedures used for this work attempted to incorporate the complete range of variables found in crushing and using recycled concrete, including determinations of crushing properties, aggregate properties, and concrete properties with varying mixture proportions.

The basic research procedure was to obtain sufficient amounts of concrete from an existing pavement to perform comprehensive experiments. Material for the standard experiments was obtained from pavement slab sections that had been removed from a highway during a reconstruction project. The slab material was crushed at a commercial crushing plant, with further processing at the laboratory. In addition, pavement cores were obtained from various highway locations for correlation experiments.

Seventy experimental tests related to the determination of aggregate properties were completed. Three hundred eighty tests were completed for the determination of concrete properties. All laboratory tests were accomplished according to current ASTM standards or procedures used by the MDOT.

RESEARCH MATERIALS AND MIXTURE DESIGN

The Michigan Department of Transportation has been involved in a major pavement joint-repair program in recent years. In this process, pavement sections surrounding transverse joints experiencing mechanical failure are removed and replaced with a high-strength concrete patch. A project of this type was completed in 1979 on a section of I-96 between Novi and New Hudson. Three slab sections of this material were selected for research.

In order to simulate procedures normally used to completely remove an existing pavement, the sections were broken into maximum 3-ft-square pieces. It was observed that most of the temperature reinforcement present in the slabs broke along the lines of fracture in the concrete. The material was then loaded and hauled to a crushing operation in Detroit. Before the breaking operation, two representative 6-in. cores were drilled from each slab. Material from this source was designated as material A for the broken material and A-1 for the cores.

Six cores were also taken from a section of I-94 Business Loop near Battle Creek to provide correlation. These were designated material B. In addition, 12 cores were obtained from a section of I-94 near Jackson. This pavement had a nominal 3-in. bituminous concrete overlay. Because it was intended to use bituminous concrete material as part of this research, six of the cores with the overlay removed were designated aggregate material C and those with the overlay as C-1. Table A-1 is a listing of the history and location of materials used in the research.

The original PCC mixtures for all of the indicated sources were made with natural gravel and sand conforming to the grading requirements listed in Table A-2. The two grades of coarse aggregate were proportioned on the basis of 50 percent each by weight. Basic mixture design was for five and a half sacks of cement/yd^3 with air entrainment.

Michigan 2NS natural sand was used for this research effort because it is used for all concrete construction purposes in the state. Because it was desirable to use a coarse aggregate similar to those used in the mixtures for concrete to be recycled, natural gravel meeting requirements of Michigan specification 6A was selected for the control mixture.

AGGREGATE PROPERTIES

The preparation of recycled aggregates for use in experimental concrete mixtures, and for test samples, approximated field

TABLE A-1

HISTORIES OF SOURCE MATERIALS FROM MICHIGAN DEPARTMENT OF TRANSPORTATION ROAD LOGS

Material Code	Source	Pavement Type and Construction Dates
A & A-1	I-96 New Hudson	9" PCC Pavement - 1957
B	I-94 Business Loop	9" PCC Pavement - 1943 Bituminous Concrete Overlay - 1965
C & C-1	I-94 Jackson	9" PCC Pavement - 1949 Bituminous Concrete Overlay - 1972

TABLE A-2

GRADING REQUIREMENTS FOR COARSE AGGREGATES USED IN SOURCE MATERIAL FOR RECYCLING

Sieve	Michigan Grade (% passing) 4A	10A	2NS
63 mm (2-1/4")	100		
50 mm (2")	95 - 100		
38.1 mm (1-1/2")	65 - 90	100	
25.0 mm (1")	10 - 40	95 - 100	
12.5 mm (1/2")		35 - 65	
9.5 mm (3/8")	0 - 5		100
4.75 mm (No.4)		0 - 8	95 - 100
2.36 mm (No.8)			65 - 95
1.18 mm (No.16)			35 - 75
600 μm (No.30)			20 - 55
300 μm (No.50)			10 - 30
150 μm (No.100)			0 - 10
L.B.W.			3 maximum

crushing operations as closely as possible. Table A-3 shows the grading of three coarse-aggregate samples from aggregate A source. Table A-4 covers the fine-aggregate-grading tests.

Portland cement concrete pavement cores (aggregate material codes A-1, B, and C) obtained from previously described locations were first tested for compressive strength (Table A-5). The resulting core fragments were then crushed in the jaw crusher, simulating primary field crushing. After this initial crushing, the same procedures as those used for the crushed slab sections were followed.

In order to investigate a case in which aggregates are produced from concrete originally made with recycled aggregates, in other words, "re-recycled" aggregate, 12 laboratory test beams, cast from concrete containing aggregate A for the coarse aggregate and varying proportions of PCC and natural fines, were crushed using the established procedure. This material was coded as aggregate D.

TABLE A-3

COARSE FRACTION GRADING TEST RESULTS FOR THREE SAMPLES OF RECYCLED PCC AGGREGATE A (CUMULATIVE PERCENT PASSING)

Sieve	Sample Number 1	2	3	Average
38.1 mm (1 1/2")	100	100	100	100
25.0 mm (1")	99	96	98	98
19.0 mm (3/4")	75	73	80	76
12.5 mm (1/2")	41	42	46	43
9.5 mm (3/8")	24	24	25	25
4.75 mm (No. 4)	Min.	Min.	Min.	Min.
L.B.W.	---	---	---	0.5[a]
Passing No. 4[b]	18	20	20	19

[a] Average for materials from each sample. (Loss by washing)

[b] Aggregates were split at the #4 sieve and not included in the calculations for the coarse fraction.

TABLE A-4

FINE FRACTION GRADING TEST RESULTS FOR THREE SAMPLES OF RECYCLED PCC AGGREGATE A (CUMULATIVE PERCENT PASSING)

Sieve	Sample Number 1	2	3	Average
9.5 mm (3/8")	100	100	100	100
4.75 mm (No.4)	100	99	99	99
2.36 mm (No.8)	63	62	60	61
1.18 mm (No.16)	42	40	38	40
600 μm (No.30)	30	28	27	28
300 μm (No.50)	20	18	18	19
150 μm (No.100)	12	12	12	12
L.B.W.	6.3	6.7	6.9	6.6
F.M.	3.34	3.42	3.47	3.41

TABLE A-5

AVERAGE COMPRESSIVE STRENGTHS OF PCC PAVEMENT CORES FROM VARIOUS LOCATIONS

Aggregate Code	Compressive Strength (psi)
A-1	5990
B	6500
C	5860

The beams had experienced 300 cycles in the freeze-thaw chamber used for durability tests and were, therefore, considered a valid approximation of concrete exposed to extreme temperature differentials. The crushed particles exhibited the same shape characteristics as the other recycled PCC aggregate, although it was difficult to identify the natural aggregates used in the original concrete.

Gradings for all of the aforementioned crushed PCC aggregates are shown in Tables A-6 and A-7. Graphs of the fine and coarse fractions indicated nearly identical crushing characteristics.

TABLE A-6

GRADING OF COARSE RECYCLED PCC AGGREGATES (CUMULATIVE PERCENT PASSING)

Sieve	Aggregate Code (% passing) A[a]	A-1	B	C	D
38.1 mm (1-1/2")	100	100	100	100	100
25.0 mm (1")	98	98	98	97	100
19.0 mm (3/4")	76	74	76	77	80
12.5 mm (1/2")	43	36	36	36	40
9.5 mm (3/8")	25	19	21	20	23
4.75 mm (No. 4)	Min.	Min.	Min.	Min.	Min.
L.B.W.	0.5	0.4	0.5	0.4	0.3
Passing No. 4[b]	20	15	16	17	21

[a] Average of three samples.

[b] Aggregates were split at the No. 4 sieve and not included in the calculations for the coarse fractions.

TABLE A-7
GRADING OF FINE RECYCLED PCC AGGREGATES (CUMULATIVE PERCENT PASSING)

Sieve	Aggregate Code (% passing) A[a]	A-1	B	C	D
9.5 mm (3/8")	100	100	100	100	100
4.75 mm (No.4)	99	99	99	99	100
2.36 mm (No.8)	61	62	68	72	71
1.18 mm (No.16)	40	38	46	48	48
600 μm (No.30)	28	26	32	32	33
300 μm (No.50)	19	17	19	20	22
150 μm (No.100)	12	10	10	12	15
L.B.W.	6.6	5.6	4.1	5.8	9.1
F.M.	3.41	3.48	3.25	3.16	3.11

[a] Average of three samples.

In order to simplify the identification of the research aggregate, a recapitulation of aggregate material codings and sources is covered in Table A-8.

In order to provide a comprehensive investigation of bulk specific gravity and percent absorption of coarse aggregate in recycled PCC, tests were made on each size fraction of coarse aggregate A. Test results were weighted on the basis of average percentage retained on each sieve size. Test results for each size fraction are shown in Table A-9. A visual examination of the aggregates at each sieve size resulted in a determination that the top-size material contained a larger proportion of unbonded and crushed natural aggregate than the material retained on the smaller sizes. The aggregates retained on the 4.75-mm (No. 4) sieve were mostly crushed mortar particles.

The results show a progressive decrease in bulk specific gravity and an increase in absorption as particle size decrease. Tables

TABLE A-8
CODING AND SOURCE INFORMATION FOR RESEARCH AGGREGATES

Aggregate Code	Description	Source
A	Crushed slab sections	I-96 - New Hudson
A-1	Crushed cores	I-96 - New Hudson
B	Crushed cores	I-94 BL - Battle Creek
C	Crushed cores	I-94 - Jackson
C-1	Crushed cores with 3" overlay	I-94 Jackson
D	Crushed beams	Laboratory - freeze-thaw test on concrete made with aggregate A
E	Crushed bituminous concrete	US 12 - Inkster
6A	Natural gravel	Morgan Sand and Gravel Company
2NS	Natural Sand	Hall Sand and Gravel Company

TABLE A-9
WEIGHTED BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF RECYCLED PCC COARSE AGGREGATE A

Sieve	Percent Retained	Bulk Specific Gravity	Absorption
25.0 mm (1")	2	2.52	2.54
19.0 mm (3/4")	22	2.36	3.98
12.5 mm (1/2")	33	2.34	4.50
9.5 mm (3/8")	18	2.29	5.34
4.75 mm (No. 4)	25	2.23	6.50
Weighted Average		2.31	5.00

A-10 and A-11 cover various properties of the coarse and fine aggregates used for the research.

Coarse aggregates produced by crushing portland cement concrete were superior to the control natural gravel in those tests designed to evaluate the possible effect of aggregate properties with respect to the durability of concrete. Recycled PCC fine-aggregate properties were essentially comparable to the durability properties of the control natural sand.

The extremely high absorptions and low specific gravities of aggregate D are assumed to result from the fact that the aggregate particles were, mainly, crushed mortar containing progressively higher percentages of entrained air.

SALT CONTENT OF RECYCLED PAVEMENT

Because MDOT uses rock salt as a deicing agent for highways, there was a concern that detrimental amounts of sodium chloride may have infiltrated the PCC material used for recycling.

Test methods used by MDOT to determine damaging amounts of salt in bridge-deck concrete were considered appropriate for this research.

TABLE A-10
VARIOUS PROPERTIES OF COARSE AGGREGATES USED FOR RESEARCH

Aggregate Code	Percent Soundness Loss	Percent Absorption	Bulk Specific Gravity	Unit Weight (lb/ft³)
A	0.9	5.00	2.31	76
A-1	1.4	4.48	2.33	--
B	2.0	4.28	2.39	--
C	0.9	3.43	2.38	--
C-1	--	2.78	2.40	--
D	0.4	8.36	2.11	68
E	--	1.44	2.38	--
6A	3.9	1.02	2.67	104
MDOT Spec.	12.0 max[a]	---	---	--

[a] Before 1973 - not in current specifications.

TABLE A-11

VARIOUS PROPERTIES OF FINE AGGREGATES USED FOR RESEARCH

Aggregate Code	Percent Soundness Loss	Percent Absorption	Bulk Specific Gravity	Organic Plate Number
A	8.3	8.31	2.16	1[a]
A-1	6.8	7.78	2.18	1[a]
B	8.8	7.17	2.23	1[a]
C	7.0	7.53	2.15	1[a]
C-1	--	5.17	2.23	--
D	5.7	11.79	2.00	1[a]
E	--	2.40	2.29	--
2NS	7.1	1.38	2.60	2
MDOT Spec.	16.0 max.[b]	--	--	3 max.

[a] Tests for organic impurities were well under the number one standard reference plate.

[b] Before 1973 - not in current specifications.

Michigan specifies that when the salt content of bridge-deck concrete exceeds 4 lb/yd^3, the concrete should be removed and replaced with new concrete. Inasmuch as test results for the recycled PCC used in this research were well under the specified amount, this factor was not considered significant (Table A-12). This is especially true considering that the transverse joints in the pavement slabs (aggregate A) would contain the highest concentrations of salt.

CONCRETE PROPERTIES

As a result of determining the proportions of fine and coarse aggregates required for mixture design compared with the percentages of these aggregates resulting from the crushing process, it was determined that approximately 30 to 35 percent of the fine aggregate necessary to use all of the coarse aggregate produced would be available in the crusher fines. Therefore, additional fines in the form of conventional fine aggregate would have to be provided.

TABLE A-12

SALT CONTENT (NaCl) OF RECYCLED PCC AGGREGATES

Aggregate Code	NaCl (lb/yd^3)
A[a]	1.89
A-1	1.72
B	1.72
C	1.72
D	1.03

[a] Average of three samples.

Because it was previously determined that the coarse and fine fractions of recycled PCC aggregate should be split and stockpiled separately to avoid segregation problems, a number of options concerning the ratios of recycled and natural fines used in mixture proportioning were considered. These ranged from using all crushed PCC fines to all natural fines in combination with 100 percent crushed PCC coarse aggregate, if concrete quality permitted.

Recycled aggregate A from the crushed slab sections was used extensively as a standard for experiments to determine concrete properties related to varying the proportions of recycled PCC crusher fines with conventional fines.

Individual concrete batches made with aggregate resulting from crushing PCC pavement cores were used as a check against the standard mixture. Concrete made with aggregate from the crushed laboratory beams provided an initial investigation to determine if concrete made with recycled aggregates could be recycled again in the future.

Percentages of the volumes of coarse and fine aggregates used in the recycled PCC concrete mixtures are identified by batch series and aggregate code in Table A-13.

Because of conflicting reports concerning the detrimental effects of asphalt overlay materials on concrete quality (*5*) and the entrainment of air in fresh concrete, mixtures were designed incorporating various amounts of crushed bituminous concrete. Volume percentages of aggregates used in concrete batches made with combinations of crushed bituminous and PCC materials are shown in Table A-14.

Batch series 11 and 12 were designed to test the effect of bituminous materials on air-entrainment; therefore, bituminous fines were combined with natural fines only, so that the possible effects of PCC fine aggregate on air-entrainment do not influence results. This combination would not be present under normal field conditions. Batch series 18 using 100 percent crushed bituminous concrete was designed for informational purposes only. The concrete mixture designs incorporating various proportions of bituminous materials provided the basis of an initial investigation and were not intended as part of a comprehensive study.

Coarse aggregates were proportioned on the basis of the average percent retained on the various sieve sizes from grading tests for aggregate A (Table A-15). Weights for each size fraction were corrected for moisture content and weighed cumulatively. In order to assure complete absorption, the individual aggregate sizes were recombined in tared containers and immersed in water for a minimum of 24 hr. Before use in a mixture, excess water was decanted, the aggregate reweighed, and appropriate corrections made for mixing water.

Fine aggregates were proportioned in their original gradings. After weighing, enough water was added to allow for absorption. The same procedure as that used for the coarse aggregate was followed before using the material in a concrete mixture. Both the cement and mixing water were proportioned by weight.

The basic concrete mixture design used for all experiments held the following factors constant:

- Water-cement ratio (W/C) = 0.43
- Cement factor, per cubic yard = 6 sacks (564 lb)
- Coarse aggregate workability factor (b/b_0) = 0.72
- Percent entrained air = 5.5 ± 1.5.

Tests to determine slump, air content, yield, and temperature

TABLE A-13
COMBINATIONS OF AGGREGATES USED FOR RECYCLED PCC MIX DESIGN

	Coarse Aggregate		Fine Aggregate			
Batch Series	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume
1	A	100	A	100	---	---
2	A	100	A	75	2NS	25
3	A	100	A	50	2NS	50
4	A	100	A	25	2NS	75
5	A	100	-	--	2NS	100
6	A-1	100	A-1	25	2NS	75
7	B	100	-	--	2NS	100
8	C	100	-	--	2NS	100
9	D	100	-	--	2NS	100
10 - Control Mix	6A	100	-	--	2NS	100

TABLE A-14
COMBINATIONS OF AGGREGATE USED FOR RECYCLED PCC MIX DESIGN INCLUDING BITUMINOUS CONCRETE

	Coarse Aggregate				Fine Aggregate			
Batch Series	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume
11	A	85.7	E	14.3	E	14.3	2NS	85.7
12	A	78.3	E	21.7	E	21.7	2NS	78.3
13	A	85.7	E	14.3	-	---	2NS	100.0
14	A	78.3	E	21.7	-	---	2NS	100.0
15	A	69.2	E	30.8	-	---	2NS	100.0
16	A	69.2	E	30.8	E	30.8	a	69.2
17	C-1[b]	100.0	-	---	-	---	2NS	100.0
18	E	100.0	-	---	E	100.0	---	---

[a] Combination of A, B, and C.

[b] Approximately 17 percent bituminous concrete determined from gradation test.

TABLE A-15
AVERAGE PERCENT RETAINED ON EACH SIEVE SIZE FOR AGGREGATE A

Sieve	Percent Retained
25.0 mm (1")	2
19.0 mm (3/4")	22
12.5 mm (1/2")	33
9.5 mm (3/8")	18
4.75 mm (No. 4)	25

TABLE A-16
PROPERTIES OF FRESH CONCRETE MADE WITH RECYCLED PCC AGGREGATE

Batch Identification	Slump (in.)	Air Content (%)	Temperature (°F)	Unit Weight (lb/ft³)	Yield[a] (%)	Observed Workability Finishing	Observed Workability Consolidation
Field Crushed Slab Sections							
1A-B-C-D	1.0	5.0	70	132.8	+0.9	Harsh	Good
1E[b]	1.5	5.0	73	133.3	-0.5	Harsh	Good
2A-B-C	1.5	4.9	71	---	--	Harsh	Good
3A-B-C	1.0	4.3	72	---	--	Harsh	Good
4A-B-C	1.75	5.3	72	138.3	+0.5	Good	Good
5A-B-C	2.0	6.6	70	137.2	+0.2	Good	Good
Laboratory Crushed Cores							
6A[c]	5.0	8.6	71	132.1	+1.2	Good	Good
7A	1.25	6.7	68	140.1	-0.9	Good	Good
8A	1.0	5.3	68	141.4	-0.8	Good	Good
Laboratory Freeze-Thaw Beams (Recycled Concrete)							
9A	1.5	5.7	72	135.9	-0.1	Good	Good
Control Mix - Gravel							
10A-B	3.25	5.8	72	146.2	-0.6	Good	Good

[a] Corrected for air content.

[b] W/C = 0.46 and b/b - 0.70 for a check on workability.

[c] Batching error - W/C = 0.49 - included for information.

were made for each experimental batch upon completion of mixing.

Average test results and observations related to the properties of fresh concrete made with recycled PCC and control aggregates are shown in Table A-16. The properties of mixes containing proportions of crushed bituminous concrete are shown in Table A-17.

Table A-18 shows the relationship of the percentage of entrained air to varying amounts of air-entraining admixture added to concrete mixtures containing bituminous material. It was

TABLE A-17
PROPERTIES OF FRESH CONCRETE MADE WITH COMBINATIONS OF RECYCLED PCC AND CRUSHED BITUMINOUS CONCRETE

Batch Identification	Slump (in.)	Air Content (%)	Temperature (°F)	Unit Weight (lb/ft³)	Yield[a] (%)	Observed Workability Finishing	Observed Workability Consolidation
Field Crushed Slab, Natural Sand, and Crushed Bituminous Concrete (to determine the effect of overlay materials on air content)							
11A-B-C	2.5	6.6	73	137.6	-0.6	Good	Good
12A	2.5	7.7	71	135.7	-0.7	Good	Good
Field Crushed Slabs and Bituminous Concrete							
13A	1.75	5.0	72	138.5	+0.1	Good	Good
14A	2.5	6.5	73	137.8	-0.1	Good	Good
15A	1.0	5.5	74	140.4	-0.4	Good	Good
16A	1.5	4.9	74	136.6	-1.0	Harsh	Good
Laboratory Crushed Cores with Bituminous Overlay							
17A	1.0	4.8	69	140.2	-0.3	Good	Good
Crushed Bituminous Concrete - Test for Information							
18A	0.25	5.8	72	133.2	+0.5	Harsh	Fair

[a] Corrected for air content.

TABLE A-18

AIR CONTENTS OF CONCRETE MADE WITH PROPORTIONS OF RECYCLED PCC AND BITUMINOUS CONCRETE

Batch Identification	Vinsol[a]	Air Content
11A	30	8.2
11B	10	4.8
11C	15	6.8
12A	20	7.7

[a] In cubic centimeters per 1.4 ft³ batch.

TABLE A-19

NUMBER OF TEST SPECIMENS MADE FOR EACH EXPERIMENTAL BATCH

Quantity	Type	Purpose
5	3x4x16 in. beams	For flexural strength tests, freeze-thaw tests, and the determination of dynamic moduli.
6	4x8 in. cylinders	For compressive strength test.

determined that concrete containing the stated materials will react normally to the addition of air-entraining admixtures.

Test specimens to determine the properties of hardened concrete were made from each experimental batch in the quantities shown in Table A-19.

Concrete test cylinders and beams were tested at 7 and 28 days. Test results are shown in Tables A-20 and A-21. Standard deviations for 28-day strengths were within an acceptable range for concrete tests.

The relationship of the various ratios of recycled PCC and natural fine aggregates used in the standard mixture to concrete strengths is illustrated in Figures A-1 and A-2. Both cases indicated that maximum strengths were achieved when recycled PCC was incorporated as part of the total fine aggregate in a concrete mixture.

The Michigan Department of Transportation specifies minimum 28-day compressive and flexural strengths of 3500 psi and 650 psi, respectively, for pavement concrete design.

A Sonometer was used to determine the fundamental transverse and torsional frequencies of test beam specimens from each experimental concrete batch. Test beams were exposed to 300 freeze-thaw cycles in accordance with Procedure B stated in ASTM C 666-77. The durability factors for concrete made with the recycled aggregates in this research were exceptionally high (Table A-22) and show test values for dynamic Young's modulus of elasticity and Poisson's ratio are within the normal range for saturated concrete (Table A-23).

TABLE A-20

COMPRESSIVE AND FLEXURAL STRENGTHS OF CONCRETE MADE WITH RECYCLED PCC AND CONTROL AGGREGATE

	Compressive Strength (psi)			Flexural Strength (psi) Center point loading		
Batch Ident.	7 day	28 day	Standard Deviation	7 day	28 day	Standard Deviation
Field Crushed Slabs						
1A-B-C-D	4080	4760	260	640	730	40
1E[a]	3750	4550	---	670	770	--
2A-B-C	4330	5540	280	700	755	35
3A-B-C	5000	5590	310	785	840	25
4A-B-C	4600	5770	280	760	865	45
5A-B-C	4100	4910	140	715	805	35
Laboratory Crushed Cores						
6A[b]	3110	4080	---	625	675	--
7A	4470	5120	---	760	870	--
8A	4580	5820	---	780	875	--
Laboratory Freeze-Thaw (Re-Recycled Concrete)						
9A	4390	5570	---	710	865	--
Control Mix - Gravel						
10A-B	4520	5260	260	695	850	70

[a] W/C - 0.46 and b/b = 0.70 for a check on workability.

[b] Batching error - W/C = 0.49 - included for information.

TABLE A-21
COMPRESSIVE AND FLEXURAL STRENGTHS OF CONCRETE MADE WITH A COMBINATION OF RECYCLED PCC AND BITUMINOUS CONCRETE

	Compressive Strength (psi)			Flexural Strength (psi) Center point loading		
Batch Ident.	**7 day**	**28 day**	**Standard Deviation**	**7 day**	**28 day**	**Standard Deviation**
Field Crushed Slabs, Natural Sand, and Crushed Bituminous Concrete (to determine the effect of overlay material on air content)						
11A-B-C	3080	3680	550	605	710	65
12A	2550	3280	---	540	640	--
Field Crushed Slabs and Bituminous Concrete						
13A	4100	4790	---	635	725	--
14A	3180	4130	---	635	770	---
15A	3330	4130	---	630	760	--
16A	2640	3110	---	620	615	--
Laboratory Crushed Cores with Bituminous Overlay						
17A	3590	4390	---	640	740	--
Crushed Bituminous Concrete - tested for information						
18A	940	1100	---	315	375	--

SUMMARY AND CONCLUSIONS

Previous investigators predicted lower strengths when using recycled PCC aggregates in a concrete mixture compared with concrete made with conventional control aggregates. However, one must be aware there will invariably be strength differentials when comparing concrete made with various conventional aggregates. In Michigan, for example, concrete is normally made with natural sand for the fine aggregate, and natural gravel, limestone, or blast furnace slag for the coarse aggregate. Although these aggregates are used on an equal design basis, the resulting concrete properties cover a range of values. The primary criterion for acceptability is that concrete made with an aggregate from a particular source must meet minimum standards. Experimental results from research indicated that aggregates produced by crushing Michigan PCC pavements were equal in quality to conventional aggregates.

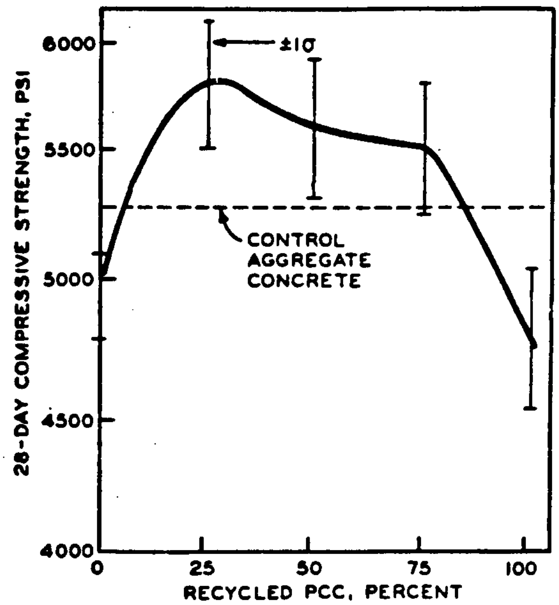

FIGURE A-1 The effects of the percent of recycled PCC fine aggregate, in total fine aggregate, on compressive strength.

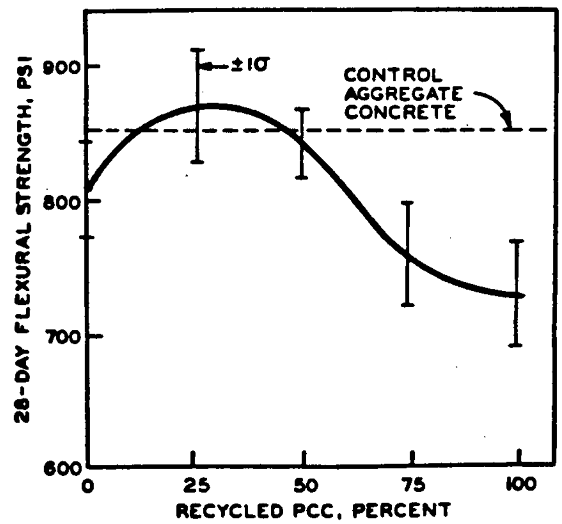

FIGURE A-2 The effects of the percent of recycled PCC fine aggregate, in total fine aggregate, on flexural strength.

TABLE A-22

DURABILITY FACTORS FOR RESEARCH MIXES

Batch Series	Durability Factor[a]	Batch Series	Durability Factor
1	99	10[b]	81
2	99	11	101
3	100	12	100
4	98	13	101
5	99	14	98
6	105	15	99
7	95	16	93
8	97	17	99
9	95	18[c]	37

[a] Tests started at 14 days of age.

[b] Control mix.

[c] Concrete using all crushed bituminous concrete for aggregates - tested for information.

TABLE A-23

DYNAMIC YOUNG'S MODULUS OF ELASTICITY (E) AND POISSON'S RATIO (u) FOR SELECTED RESEARCH TEST SPECIMENS

Batch Ident.	E (106 psi)	u	Batch Ident.	E (106 psi)	u
1D	4.48	0.18	10B[a]	5.81	0.20
2B	4.69	---	11A	4.44	0.23
3A	4.97	---	12A	4.00	0.19
4A	5.30	0.20	13A	5.18	0.25
5B	4.87	---	14A	4.92	0.24
7A	5.28	0.18	15A	5.11	0.27
8A	5.55	0.22	16A	4.15	0.26
9A	4.92	0.26	17A	4.97	0.18

[a] Control mix.

All research concrete mixtures, proportioned with recycled PCC coarse aggregate and various ratios of natural sand and recycled PCC fines, exceeded minimum design standards. Within a certain range, combinations of recycled fines and natural sand produced concrete with higher strengths than those of concrete made with control aggregates. As with the results reported by others, recycled portland cement concrete made exclusively with either natural or recycled fine aggregate produced lower strengths than control aggregate concrete. Nevertheless, strengths were appreciably higher than minimum materials in a major portion of the state's existing PCC highway pavements. Usual reasons for pavement removal are mechanical failures resulting from subgrade, drainage, or joint problems. However, the methods formulated in this research, for experiments with pavement cores, provide a systematic means of determining the properties and mixture design requirements of aggregates resulting from recycling any existing PCC material source. There is a high degree of assurance that the result of using these methods will be the same as actual field crushing and design requirements.

One of the most interesting aspects of this research was the experiments involving the recycling of recycled PCC concrete. Test results for both aggregate and concrete properties indicated that the re-recycled aggregate was high in quality and durability. Therefore, one may project that existing PCC pavements, in addition to providing an aggregate source for the future, will continue to generate an adequate supply of aggregates for pavement replacement after once being recycled.

Another point of interest is that recycling an existing pavement produces about 150 percent of the total aggregate volume needed for the concrete required to replace the section removed. Therefore, additional high-quality aggregates will be available for such construction purposes as concrete shoulders, concrete barriers, necessary concrete pavement widening, base aggregate, and a variety of other uses.

Although the concrete mixture designs used for experiments in this research are related to using recycled PCC aggregates for pavements, there is strong evidence this material would provide an excellent aggregate for concrete used in bridges, buildings, and other structures.

The resulting finding of this research is that using recycled PCC aggregates for portland cement concrete offers a feasible alternative to conventional aggregates on an equal design basis. This is especially true for recycling an existing PCC pavement, where significant cost savings can be realized.

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