

# Portland Cement Concrete Pavement Pulverizing Equipment

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Portland cement concrete (PCC) is most commonly broken with gravity-drop hammers, trailer-mounted diesel hammers, spring-arm hammers, and vibrating-beam breakers. PCC pavement breaking, steel removal, hauling, crushing, and sizing can be performed for a price in terms of pavement of about \$3.50/yd<sup>2</sup> to \$4.50/yd<sup>2</sup> or \$7.00/ton to \$9.00/ton of aggregate produced. Pavement breaking and steel removal prices are in the range of \$0.50/yd<sup>2</sup> to \$1.50/yd<sup>2</sup>. Steel removal remains a labor-intensive, low-production operation. Breaking and crushing operations need to be improved in order that large quantities of coarse aggregate can be produced from PCC. Field operations need improvement to prevent or reduce the amount of base course contamination. About 3,200,000 yd<sup>2</sup> of PCC was recycled in the 1985 construction season. Considering the condition of pavements in the United States, current recycling quantities, and expected growth of recycling, 50 to 100 equipment units will be required within 20 years to break or pulverize PCC pavements.

Recycling or reuse of existing pavement materials for pavement rehabilitation, reconstruction, and maintenance is not a new concept; however, the literature indicates that the amount of various forms of pavement materials recycled from 1915 to 1975 was small in comparison with the amount of recycling expected to occur between 1975 and 1990.

Specifically, recycling offers the following major benefits, compared with conventional techniques:

1. Conservation of aggregates,
2. Conservation of binders,
3. Energy conservation,
4. Preservation of the environment,
5. Preservation of existing pavement geometrics, and
6. Reduced cost.

## PORTLAND CEMENT CONCRETE RECYCLING

Portland cement concrete (PCC) recycling is the form of recycling addressed in this report. A definition proposed by FHWA and NCHRP is as follows (1):

Portland cement concrete pavement recycling: a process by which an existing portland cement concrete pavement is processed into aggregate and sand sizes, then used in place of,

or in some instances with additions of, conventional aggregates and sand into a new mix and placed as a new portland cement concrete pavement.

A broader definition, however, has been used for this report. The end use of the pulverized PCC is expanded to include the following materials:

1. PCC,
2. Econocrete,
3. Cement-treated base or subbase,
4. Asphalt concrete (AC),
5. Asphalt-treated base or subbase,
6. Cover stone for chip seals,
7. Granular or unstabilized base and subbase, and
8. Riprap or filter material.

Recycling of PCC pavements using central plants is not a new concept. During World War II, a crushed-concrete pavement was used as an unstabilized base in Illinois. Cement-treated subbase made with crushed concrete was used at Love Field in Dallas, Texas, in 1964. The first Econocrete or lean concrete section made with recycled PCC was placed in California in 1975, and Iowa placed the first PCC pavement made from an old crushed PCC in 1976. The first large-scaled job using recycled PCC as an aggregate for asphalt concrete occurred in Texas in 1969.

Concrete pavement recycling became an alternative pavement rehabilitation technique in several states between 1983 and 1985. The departments of transportation are interested in PCC recycling for the following purposes:

- Providing aggregate where high-quality aggregate is no longer economically available,
- Eliminating the need for locations to waste large amount of pavement rubble,
- Conserving present aggregate sources,
- Reducing the need for disrupting land for quarrying purposes,
- Saving fuel and energy by reducing aggregate transportation,
- Reducing damage to haul roads near paving projects,
- Achieving a monetary savings while constructing high-quality roadways, and
- Rehabilitating D-crack pavements.

The normal construction steps associated with PCC recycling are

1. Breaking;
2. Steel removal (if required);

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3. Loading and hauling;
4. Crushing and sizing;
5. Blending with other aggregates and production of new PCC or other pavement construction materials; and
6. Hauling, placing, and curing.

In the remainder of this report, the results of the FHWA study *Portland Cement Concrete Pavement Pulverizing Equipment (2)* are discussed.

**SUMMARY OF EXISTING PULVERIZING TECHNOLOGY**

For purposes of discussion, the equipment used for PCC pavement breaking, removal, and sizing can be separated into the groups or categories of equipment shown in Figure 1. The major categories are cold milling, slab removal, and slab breaking.

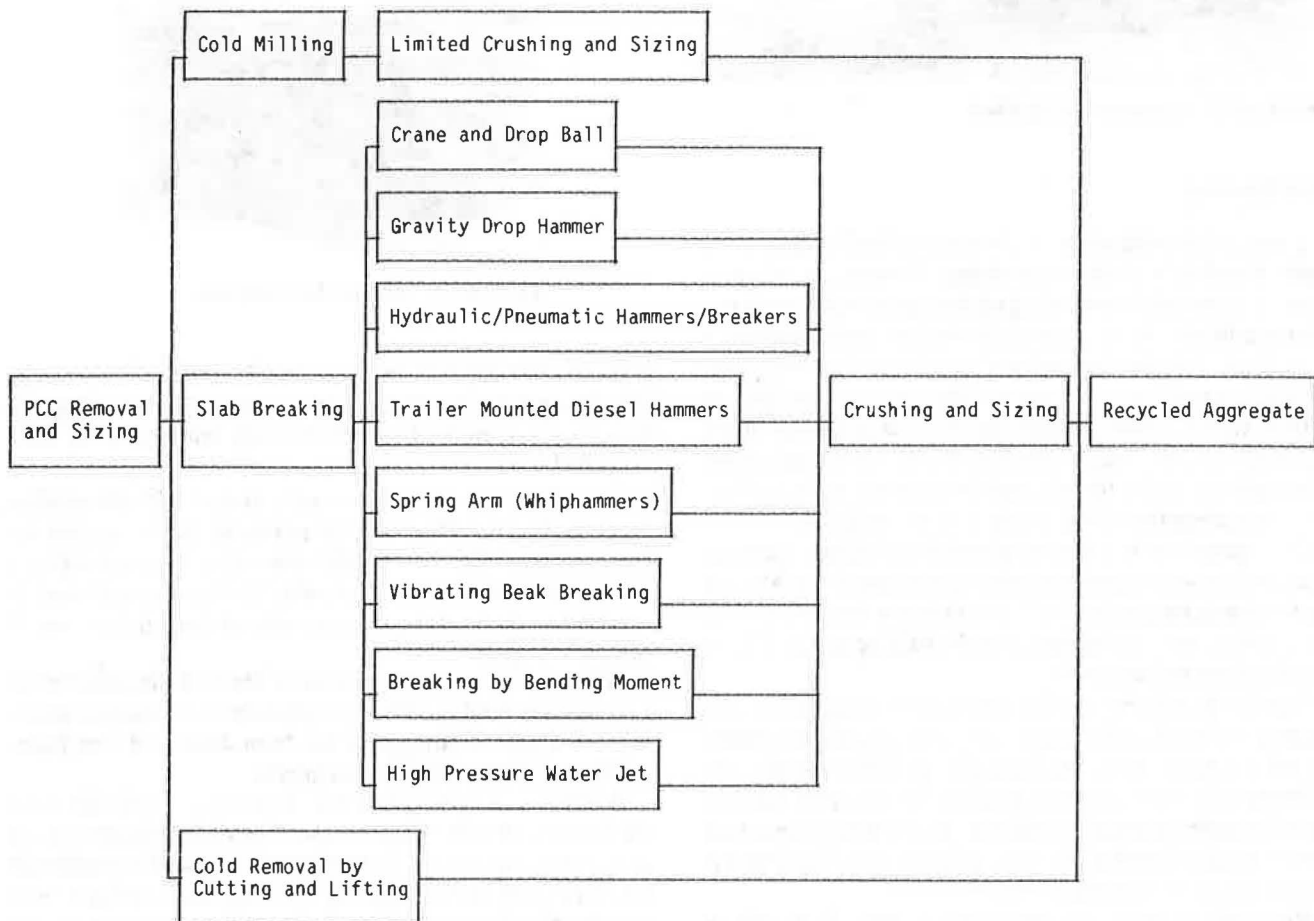
**Cold Milling**

Major manufacturers of construction equipment market a variety of large cold milling machines. This type of equipment can economically remove asphalt concrete (AC), treated bases, untreated bases, and subgrades, but is not suitable for

removal of PCC to its full depth. Cold milling of PCC is normally at least two to three times the cost of cold milling of AC. Tooth wear, slow production rates, and problems with the steel in the concrete are the major reasons for the high costs. To date, cold milling machines have not been used on any large projects for full depth removal of PCC pavements. Partial depth removal (usually less than 1 to 2 in.) of PCC is commonly performed as part of an overall pavement rehabilitation process. Figure 2 shows typical cold milling equipment.



**FIGURE 2** Cold milling equipment.



**FIGURE 1** Types of PCC breaking, removing, and sizing operations.

## Slab Removal

Concrete can be pulverized by removing a large slab of concrete and hauling it to a central plant where the slab size is reduced (often with a hydraulic hammer) to a size suitable for crushing. Prior to removal with a forklift or similar equipment, the concrete must be sized to the capabilities of the lifting and hauling equipment. Concrete saws and cutting wheels can be used as shown in Figure 3. High-pressure water jets can also be used to cut concrete slabs.

Slab removal operations of this type have been performed as part of slab removal and replacement rehabilitation operations as well as for a recycling project (3). Production has been slow when this process has been utilized. Contamination from base course material has been minimal.



FIGURE 3 Concrete cutting wheel.

## Slab Breaking

At present, this is the most widely used method for pavement removal and sizing prior to crushing. However, production rates can vary widely depending on the type of equipment and local conditions. Among the major factors are the thickness of the PCC slab, the size and spacing of any reinforcing steel present, the resistance to impact of the concrete, and the size of PCC rubble desired. Other factors include the size of the breaking tool, the speed of machine travel, the strength of the base, subbase, and subgrade, and the moisture content of the base. Subcategories of this equipment are as follows:

**Crane and drop ball.** The crane and drop ball technique has been used on several projects to break concrete slabs. A heavy steel ball weighing from 2 to 7 tons (1.8 to 6.3 metric tons) is hoisted by a crane and dropped on the PCC roadway. Figure 4 shows drop ball equipment.

**Gravity-drop hammers.** Gravity hammers have been used for concrete breaking for many years. The equipment operates by (a) lifting a mass mechanically or hydraulically, (b) releasing the mass, and (c) striking the concrete with an interchangeable impact foot. Gravity in combination with the mass is used to develop the striking force. A typical gravity-drop hammer is shown in Figure 5.

**Hydraulic or pneumatic hammer/breakers.** Hydraulic or pneumatic hammers have been used extensively for localized



FIGURE 4 Drop ball.



FIGURE 5 Gravity-drop hammer.

removal of PCC pavement and for building demolition work. These hammers can either be boom mounted (mounting on backhoes is common) or permanently mounted to a self-propelled unit.

These hammers come in a variety of sizes with the smaller model delivering 450 ft-lb (610 joules) at 200 blows/min to 2,000 ft-lb (2,712 joules) at 600 blows/min. Most models can run on either the air or hydraulic fluid of the unit that is carrying it or on a separate supply. A typical hammer is shown in Figure 6.

**Trailer-mounted diesel hammers.** The first diesel-powered hammer was built in 1951 by a midwestern contractor. Since then, this type of equipment has been developed into high-production PCC-breaking equipment.

A diesel pile-driving hammer is mounted vertically on a trailer unit. Many of these breakers have added features such as walking devices to allow the towing vehicle to maintain constant speed, interchangeable breaking heads, and hydraulic systems to fold down the unit for travel. Breakers in this category can deliver over 80 blows/min at 30,000 ft-lb (40,680



FIGURE 6 Hydraulic/pneumatic hammer.

joules) per blow. This allows the breakers to achieve both PCC cracking and breaking the bond between the PCC and any reinforcing steel present.

A vertically mounted diesel pile-driving hammer can be an effective PCC-breaking machine with excellent production rates. The high rates of production for these devices are probably the most significant advantage over other types of breaking equipment. Rates of between 1,000 and 1,200 yd<sup>2</sup>/hr (800 to 1,000 m<sup>2</sup>/hr) for 8-in. (200-mm) thick nonreinforced concrete pavement have been recorded. In addition, the high-impact forces are capable of thoroughly breaking the bond between the concrete and the reinforcing steel, making steel removal easier and less costly.

Another major advantage of the diesel pile-driving hammer is the ease with which the size of the PCC rubble can be controlled by altering both the width of each pass and the speed of travel. This eases the removal, loading, and crushing operations.

The major disadvantage is the relative lack of versatility. Most of these breakers only work on flat roadways and cannot remove curbs and gutter or any other PCC objects. The high-impact forces (which can be adjusted somewhat) also pose a threat to underground utilities and culverts. This factor forces the contractor to use additional breaking equipment in those areas that have underground utilities. The height of diesel pile-driving hammers prevents their use in low-clearance areas, therefore requiring other breaking equipment to be used also.

Although the cost for machines in this category can be substantial, high production rates may make them both feasible and desirable. Figure 7 shows a typical diesel-powered hammer/breaker.

*Spring-arm whiphammers.* A Michigan company is currently marketing a machine that uses whip-arm action to deliver blows of up to 300,000 lb (135 000 kg) (as reported by the manufacturer).



FIGURE 7 Diesel power hammer.

The whiphammer uses a flexible arm made up of leaf springs that increase the velocity of the tool head. The leaf springs also insulate the machine from reverse shock. The whiphammer flexible arm is powered by a 78-hp diesel engine that generates 1,500 psi (105 kg/cm<sup>2</sup>) hydraulic fluid at 50 gal/min (190 liters/min). The equipment is truck mounted for easy mobility.

Production rates vary widely depending on existing conditions. As a guideline, 9 to 10 in. (225 to 250 mm) of reinforced pavement with a compressive strength of 3,500 psi (246 kg/cm<sup>2</sup>) can be broken at rates of 250 to 500 yd<sup>2</sup>/hr (200 to 400 m<sup>2</sup>/hr) to produce material of which 80 percent will be 12 in. or smaller in size.

This machine is maneuverable and can work well in low-clearance areas. For this reason, the machine has been used inside manufacturing facilities. In addition, the whip arm has a working range of a 7-ft arc over 60° (a 210-cm arc over 60°). This ability allows the machine to remove curbs and gutters and to work around obstacles.

In the first year of use, the whiphammer was used for PCC breaking in 24 states. Most of the projects involved cracking PCC in preparation for AC overlays. Figure 8 shows a picture of the machine.

*Vibrating-beam breakers.* A Nevada company has introduced and tested a completely new type of pavement breaker (Figure 9). Based on the tuning-fork principle, the



FIGURE 8 Spring-arm whiphammer.





FIGURE 9 Vibrating-beam breaker.

machine uses high-frequency, low-amplitude impacts for applications in the construction industry.

The machine uses power transmitted through a 6-1/2-in.  $\times$  18-in.  $\times$  12-ft (163-mm  $\times$  450-mm  $\times$  360-cm) forged-steel beam. Within the fundamental frequency of the beam, hydraulic-driven eccentric weights convert circular motion into vibratory motion. This vibrating mass stores energy much like a pendulum, allowing a greater flow of work potential to the tool.

Attached to the end of the beam is a 12-in. (300-mm) square breaker plate or cutting knife. These tools move through an amplitude of 1 1/4 to 1 1/2 in. (31 to 38 mm) at a rate of 44 blows/sec. This low amplitude of movement eliminates problems with underground utilities.

Production rates can vary just as they can with other breaking equipment. Rates of up to 800 yd<sup>2</sup>/hr (670 m<sup>2</sup>/hr) for 9-in. (225-mm) thick concrete have been recorded. In addition to high production rates, the PCC is broken into smaller-sized aggregate particles as compared with other conventional breakers. One contractor broke 700 yd<sup>2</sup>/hr (585 m<sup>2</sup>/hr) of 8-in. (200-mm) reinforced concrete with 90 percent of the rubble being 8 in. (200 mm) or less in diameter.

Another advantage is the low noise levels produced during the breaking process. This can be an important factor in urban recycling projects.

The unit is self-propelled and maneuverable. However, the breaking action is limited to flat surfaces such as roadways. Curb and gutter removal is impossible. Overhead clearance is not a problem.

**Breakers using bending moment.** The nibbler is a British pavement breaker designed around the concept of breaking concrete by applying a bending moment (Figure 10). The nibbler is positioned so that two shoes are engaged beneath the slab and a hydraulic ram is operated to apply pressure to the top of the slab at a point ahead of the shoe. This clamps the nibbler down on the concrete. When an external moment is applied, a piece of concrete is broken off.

The nibbler was extensively tested in site trials. In those tests, it broke 62 yd<sup>2</sup>/hr (52 m<sup>2</sup>/hr) of PCC for thicknesses ranging between 5 and 10 in. (125 and 250 mm). When the concrete was reinforced, the reinforcing bars were broken at the same time as the concrete.

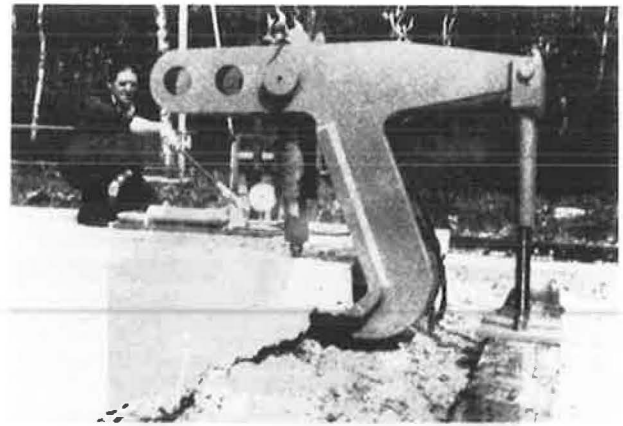


FIGURE 10 Breaking by bending moment.

Noise and vibration were negligible in the site trials. In addition, there is no risk of damage to underground utilities in this process (4).

**High-pressure water jets.** High-pressure water jet systems for the rapid removal of concrete have been developed and tested. Using controlled-cavitation erosion, bridge deck concrete has been effectively removed using water as the only working medium (Figure 11).



FIGURE 11 High-pressure water jet.

Water pressure of 10,000 to 15,000 psi (703 to 1055 kg/cm<sup>2</sup>) is used to selectively remove concrete without damaging other areas of the bridge deck. Single or multiple nozzles can be used to remove the decking. At these pressures, the system can be fabricated from commercially available components and does not require the use of an intensifier or rigid plumbing.

The major advantage to this system is the selective removal of concrete. Otherwise, sound bridge structures are not affected. This includes the removal of corrosion on the existing reinforcing steel without affecting the steel concrete bond in other areas of the bridge deck. Environmentally, this system does not cause the release of dust or other contaminants that are present in other bridge-removal techniques such as jackhammering and subsequent sandblasting. However, disposal of the water used in the removal operation may

create a problem. The high-pressure water jet system has been used to a limited extent on pavements.

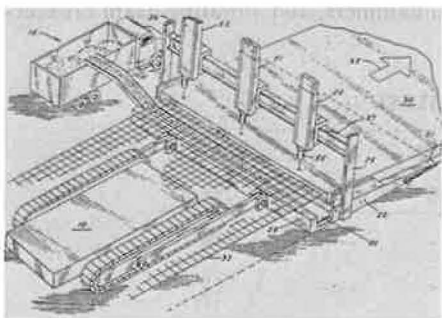
### Mining Industry Equipment

Rock-breaking concepts used by the mining industry have some interesting theoretical applications to PCC recycling but, to date, review has produced few practical applications.

### NEW TECHNOLOGY

Although the equipment previously discussed for PCC pavement breaking, crushing, and sizing is not classified as new technology, the vibrating beam, whiphammer, breaker using bending moment, and use of water jets are relatively new concepts.

However, equipment with even greater production capabilities, capable of salvaging a larger portion of the PCC without contamination from the base material and of producing larger quantities of coarse aggregate, is presently under development by a Wisconsin contractor and by a Minnesota equipment developer. The concepts involve lifting the slab from the base layer and crushing and sizing the material in place (Figure 12). The operation will be continuous.



**FIGURE 12** In-place continuous breaking and sizing equipment.

The planned equipment will offer the following advantages:

1. Production of a maximum amount of coarse aggregate,
2. Minimum base course contamination,
3. Production of a maximum amount of recyclable steel,
4. Minimum traffic control problems, because the equipment can work in an area one lane wide,
5. Reduced damage to haul vehicles by not having large pieces of PCC fall into the trucks,
6. Reduction or elimination of the amount of crushing and sizing at a central plant,
7. Reduced work required to finish the base course prior to placing new pavement,
8. Reduced labor costs, and
9. Increased production.

The equipment has been under development with private investments for about 6 years. Additional private capital is being obtained to produce a prototype.

### POTENTIAL MARKET SIZE

#### PCC Pavement Mileage

Existing public road and street centerline mileage in the United States is 3,880,000 mi (6 243 000 km) (5). Of this centerline mileage, 2,015,000 mi (3 242 000 km) is surfaced. Mileage of surfaced roadway by surface type is as follows:

Roadway Type	Length (mi)	Length (km)
Low-type [asphalt surface less than 1 in. (25 mm) thick]:	505,000	813 000
Intermediate type [asphalt surface with base less than 7 in. (175 mm) thick]:	481,000	774 000
High-type flexible [asphalt surface with base greater than 7 in. (175 mm) thick]:	893,000	1 437 000
High-type rigid (portland cement concrete surface):	136,000	219 000
Total	2,015,000	3 242 000

Of the 136,000 mi (219 000 km) of concrete pavement, 65,000 mi (105 000 km) are located in rural and 71,000 mi (114 000 km) in urban areas. Responsibility for the construction, rehabilitation, and maintenance of this road mileage is under the jurisdiction of federal, state, and local governments. PCC pavement mileage by jurisdiction is given in Table 1.

#### PCC Recycled Mileage

A summary of PCC pavement recycling projects by year and state is presented in lane-miles in Table 2.

PCC pavement mileage and the mileage of recycled PCC pavement for nine states are presented in Table 3. The mileage of rigid pavement has been converted from centerline mileage to lane-miles based on data (5) and on several simplifying assumptions. Rigid pavement mileage is representative of all rigid pavements in the states regardless of the jurisdiction or type of funding. A factor of 4.2 was used to convert Interstate centerline mileage to center-lane mileage and a factor of 2.1 was used to convert the other PCC pavement mileage.

Note that the nine states considered have an estimated 20 percent of the total rigid-pavement lane-miles in the United States. In 1985, the percentage of rigid pavements recycled by states with recycling projects ranged from 0.36 to 1.60 percent with an average of 0.58 percent. These percentages are shown in Figure 13 by year for the United States.

TABLE 1 PCC PAVEMENTS MILEAGE BY JURISDICTION (5)

Jurisdiction	Location	Center Line Mileage
State	Rural	45,000
	Urban	19,000
	Subtotal	64,000
Not State	Rural	7,000
	Urban	13,000
	Subtotal	20,000
Federal	Rural	0
	Urban	13
	Subtotal	13
Local	Rural	13,000
	Urban	39,000
	Subtotal	52,000
TOTAL		136,000

After Reference 5

## PRICE DATA

Table 4 contains a summary of recycling price information for the states of Iowa, Michigan, Minnesota, North Dakota, and Wisconsin. Prices for breaking, removing, and crushing range from \$1.75/yd<sup>2</sup> to \$5.50/yd<sup>2</sup> (\$2.09/m<sup>2</sup> to \$6.58/m<sup>2</sup>). Average prices are about \$3.50/yd<sup>2</sup> to \$4.50/yd<sup>2</sup> (\$4.19/m<sup>2</sup> to \$5.38/m<sup>2</sup>) or \$7.00/ton to \$9.00/ton (\$7.71/metric ton to \$9.92/metric ton).

On a Michigan project, prices were approximately \$1.13 per yd<sup>2</sup> (\$1.35/m<sup>2</sup>) for breaking when the price for breaking, hauling, and crushing was \$4.08/yd<sup>2</sup> (\$4.88/m<sup>2</sup>). On a Wisconsin project, breaking and hauling prices were \$1.85 per yd<sup>2</sup> (\$2.21/m<sup>2</sup>); the crushing price was \$2.62 per yd<sup>2</sup> (\$3.13/m<sup>2</sup>) for a total price of \$4.47/yd<sup>2</sup> (\$5.35/m<sup>2</sup>). A midwestern contractor has indicated that breaking and steel removal range from \$0.35 to \$0.75 per yd<sup>2</sup> (\$0.42/m<sup>2</sup> to \$0.90/m<sup>2</sup>); hauling (for a 5-mi one-way haul) and crushing costs were \$3.00 per ton (\$3.31/metric ton). This same contractor indicated that 60 percent of the costs for breaking, removing steel, hauling, and crushing were associated with equipment; 40 percent of the costs were associated with labor.

## SUMMARY

1. PCC pavement breaking is most commonly performed with gravity-drop hammers, trailer-mounted diesel hammers, spring-arm hammers, and vibrating-beam breakers.

TABLE 2 PCC RECYCLED QUANTITIES (LANE-MILES)

State	Recycled Pavement Mileage					Total
	1982	1983	1984	1985	1986	
Florida	4 (1)	----	----	----	----	4
Georgia	----	21 (1)	1 (1)	----	----	22
Iowa	----	23 (2)	----	62 (3)	----	85
Kansas	----	----	----	** (2)	----	**
Michigan	3 (1)	24 (1)	94 (3)	144 (2)	32 + (1)	297
Minnesota	----	47 (3)	----	----	----	47
New Mexico	----	----	----	----	111 (4)	111
North Dakota	----	45 (2)	26 (1)	85 (3)	----	156
Oklahoma	----	31 (1)	----	----	----	31
Oregon	----	----	----	27 (1)	----	27
Wisconsin	----	24 (1)	152 (2)	46 (2)	26 + (1)	248
Wyoming	----	----	----	44 (1)	----	44
Total	7	215	273	408	169 +	1,072 +

NOTE: Quantities are estimates.  
 One lane mile represents 12 foot wide pavement 5,280 feet in length.  
 (1) Number of projects represented  
 \*\*Anticipated project (unknown quantity)  
 ----Data not applicable

TABLE 3 RECYCLED VERSUS PCC PAVEMENT MILEAGE FOR ALL PCC PAVEMENTS IN THE U.S.

State	Mileage of Rigid Pavements, Lane Miles	Rigid Pavement Mileage % of Total U.S.	Recycled Mileage							
			1983		1984		1985		1986	
			Lane Miles	%*	Lane Miles	%	Lane Miles	%	Lane Miles	%
Georgia	9,870	3.0	21	0.2	1	0.01	---	---	---	---
Iowa	8,789	2.7	23	0.3	---	---	62	0.7	---	---
Michigan	11,033	3.3	24	0.2	94	0.9	144	1.3	32+	0.3+
Minnesota	10,781	3.3	47	0.4	---	---	---	---	---	---
New Mexico	4,137	1.3	---	---	---	---	---	---	111	2.7
North Dakota	6,838	2.1	45	0.7	26	0.4	85	1.2	---	---
Oregon	7,583	2.3	---	---	---	---	27	0.4	---	---
Wisconsin	9,061	2.7	24	0.3	152	1.7	46	0.5	26+	0.3
Wyoming	2,751	0.8	---	---	---	---	44	1.6	---	---
SUBTOTAL	70,843	0.2	184	---	273	---	408	---	169+	---
OTHER STATES	260,766	0.8	31	---	---	---	---	---	---	---
TOTAL U.S.	331,609	---	215	---	273	---	408	---	169+	---

Comments: \*Percent of total rigid pavement in state

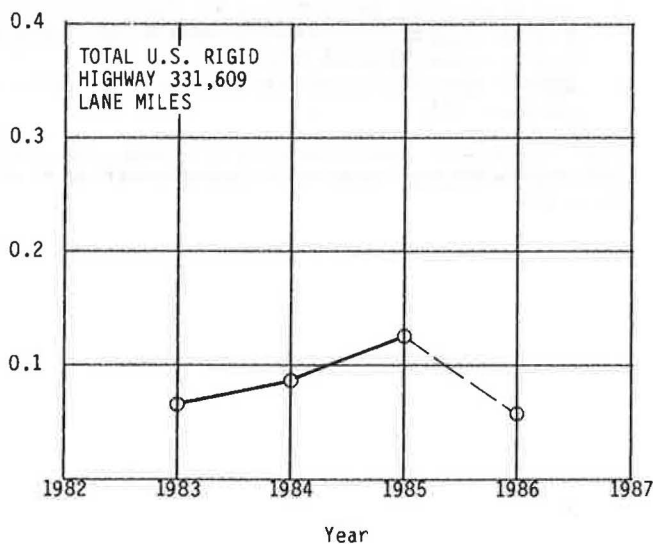


FIGURE 13 PCC recycling in the United States.

2. Typically, 90 to 95 percent of PCC pavement can be recovered from a project. The amount of coarse aggregate produced ranges from about 50 to 80 percent depending upon the properties of the PCC and the construction operation used.

3. PCC pavement breaking, steel removal, hauling, crushing, and sizing can be performed for a price of about \$3.50/yd<sup>2</sup> to \$4.50/yd<sup>2</sup> (\$4.19/m<sup>2</sup> to \$5.38/m<sup>2</sup>) of pavement

or \$7.00/ton to \$9.00/ton (\$7.71/metric ton to \$9.92/metric ton) of aggregate produced.

4. Pavement breaking and steel removal prices are in the range of \$0.50/yd<sup>2</sup> to \$1.50/yd<sup>2</sup> (\$0.60/m<sup>2</sup> to \$1.79/m<sup>2</sup>); hauling and crushing prices are in the range of \$2.50/yd<sup>2</sup> to \$3.50/yd<sup>2</sup> (\$2.99/m<sup>2</sup> to \$4.19/m<sup>2</sup>) of pavement area. Equipment costs are about 60 percent of the costs, and labor is about 40 percent of the costs.

5. Steel removal remains a labor-intensive, low-production operation. Significant improvements in steel removal and breaking in combination with steel removal need to be made.

6. Breaking and crushing operations need to be improved in order that large quantities of coarse aggregate can be produced from the PCC. Field operations need improvement to prevent or reduce the amount of base course contamination.

7. Project planning and design engineers need to consider the use of the PCC fines produced in the recycling operation. Recycled PCC can be used as aggregate for PCC as well as Econcrete, granular base and subbase, AC, and PCC- and AC-stabilized bases and subbases.

8. Methods need to be developed that allow the contractors to predict the ease of breaking and crushing for a particular project. Field and laboratory tests should be considered.

9. Rehabilitation alternatives competing with PCC recycling include PCC overlays, AC overlays, and cracking and seating followed by an AC overlay. AC overlays have been



TABLE 4 PCC RECYCLING PRICE DATA

State	Project (year)	Number of Projects Represented	Costs for Breaking, Removing & Crushing (dollars/sq. yd.)		Cost Breakdown* (dollar/sq. yd.)		Remarks
			Range	Average	Assume 60% Equipment	Assume 40% Labor	
Iowa	1983	1	---	4.75	2.85	1.90	---
Michigan	1983	---	3.80 to 4.35	4.08	2.45	1.63	---
Minnesota	1983-1985	6	1.75 to 3.59	3.07	1.84	1.23	Material Stockpiled (Not Crushed)
North Dakota	1983-1984	3	2.10 to 4.37	3.49	2.09	1.40	---
Wisconsin	1984	1	3.44 to 5.50	4.47	2.68	1.79	---

Comments: \*Cost breakdown assumes 60% and 40% of average cost for breaking, removal, and crushing and for equipment and labor, respectively.

used historically, while cracking and seating have become popular in several states.

10. About 3,200,000 yd<sup>2</sup> (2 676 000 m<sup>2</sup>) of PCC pavement was recycled in the 1985 construction season. Considering the condition of pavement in the United States, the current recycling quantities, and the expected growth of recycling, 50 to 100 equipment units will be required in 20 years to break or pulverize PCC pavements.

11. Desirable equipment improvements include (a) increased production, (b) improved steel removal techniques, (c) reduced disturbance of the base, subbase, and subgrade, (d) reduced labor costs, (e) increased production of the coarse aggregate fraction, and (f) reduced noise.

12. Improvements in equipment will reduce costs, thereby making PCC pavement recycling a more attractive rehabilitation alternative.

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