169

Materials

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **169**

REMOVING CONCRETE FROM BRIDGES

TRANSPORTATION RESEARCH BOARD
National Research Council

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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REMOVING CONCRETE FROM BRIDGES

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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
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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NOTICE

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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The Transportation Research Board evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

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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 maintenance engineers, bridge engineers, and others interested in methods and procedures for removing concrete from bridges. Information is provided on equipment and procedures used by states to remove concrete from highway bridges.

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.

Repairing structural concrete involves removal and replacement of deteriorated concrete. This report of the Transportation Research Board describes the equipment and procedures used for both complete and partial removal of concrete from bridge decks and substructures.

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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Frank N. Lisle, Engineer of Maintenance, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Figure 2 in this synthesis is printed with the permission of Cutting Technologies Inc., and Figure 5 with the permission of Elco International Inc. Figure 12 appears courtesy of P.L. Palmear, Ontario Ministry of Labour, and Figures 13 and 15 courtesy of H. Ingvarsson, Swedish Road Administration. Information on hand-arm vibration syndrome taken from Reference *49* appears with permission of the *New Scientist*.

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

REMOVING CONCRETE FROM BRIDGES

SUMMARY

Most contracts for the rehabilitation of bridges include the removal of concrete. On deteriorated bridges, the quantity of removal is difficult to predict. Removal procedures not only are slow and expensive but often they control the progress of a contract and are responsible for most of the cost overruns. Furthermore, the service life of the rehabilitated structure is strongly influenced by the percentage of unsound or chloride-contaminated concrete removed, the cleanliness of the reinforcing steel, and the quality of the remaining concrete surface. The administration of contracts involving the removal of concrete is also made difficult by the opposing interests of the agency and the contractor. The agency's interest is to ensure that all the deteriorated concrete is removed without damage to the concrete left in place or to the reinforcing steel. The contractor's interest is to complete the work as quickly and economically as possible, and this encourages the use of high-production equipment more likely to damage the structure. Additional pressures are created in contracts that contain incentive-disincentive clauses. Difficulties in determining quantities also complicate payment for concrete-removal operations. This synthesis describes the equipment available for removing concrete from bridges, methods of surface preparation, and practices used for estimating quantities and for contract preparation and administration. Suggestions for future research, the results of a state-of-the-practice survey, and an extensive list of references are also included.

Equipment used for the complete removal of a concrete component includes saws, drills, breakers, splitters, crushers, and ball and crane, as well as blasting. Saws are often used to cut a deck into sections, but care must be taken not to cut the top flanges of girders or floor beams. Breakers are usually machine mounted and can be used on most components. Restrictions are often placed on the size and manner of operation of these breakers, because the risk of damage to the remainder of the structure is high. Mechanical splitters and crushers are relatively new pieces of equipment that offer the advantages of little noise, vibration, or damage to concrete left in place. Splitting can also be accomplished using expansive chemicals.

Hand-held pneumatic breakers are the most common method of removing deteriorated concrete. Although widely available and inexpensive, breakers are noisy and slow, damage the remaining concrete, and can cause the occupational disease hand-arm vibration syndrome. Hydrodemolition is a new development, using high-pressure water to remove concrete. Under ideal conditions, the process is rapid and removes all the unsound concrete without damage to reinforcement or sound concrete. However, the equipment is expensive and the experience has been mixed. There are also a number of thermal processes that can be used to remove concrete, but all are either in the development stage or in limited use.

The objectives in preparing a surface for repair are for it to be clean and sound; surface roughness has little effect on bond strength. Mechanical equipment, such as scabblers or, more commonly, scarifiers, is used when the concrete surface must be removed. Blast cleaning, usually with abrasives, is used following scabbling or scarifying or when cleaning is specified as the only method of surface preparation. Chemical cleaning is no longer used for bridge applications.

The criteria for the removal of concrete from corrosion-damaged bridges have changed over the years, and the trend has been to remove more concrete before repair. It has been shown that deeper and more extensive concrete removal increases the service life of the rehabilitated structure. It has also been shown that it is very difficult to clean pitted reinforcement, and this is a likely cause of continued corrosion. Estimating the quantity of concrete to be removed before award of a contract, and identifying an equitable method of payment, result in serious problems in contract preparation and administration. The most common approach is to define several classes of removal and bid a unit price for each class. Payment is then made on the basis of quantities measured in the field.

Research is needed to develop or modify equipment to satisfy the requirements of rapid, controlled removal without damage to the remaining concrete or steel. There is also a need for improved methods of detecting deteriorated concrete, for estimating removal quantities, and for research into the relationship between removal criteria and service life. Suggestions are also made to develop innovative contracting procedures and better methods of quality assurance.

A survey of current practice revealed a wide variety of equipment and contracting procedures in use by the states. Many reported dissatisfaction with current methods and significant cost overruns.

CHAPTER ONE

INTRODUCTION

Most contracts for the rehabilitation of bridges include the removal of concrete. The number of bridges requiring rehabilitation, especially to repair corrosion-induced damage, has increased considerably in recent years (*1*), and inevitably this has focused attention on the methods used to remove deteriorated concrete. Other situations that involve concrete removal are replacing a bridge or component, widening a deck, or improving the skid resistance through the application of a bonded overlay. In the case of a deck widening, not only must the existing curb and parapet be removed, but the piers and abutments must be modified.

Concrete-removal procedures are tedious and expensive. They often control the rate of progress and are responsible for most of the cost overruns on a rehabilitation contract. Furthermore, the service life of the rehabilitated structure is strongly influenced by the quantity of concrete removed (*2*), the cleanliness of the steel (*3*), and the quality of the surface that is prepared. Removing concrete from around reinforcing steel without damage to the rebars or the concrete left in place is particularly expensive, and the costs of removal have a major influence on the selection of the method of rehabilitation. As more concrete is removed, the costs may increase to the point at which complete removal and replacement of the component is more cost-effective than partial removal and rehabilitation. Although the quantity of concrete removed is higher, complete removal permits the use of techniques with higher production rates, with the result that the overall cost is lower and the life of the new component is longer.

In general, contracts are most successful when end-result specifications are used and when both the agency and contractor have a mutual benefit in the method of payment. In such cases, the agency can define the quality and quantity of work required, the contractor can use initiative and resources to carry out the work most efficiently, and the payment is equitable to both parties. Unfortunately, it is very difficult to satisfy these conditions when the removal of concrete is involved. In the common case of the removal of deteriorated concrete, it is the agency's interest that all the deteriorated concrete be removed without damage to either the concrete left in place or the reinforcing steel, and that the surface to receive the repair material is clean and sound. The contractor's primary motivation is to complete the work as quickly and economically as possible, usually without a financial interest in the long-term performance of the structure. Additional pressures are placed on the contractor through the growing use of incentive-disincentive clauses in the contract, especially for work in urban areas or on important structures (*4–6*). These clauses specify a completion date and the bonus or penalty to be paid for early or late completion. The bonus/penalty clauses can be as much as $50,000/day or more. Under ideal conditions, it is difficult for the agency to verify the quality of the work, but when the stakes are so high it is considerably more difficult. Such clauses also place additional pressures on the agency to ensure that any limitations on equipment or operations are defined in the contract. If the contractor is forced to change methods after award of the contract, the potential for litigation is very high.

There is a wide variety of equipment used to remove concrete from bridges. Some of it, such as pneumatic breakers, has been used for almost a century; other equipment, such as hydrodemolition equipment, is relatively new. Although the range of available equipment is large, rarely can different types of equipment be used interchangeably. The optimum choice of equipment for a particular application is determined by:

- the quantity and quality of concrete to be removed,
- the time available to complete the work,
- the type of concrete component and its accessibility,
- the cover to the reinforcement, and
- restrictions with respect to vibration, noise, dust, and disposal of the detritus.

The purpose of this synthesis is to (a) report the procedures used to estimate the quantity of concrete to be removed, (b) describe the methods and types of equipment available, and (c) identify the conditions under which each method is most effective. Although the separation is sometimes arbitrary, it is convenient to divide the procedures into those used for the complete removal of a concrete component, those used for partial removal, and those used to prepare a surface for repair. The synthesis also identifies ongoing and needed research and reports the results of a survey of current practice.

CHAPTER TWO

EQUIPMENT AND PROCEDURES FOR COMPLETE REMOVAL

SAWING

Blade Saws

The most common type of saw blade for cutting concrete is the wet-cutting diamond blade, shown in Figure 1, which is made by welding or silver brazing diamond-impregnated segments to the perimeter of a steel core. Each diamond segment consists of numerous small diamond particles embedded in a metal matrix called the bond (*7*). There are spaces, called gullets, between the segments to allow the cooling water to reach the cutting surface and allow the steel core to expand without warping when the blade is in use. A pin hole fits the saw's drive pin and is a safety device to prevent the blade from spinning on the spindle if the spindle nut becomes loose (*8*). There are many manufacturers of diamond blades, and some manufacturers produce several different qualities of blade by varying the composition of the metal bond and the type, size, and concentration of diamonds. A 12-in. (300-mm) blade costs anywhere from $300 to $1400. The introduction of synthetic diamonds for industrial use has led to both reduced costs and increased cutting speeds (*9*). Natural and synthetic diamonds are now often used in combination.

If a normal diamond blade is used without water, the blade overheats and the segments become detached. Dry-cutting blades are made by laser welding the diamond-impregnated segments to the steel core. These blades can operate at temperatures between 400°F and 550°F (204°C and 288°C).

A third type of blade is the silicon-carbide abrasive blade with woven fiberglass reinforcement. This type of blade wears rapidly and is only suitable for use on reinforced concrete when the amount of cutting is very small.

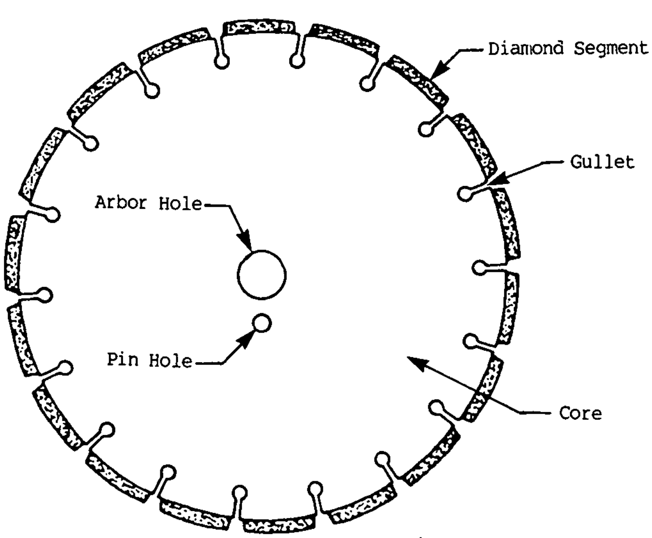


FIGURE 1 Wet diamond saw blade.

Most dry-cutting diamond blades are designed for use with portable, low-horsepower machines with which the operator can control the cutting speed and hence the amount of heat generated by cutting. Best results are achieved when the peripheral blade speed under load is 165 to 195 ft/min (50 to 59 m/min). Dry-cutting blades mounted on hand-held saws are useful for work on vertical surfaces because they are lightweight and less tiring to maneuver. When precise cutting is required, the saw can be mounted on short sections of steel track (*10*). For such applications on vertical surfaces, water-cooled equipment would be difficult to set up and cumbersome to handle.

For work on horizontal surfaces, the wet-cutting diamond blades are normally mounted on self-propelled gasoline or diesel-powered saws. Saws with hydraulic, pneumatic, and electric power are also available, though these units are most often used in buildings where exhaust fumes cannot be tolerated. The largest saws have engines of 50 hp or more and are equipped with hydrostatic transmission, water pump, cutting depth indicator, cutting line guide, and lifting frame. These units can weigh more than 1000 lb (450 kg).

A more recent development has been the introduction of tracked diamond sawing. This uses hydraulically powered machines in which the saw head is mounted on a rack and pinion track and is self-propelled. This allows for very accurate and rapid cutting. The major application for this equipment is in modifications to buildings. It has been used on highway bridges for the removal of curbs and parapets, because it is particularly well suited to making a cut at any angle.

Wet-cutting diamond blades work best under a steady, even pressure without the blade being forced beyond its cutting capacity. The recommended operating speed for reinforced concrete is 7000 to 9000 ft/min (2100 to 2700 m/min) measured at the perimeter of the blade. For a 12-in. (300-mm)-diameter blade this corresponds to approximately 2550 rpm. Usually, 1.3 to 2.6 gal of water/min (5 to 10 L/min) are needed to cool the blade, and the water should be directed to both sides of the blade. If insufficient water is used, the swarf (fine particles that are the product of cutting) is not removed quickly enough and undercuts the part of the steel core where the diamonds are attached. Without sufficient water, the blade will also overheat, causing loss of segments. Speed of cutting and blade life depend on the hardness of the aggregate, the amount of reinforcement, and the way in which the saw is operated. Hard aggregates not only shorten blade life and slow the cutting rate but also require a saw with more power. Blades used to cut hard aggregates such as quartz or granite should have segments with tough diamonds and soft metal bonds. Otherwise, the diamond particles will wear down even with the bond and the blade will become glazed and unable to cut. Conversely, for cutting soft aggregates such as limestone, the blades should have hard metal bonds so that the diamond particles are not lost before their cutting life is used up. It has been found that blade life is shorter and cutting is slower when two or three shallow cuts are made instead of one deep cut.

Reinforcement in the concrete has a major effect on blade life and cutting speed. When steel is encountered, it is advisable to reduce blade speed, reduce the pressure on the blade, and increase the flow of water.

The most common application of sawcutting for concrete removal in bridge work is to cut a bridge deck into slabs that are then lifted out by crane (*11, 12*). This method of removal is relatively rapid and there is no falling debris. It is often used in conjunction with prefabricated deck panels, sometimes with the work being done at night and the bridge being kept open during the day. The best known example of the use of this technique was the reconstruction of the deck on the Golden Gate Bridge (*13*). There are three major problems that can arise when sawcutting is used for this application:

- The sawcut may coincide with a rebar along its entire length, thereby slowing progress.
- The partially cut slab may move and pinch the blade.
- The top flanges of floor beams and girders may be cut.

It is very difficult to avoid the first situation. Although a covermeter may be of assistance in some cases, the meter will not detect the bottom bars in the slab. In any event, the reinforcing steel is rarely straight, so the probability of hitting a significant length of rebar is quite high. In the second situation, wedges should be used to open the sawcut wider than the kerf, though this is sometimes very difficult. Cutting the top flanges of floor beams and girders was the most common form of damage associated with concrete-removal practices reported in the survey in Appendix A. As a result, many agencies have placed restrictions on the use of full-depth sawing in cases where structural members are in contact with deck soffit. These restrictions range from outright prohibition to maintenance of a safe clearance between the top of the structural member and the bottom of the sawcut.

Another common application of full-depth sawcutting is in widening a bridge. Two approaches are possible. The first is to leave steel protruding from the concrete for use as lap bars. A full-depth sawcut is made at the distance of the lap length of the reinforcing bars from the joint and a second sawcut along the joint to a depth slightly less than the depth of the reinforcement. The disadvantage of this method is that it is difficult to remove the concrete to the joint line to provide a vertical face and without damaging the reinforcement. The second approach is to make a full-depth sawcut along the joint line. The edge of the slab must then be drilled and tie rods anchored in such a way as to provide the required structural capacity across the joint.

Sawcutting is noisy but produces negligible vibration. Wet-sawing does not generate any dust. The technique is well suited to the staged replacement of deck panels, but particular care is needed to avoid damage to supporting members.

Diamond Wire Saws

A different method of sawcutting concrete is to use a diamond wire cutting system. The technology originated in Europe in the early 1970s for use in stone quarries. It was not used regularly in the United States for cutting reinforced concrete until the early 1980s, although efforts were made in the 1970s with limited success (*14*).

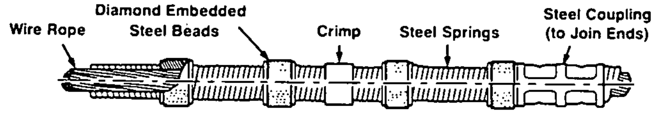


FIGURE 2 Diamond-cutting wire.

There are many types of diamond beads and wire assemblies available and many more are under development. The most common type is illustrated in Figure 2. It has industrial diamonds electroplated to a steel bead that is strung on a wire rope. Each bead is separated by partially compressed steel springs. The springs allow the beads to move slightly, to eliminate shock loads to the wire and the driving equipment when the beads catch on sharp edges. Steel sleeves are crimped to the wire rope at predetermined intervals to limit the sliding of the beads on the wire rope. Alternatively, bead spacing may be maintained by plastic spacers. The ends of the wire are joined using a steel coupling, resulting in a continuous wire. Any length of wire can be created, depending on the size of the concrete to be cut, but lengths of 40 to 100 ft (12 to 30 m) are most common.

In order to cut out a section of slab, a small hole is normally drilled through the concrete at each corner of the concrete to be removed and the wire passed through two of the holes. After coupling the wire, it is passed around idler wheels, which guide the wire, and routed over the drive wheel. The drive wheel is either hydraulically or electrically powered, and provides a wire speed of 3000 to 6000 ft/min (910 to 1830 m/min). Hydraulic drives are preferred because the drive speed is both adjustable and reversible. The drive wheel is mounted on a carriage so that it can slide and maintain tension on the wire as the cut progresses. When the limit of movement of the drive wheel is reached, the cutting operation is stopped and either the carriage moved or the wire shortened. Water is used for cooling and for removing the swarf.

Production rates are a function of the type of wire used, the type of aggregate, the amount of reinforcement, and site conditions. Typical rates are 5 to 40 ft^2/hr (0.5 to 4 m^2/hr). The life of the wire is relatively short, about 1 to 10 ft^2 of cut/lineal ft (1 to 10 m^2/lineal m) of wire. In one application in Italy (*15*), consumption was found to be about 3.2 ft (1 m)/11 ft^2 (1 m^2) of cut for reinforced concrete containing 1 percent steel. Other measurements, with wire from a different manufacturer, led to an estimate of useful life of about 21 ft^2 (2 m^2)/3.2 ft (1 m) of wire (*16*) for concrete with about 0.3 percent reinforcement. This has an important implication, because as the wire wears, its diameter is reduced so that the kerf is reduced as the work progresses and a replacement wire will not fit the same kerf. It is therefore important that the wire that starts the cut have sufficient life to finish it.

Wire sawing is a relatively new technology, and there have been few applications to bridges. In one example on Long Island, the technique was used to remove the bridge deck, spandrell beams, and pier caps of a 14-span structure in a period of 19 days.

Despite limited use, the method does have the advantages of no vibration or dust and little noise, and it can be used to make cuts at any angle. Its use can be expected to increase as the equipment becomes more available, provided that the costs are competitive with other methods.

DRILLING

Drills are rarely used as the sole method of removing concrete, but the drilling of holes is the first step when using such removal methods as splitting or blasting. Drill holes are also made in the corners in combination with wire sawing and before blade sawing in situations where it is necessary to avoid overcutting the corners. They can also be used to weaken a component (e.g., in removing part of a deck before widening).

Most drill bits are core bits made like segmented diamond saw blades by brazing diamond segments onto the end of a steel tube. These bits must be water cooled. Laser-welded bits for drilling small holes without water are becoming available (*7*). Carbide bits, both dry and water-cooled, are also made for holes less than about 1 ½ in. (40 mm) in diameter. The water-cooled bits are designed specifically for rapid drilling in reinforced concrete. The factors that affect the performance of diamond saw blades and the selection of the type of blade also apply to diamond core bits.

Core drills are inexpensive: a basic drill and stand costs about $2000, and a 4-in. (100-mm) bit costs in the range of $200 to $600, depending on quality. The smaller drills are electrically powered; the larger drills are hydraulically or pneumatically powered. Numerous accessories, such as vacuum pads for attaching a drill stand to a vertical surface, are available from the many manufacturers of this type of equipment.

As with saw blades, reinforcing steel has the most significant effect on performance. It has been found that 1 percent steel reduces bit life by about 25 percent, and 3 percent steel by about 90 percent (*7*).

Drilling can be used to remove large pieces of concrete by boring overlapping small holes around the perimeter of the piece. This technique is known as stitch-drilling. The process has the advantages that it can be used to cut almost any shape and to almost any depth. However, stitch-drilling is usually only easier and less expensive than sawing for holes deeper than 18 in. (460 mm), and this situation is not common in bridge work.

The most common application of the use of intermittent holes is in widening a deck. Holes are drilled every 8 in. (200 mm) or so to facilitate a vertical face when the concrete is removed with hand-held breakers. The major drawback to this method is that the holes must avoid the transverse reinforcement; otherwise the purpose of making the steel continuous through the joint is defeated.

Core drills are widely available, do not create much dust or vibration, and are reasonably quiet. Although they are not a primary method of removing concrete, they are important in conjunction with several other methods.

RIG-MOUNTED PERCUSSIVE TOOLS

Breakers

Machine-mounted hydraulic breakers are a very common piece of equipment for the demolition of concrete. The breakers, which come in a wide range of sizes, are usually mounted on the hydraulic boom of an excavator, resulting in a machine that has both reach and maneuverability. Pneumatically powered breakers are also available.

In hydraulically operated breakers, oil under high pressure moves the piston, which strikes the tool head on each stroke. Most units have a low-pressure gas chamber behind the piston that is compressed during the return stroke and serves to absorb the recoil of the piston and store energy for the next blow. Hydraulic breakers range in size from units weighing 200 lb (91 kg) and delivering 125 ft lb (169 J) of energy per blow at 1,300 blows/min to those weighing 25,500 lb (11,570 kg) and delivering 20,000 ft lb (27,000 J) of energy per blow at 150 blows/min (*17*). Most of the breakers operate at an oil pressure of about 2000 psi (14 MPa). The smallest units require an oil supply of 4 gpm (15 L/min), and the largest 110 gpm (420 L/min). In all cases the size of the mounting platform must be matched to the size of the breaker, and in some cases, additional damping devices are used both for quicker operation and to reduce shock and vibration transmitted to the machine and operator.

There are fewer manufacturers of rig-mounted pneumatic breakers than there are of hydraulic breakers, and the range of sizes is much narrower. The smallest weigh 450 lb (204 kg) and deliver 400 ft lb (540 J) per blow at 1100 blows/min. The largest weigh 1640 lb (740 kg) and deliver 2000 ft lb (2700 J) per blow at 600 blows/min. The principle of operation is very similar to that of the hydraulic breakers except that power is supplied by compressed air at 90 to 100 psi (620 to 690 kPa). The size of compressor required varies between 125 cfm (3.5 m^3/min) to 750 cfm (21 m^3/min), depending on the size of the breaker.

Three different tools are available for use in removing concrete: (a) a blunt point, (b) a chisel point, and (c) a conical bit that is known as a moil point. Only the moil point is normally used on bridge decks. The size of the chisels increases from 2 in. (50 mm) to more than 6 in. (150 mm) with the size of the breaker, but most are in the range of 3 to 4 in. (75 to 100 mm).

Although the largest breakers clearly are not suitable for use on bridge decks (they are used mainly for breaking rock), the dilemma for agencies and contractors alike is to decide whether rig-mounted breakers can be used to remove concrete from bridges and, if so, what size of equipment is suitable. In some cases the maximum size is determined by the size of the excavator needed to satisfy conditions of restricted access. In other cases, there is a natural desire to use the largest breaker possible in order to increase production rates, but as the size increases, so does the risk of damage to concrete to remain in place. In the responses to the survey in Appendix A, damage to the top flanges of steel and concrete girders by rig-mounted breakers was the second-most-common form of damage reported. Unfortunately, there is no clear boundary between the size of breaker that will cause damage to concrete remaining in place and that which will not. In fact, it is unlikely that such a limit could be established, because it is influenced by both the site conditions and the skill and care of the operator. Consequently, various forms of restrictions on the use of breakers have appeared in specifications, and although these appear arbitrary, they reflect both engineering judgment and local experience.

Alabama prohibits the use of rig-mounted breakers in situations where the reinforcement or girders will be reused. A number of jurisdictions permit the use of rig-mounted breakers for deck removal but do not allow their use directly over the beams, and sometimes within a prescribed distance of the edges of the flanges. Some agencies have placed limits on the size of breakers that will be allowed for deck removal, but there is little uniformity. Illinois limits breakers to those having a striking energy of no more than 1200 ft lb (1620 J). Ontario places the limit of 440 ft lb (600 J), but also has several other restrictions. Rig-mounted breakers can only be used on decks supported by steel girders, and then only within 4 in. (100 mm) of the flanges. For other applications, rig-mounted breakers are not permitted for the removal of concrete located within 12 in. (300 mm) of concrete to remain in place. In all cases, the contractor is required to have written approval for the equipment before the work begins.

The responses to the survey and reports in trade journals (*18, 19*) indicate that the use of rig-mounted breakers for concrete removal is widespread. For decks, the breaker is often mounted in place of the backhoe bucket on a rubber-wheeled front-end loader. For other applications, such as pier removal, where reach may be a factor, or the removal of foundations, where there are no restrictions on the size of equipment, breakers may be mounted on large excavators. For deck removal, two different techniques are possible. The breakers can be used to punch out the perimeter of a section of deck slab, the reinforcement cut with a torch, and the slab lifted directly onto a truck for disposal as illustrated in Figures 3 and 4. Alternatively, the breaker can be used to break the concrete into pieces sufficiently small that the reinforcement is separated. In such cases the rubble is caught by false decking installed beneath the bottom flanges of the girder or by cradles suspended beneath the deck. The choice between the two methods is largely determined by the disposal site; crushed material can be used for riprap, backfill, or subbase, whereas slabs are rarely suited for secondary use. The use of rig-mounted breakers is relatively safe, and the only problem reported has been minor injuries resulting from the breakage of tool points (*20*).

The advantages of rig-mounted breakers are high production rates, a large reach, and easy maneuverability. Some breakers can be operated underwater. Productivity varies greatly with the size of hammer, type of concrete, amount of reinforcement, and ease of access. Rates have been quoted (*21*) for unreinforced concrete in the range of 1.2 and 120 yd^3/hr (0.9 to 90 m^3/hr) and for reinforced concrete between 1.6 and 94 yd^3/hr (1.2 and 72 m^3/hr). The apparent contradiction between the rates at the bottom of the ranges is that it is presumed that a larger breaker is required for reinforced concrete. Productivity rates on bridge decks are near the low end of the range because of the restrictions that are common. Production rates of 2 yd^3/hr (1.5 m^3/hr), which includes removal, breaking the concrete into sizes small enough to remove the reinforcement, and loading, can be considered typical (*19*).

FIGURE 3 A hydraulically powered breaker being used to punch out the perimeter of a section of bridge deck.

FIGURE 4 Use of a crane to remove a section of deck slab.

The disadvantages of rig-mounted breakers are that they are noisy, generate dust and vibration, and can cause considerable damage to girders and to concrete to be left in place. Without restrictions on the size of breakers and location of use, and, even more important, without a commitment from the operator and inspection staff to prevent damage, the potential for damage is very high. For this reason, the decision to use rig-mounted breakers (establishment of conditions under which their use will be permitted) must be made with considerable care and judgment.

Whiphammer

The whiphammer is a different form of rig-mounted percussive tool. It consists of a truck-mounted, hydraulically operated hammer attached to the end of a heavily restrained leaf spring arm (*22*). A cab on the rear of the truck bed enables the operator to control both the movement of the hammer and the truck. The steel hammer is raised hydraulically and swung downward so that the whip-like spring, from which the hammer takes its name, adds to the force with which the hammer strikes the concrete. There are six hammer heads available, including one for bridge decks that is designed to avoid penetration and thereby prevent damage to the beams. The number of blows per minute is variable up to a maximum of 42, with the normal operating range being 35 to 40. Each blow represents up to 300,000 ft lb (405 kJ) of energy.

Whiphammers have been used for both bridge decks and parapet wall removal (*6*). Production rates for bridge deck removal are in the range of 400 to 1200 ft^2/hr (37 to 110 m^2/hr), with 800 to 1000 ft^2/hr (74 to 93 m^2/hr) being considered typical. Production rates for parapet wall depend on such items as maneuverability of the truck, beam location, amount of reinforcement, and condition of the concrete. Rates up to 100 lineal ft/hr

(30 m/hr) have been achieved. The concrete is broken into fairly small pieces, and it is claimed that 90 percent are 6 in. (150 mm) or less.

The unit costs approximately $140,000 and, like all percussive tools, requires regular maintenance and replacement of some parts. The leaf springs require daily greasing, weekly servicing, and replacement of individual leafs as necessary; the hammer head requires replacement every week or so.

The equipment is relatively new, and the experience on decks is therefore limited. Only a few states reported using the whiphammer. Idaho stated that it was the preferred method of deck removal, but also noted that some damage to stringers had occurred. Others reported excessive vibration and damage to beams. The whiphammer has the advantage of high production rates, but this is at the expense of a very high energy input per blow. Until more experience is gained, the equipment appears better suited to use where the entire superstructure is being replaced rather than just the deck, because of the possibility of damage to the beams if they are to be reused.

SPLITTING

Mechanical Splitters

Mechanical splitting is a technique developed in Europe for breaking rock using a wedging action. More recently, it has also been used to demolish reinforced concrete. The major components of a mechanical splitter are illustrated in Figure 5. The splitting action is developed by a steel plug or wedge positioned between two hardened steel shims or feathers. The wedge is inserted into a predrilled hole in the retracted position, and when hydraulic pressure is applied to the piston, the plug advances and the feathers are forced against the sides of the hole. A break normally occurs within seconds. One manufacturer makes a splitter that operates as shown in Figure 6. Instead of a downward action of the plug, the piston draws the plug inward to spread the feathers. The force exerted by the feathers is in the range of 125 to 410 tons (1100 to 3650 kN), depending on the manufacturer and model of splitter. Hydraulic pressure is supplied by a pump that can be powered by a gasoline, pneumatic, or electric motor. Most pumps are capable of operating two or more splitters simultaneously.

The key elements to the successful use of a mechanical splitter are the hole pattern and controlling the direction of the break. The holes must be straight and of the required diameter. Holes that are crooked can bend the plug and feathers. Holes that are too short can damage the plug. The direction of the break is controlled by the alignment of the feathers, which on some models expand at 90° to the handle for easy reference.

The amount of concrete that can be removed at one time is a function not only of the hardness of the concrete but, even more important, of the amount and orientation of the reinforcement. The hole pattern is determined by a combination of experience and test breaks. Holes are typically spaced 1 to 3 ft (300 to 900 mm) apart. The splitter is normally used by working away from free surface to allow for the movement of broken concrete. The process is more efficient if there are two free surfaces and the splitter is placed at a 45° angle to the two surfaces. Once the concrete has been cracked and the bond to the reinforcement broken, the concrete can be removed with percussive tools. Alternatively, wedges can be inserted as shown in Figure 6 and the crack widened to expose the reinforcement, which can then be cut with a torch. Using this method, large sections can be cut and lifted out by crane.

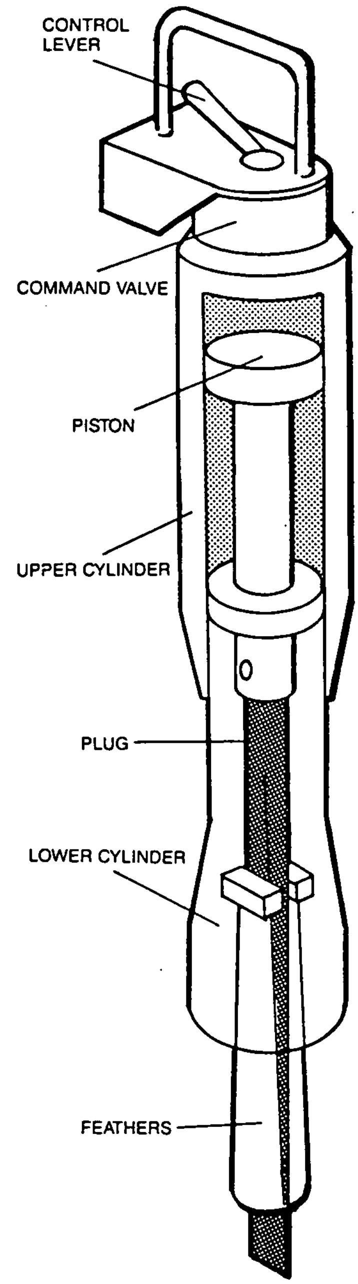


FIGURE 5 A mechanical splitter with an advancing plug.

It is also possible to remove a large mass of concrete without working from a free surface, as illustrated for the case of pier cap in Figure 7. The sequence of operations is as follows: Two lines of holes are drilled at least 1 ft (300 mm) apart. Several splitters are used to fracture the concrete, first along the top line and then the bottom. A third line of holes is drilled between the two broken lines, and the splitter is used on a 45° angle, working in from one face. The broken sections can be removed with a

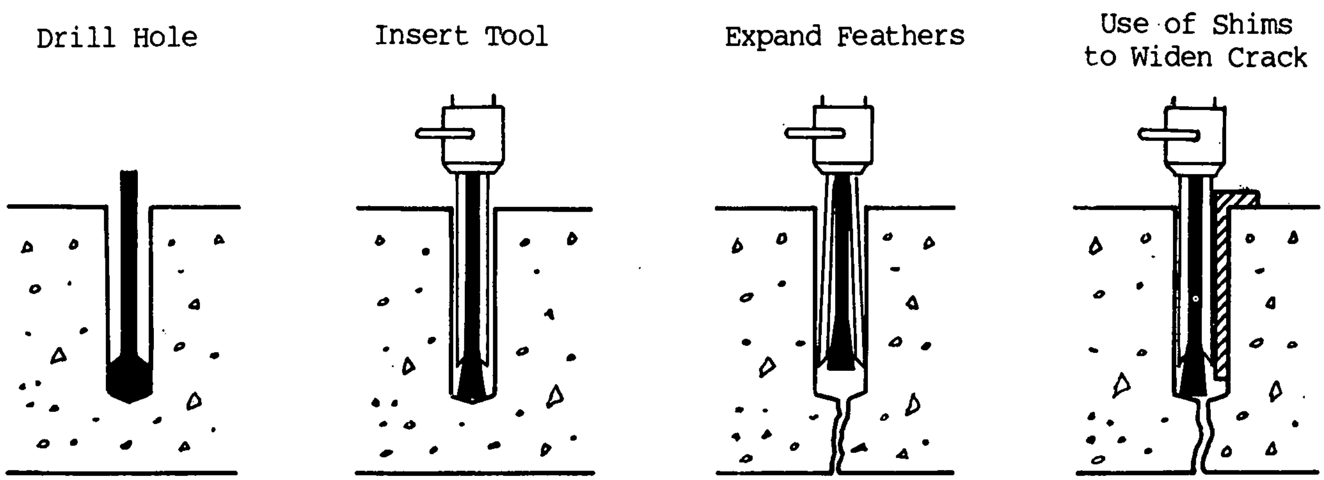


FIGURE 6 Operation of a mechanical splitter with a retracting plug.

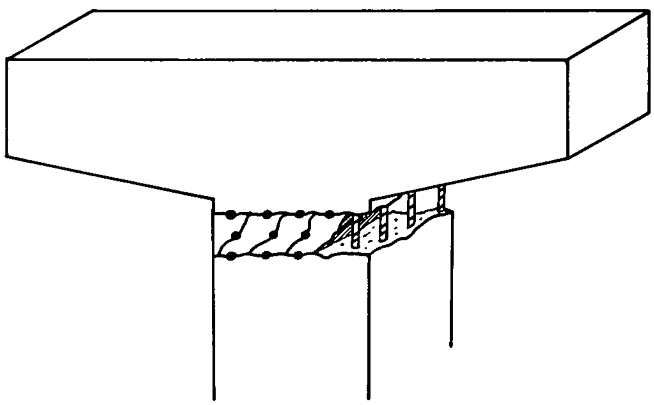


FIGURE 7 Use of a splitter to remove a pier cap.

breaker and the reinforcing steel cut to free the section. This technique can also be used in combination with a sawcut (no deeper than the cover to the reinforcing steel) to remove a curb and parapet and leave a clean, vertical surface before widening a bridge deck.

Mechanical splitting has been used in several states, but the experience has not been well reported. The technique has the advantage that there is no vibration and little dust and the concrete left in place is undamaged. The splitter can also be used underwater. The splitting operation makes little noise, but breakers, which are noisy, are often used to remove the cracked concrete. The equipment costs $10,000 to $12,000 for a splitter and hydraulic pump with motor. The major disadvantage is the time required to cut the reinforcement and remove the broken concrete.

Chemical Splitting Agents

Expansive chemicals can also be used to split concrete. The exact composition of the products on the market is proprietary information, but the main component is calcium oxide, which, when hydrated, expands about three times in volume. Organic and inorganic compounds are added to control the rate of reaction and improve workability. Most of the commercial products are of Japanese origin, and they are known there generically as nonexplosive or static demolition agents. They were first developed in 1979. The powder is mixed with cold water to form a slurry and inserted into boreholes drilled in a predetermined pattern. As the slurry hydrates, it expands over a period of 48 hr, first cracking the concrete and then causing the cracks to propagate and widen. Typical pressures of 3000 psi (20 MPa) after 12 hr and 9000 psi (62 MPa) after 48 hr have been reported. A new generation of faster-acting products, developed in the late 1980s, is capable of generating pressures of 14,000 psi (100 MPa) within 1 hr (*23*). The Japanese have developed a standard method of measuring the expansive pressures based on the circumferential stress in a steel pipe filled with slurry mixed under prescribed conditions (*24*). The products are generally formulated in grades for use at different temperatures within the range 32°F to 95°F (0°C to 35°C). A Chinese product line includes a winter grade suitable for use in temperatures of 14°F to 23°F (−10°C to −5°C) (*25*).

The principles of hole spacing and the methods of removing the cracked concrete are the same as those for mechanical splitting. The stress that is developed is a function of the amount of water used and the size of the hole. The drill pattern is determined by experience, supplemented where necessary by theoretical calculations (*26, 27*) and test breaks. The typical hole size is 1¼ to 2 in. (32 to 50 mm) diameter at a spacing of 1 to 2 ft (300 to 600 mm). In plain concrete it has been found that the first-generation products are most effective when the ratio of the distance to the free edge/hole diameter is 12 or less. For the fast-acting products, the ratio should be no more than 8 because, although the expansion is more rapid, the total expansion is less. Long holes are more effective than short holes. If there is water in a hole or fissures intercept it, a polyethylene liner is used in the hole. Horizontal holes are difficult to fill without wastage, and must be plugged until the slurry stiffens. After filling, the holes should be covered, because there is a danger that the heat developed by the hydration reactions will turn the mixing water into steam that will blow out the contents of the hole in an explosive manner (*28*). One of the new, fast-acting products is used with a capping agent that is inserted in the top of the hole. The capping agent is also expansive but has a very short working time, hydrates more quickly than the demolition agent, and is reported to prevent blow-out (*23*).

Chemical splitting agents are relatively new in the North American market, and thus there is little experience in their use on highway structures. Florida reported an unsuccessful experience, though the cause was thought to be deficiencies in the materials used. The technique has the same relative merits as mechanical splitting except that the product is expensive. Material costs alone are $14/ft ($46/m) of 2-in.-diameter hole.

Other Splitting Agents

Other methods of splitting concrete are described in the literature (*29*). These include:

- A water gun that shoots water at a pressure of 5800 psi (40 MPa) into a drilled hole.
- A gas cylinder that is connected by a flexible pipe to a drilled hole fitted with a special rubber stopper. The gas valve is opened to exert pressure in the hole.
- Liquid carbon dioxide enclosed in a metallic tube that is inserted in a hole in the concrete. It is then heated by an electrical filament, causing a rapid expansion. However, no record of the use of these techniques in North America has been found.

CRUSHERS

Concrete crushers remove pieces of concrete by applying opposing forces on either side of a concrete member. Crushers range in size from units weighing 86 lb (39 kg) and suitable for hand-held operation to units weighing upwards of 7 tons (6,350 kg) that must be mounted on excavators in the 40-ton (36,300-kg) range.

The small units are of European and Japanese manufacture and are hydraulically operated from an electrically powered compressor. The jaws range from 10 to 18 in. (250 to 450 mm) opening capacity and are fitted with steel points. The major application for this type of equipment is in the small-scale private-sector work such as hospitals (*30*), where there are restrictions on vibration, noise, dust, and use of water.

The large rig-mounted crushers are fitted with blades; hence the common industry term of shears. In some models the cutting head rotates, which increases the amount of concrete that can be reached without having to move the excavator. This type of equipment was first used for bridge deck removal in the United States in 1984 and has been used successfully on a number of projects since that time (*31, 32*). The models used for the removal of concrete in bridges typically have a jaw opening in the range of 14 to 33 in. (350 to 840 mm) and exert a force at the center of the blade of between 100 and 422 tons (1 to 4.2 MN).

In addition to there being no noise, dust, or vibration, rig-mounted crushers have the advantages of safety and high production rates. The equipment easily cuts through reinforcing bars, which eliminates the need for torch cutting, and has also been used successfully to remove a post-tensioned deck that was damaged by fire. The shears can be used to remove both decks and parapet walls or metal guardrail. Where site conditions require, the concrete can be caught in a cradle suspended directly under the bridge and loaded directly into a dump truck for disposal. Alternatively, the concrete can be crushed again to remove all the reinforcement and recycled. There have been no reports of damage to bridge girders, though at some sites it has been necessary to remove a small amount of concrete from the tops of girders by hand. Production rates for bridge deck removal of upward of 100 to 120 ft^2/hr (9 to 11 m^2/hr) have been reported, depending on the job conditions.

WATER JET CUTTING

Water jets were originally used in mining and quarry operations, and are now being used in industry for precision cutting in a multitude of applications. These include cutting materials that distort if clamped, such as textiles; cutting materials on which dust cannot be tolerated, such as fiberglass; cutting food, where the need for cleaning the cutting edge is eliminated; and cutting complex shapes from plastics, composites, glass, and metals in the aerospace and automotive industries. The major advances that have led to the increased use of water jets for cutting have been the development of high-pressure pumps and the use of hydraulics for controlling the nozzle.

Water jets operating at a pressure from 40,000 to 60,000 psi (280 to 410 MPa) can be used to cut plain concrete. However, for cutting reinforced or prestressed concrete an abrasive must be introduced into the water jet, though lower water pressures can be used. There are three groups of abrasives: mineral, metal, and artificial (mainly ceramics). Garnet generally shows the best cutting ability, especially in situations where a harder abrasive is required. The abrasive is stored in a hopper and metered to the nozzle. Nozzles can be hand held or track mounted and operated under remote control. The latter method increases the safety of the operator and produces a straight line cut. Tests with a Japanese unit operating at 40,000 psi (280 MPa), 5.5 gal/min (21 L/min), an orifice of 0.04 in. (1 mm), a standoff of ⅜ in. (10 mm), and garnet as the abrasive showed that optimum cutting speeds were in the range of 0.8 to 4 in./min (20 to 100 mm/min), depending on the thickness of the concrete and the amount of reinforcement (*33*). It was found that for members less than 12 in. (300 mm) thick, it was better to adjust the cutting speed to cut through the member in a single cut rather than make several passes at higher cutting speeds. For members more than 12 in. (300 mm) thick, best results were obtained by making several cuts.

Water jetting has the advantages of being free from vibration and dust while permitting a controlled cut without damage to the concrete left in place. Although the cutting process is relatively quiet, the power units can be very noisy unless muffled. For most sites a method of collecting the water and the abrasive is required, and protection must be provided on the backface of members that are to be cut full depth.

The major disadvantage of abrasive water jets is the risk of maiming the operator or a bystander. Operators require proper waterproof clothing, but this offers protection only against rebounding spray. Although hand-held lances are reasonably satisfactory for use on decks and parapet walls, they are not well suited for use from scaffolds. Hand-held lances have been used for removing parts of bridge substructures, but, because the reaction force from the lance induces fatigue and the working conditions are cramped and unpleasant, the work must be considered dangerous. Where practical, the use of a track-mounted lance is preferable.

The high pressures and the use of abrasives result in high capital and maintenance costs. Research has been initiated to develop cavitating water jets that operate at lower pressures and do not use abrasives (*34*). The cavitating jet is created by putting an obstruction in the orifice of the water jet's nozzle. The obstruction causes millions of microscopic bubbles to be introduced into the water stream. These collapse on contact with a hard surface, resulting in the shock waves that cause cavitation. This technology is claimed to have the potential for cutting concrete at up to 50 percent less than the costs of abrasive jet cutting. However, the equipment has still to be proved in the field and its effectiveness on reinforced concrete determined.

BALL AND CRANE

This is one of the oldest and most common methods used for demolition of concrete and masonry structures. A wrecking ball is attached to a crane and either dropped or swung into the element to be demolished. The wrecking ball may weigh up to 7 tons (6100 kg), though balls in the range 0.5 to 2 tons (450 to 1800 kg) are more usual. Although the term "wrecking ball" is used, the mass that is used to strike the concrete does not have to be any particular shape, and brick-shaped steel ingots of the type shown in Figure 8 are fairly common. The impact of the ball breaks the concrete into small pieces, though cutting of the reinforcement is usually necessary before the concrete can be loaded for disposal off-site.

The National Association of Demolition Contractors recommends that the weight of the ball not exceed 50 percent of the safe load of the boom at maximum length or angle of operation, or 25 percent of the nominal breaking strength of the supporting line, whichever is less (*21*). The ball should be attached to the line with a swivel connection to prevent twisting of the line. Taglines are often used to control the swing of a wrecking ball and are necessary with most other shapes. It is essential to control the swing of the ball, because missing the target could tip the crane or overload the boom or the ball could strike the crane in an uncontrolled return swing.

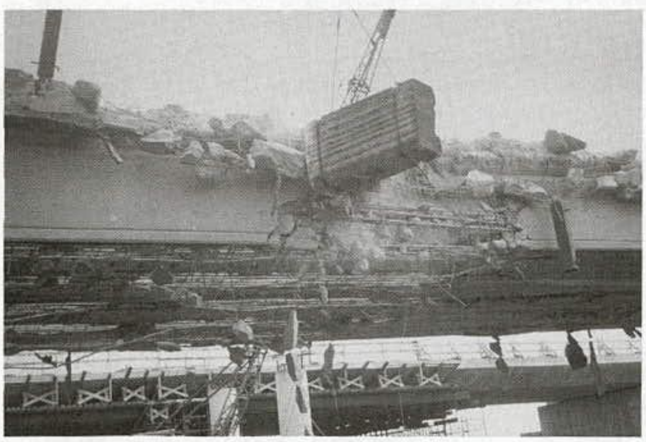


FIGURE 8 Use of a steel ingot as a "wrecking ball" to demolish a prestressed concrete bridge.

The use of a ball and crane has the advantages of simplicity and widespread availability. Furthermore, the operator is located some distance from the concrete being demolished, and this can offer significant advantages in safety in such situations as the demolition of prestressed concrete or where the concrete is badly deteriorated. The disadvantages are that it demands skill on the part of the operator, the process can cause considerable dust and noise, and there are substantial vibrations that cannot be controlled. In addition, some components such as piers in deep water may be inaccessible. Special safety precautions are required when working near power lines. Although a number of respondents to the survey in Appendix A stated that a ball and crane is used for the partial removal of concrete, it is difficult to envisage situations in which the operation could be controlled to prevent damage to concrete to be left in place. The technique is much better suited to the complete removal of a structure in situations where there are few restrictions on operations.

BLASTING

Blasting consists of detonating explosives to produce a shock wave and rapidly expanding gases that, when confined within a series of boreholes, produce controlled fracture of the concrete. For example, the detonation velocity of nitroglycerine is about 23,000 ft/sec (7,000 m/s). The pressure in the drill hole rises to about 350 to 2,900 ton/in.^{2} (5 to 40 GPa) and the temperature reaches 4,500°F to 7,200°F (2,500°C to 4,000°C) (*35*). The energy is released in thousandths of a second, and this affects the concrete in two ways: (a) the shock wave forms cracks in the concrete around the drill hole and (b) the gases that are released widen the cracks and fracture the concrete.

The process begins with drilling holes at a predetermined angle and spacing. The holes are then charged with an explosive. Although various formulas have been developed to calculate the size of the charge and the borehole pattern, the degree of success is strongly dependent on the skill and experience of the operator. A first approximation of the charge and hole spacing required for various categories of plain and reinforced concrete is given in Table 1. After detonation, the reinforcing steel is usually cut with an oxyacetylene torch, and the concrete may be broken into smaller pieces using percussive tools before removal.

There are four major classes of explosives: dynamite, mixtures of ammonium nitrate and fuel oil (ANFO), slurries, and blends of ANFO and emulsions (*37*). Dynamite, which is based on nitroglycerin, was invented by Alfred Nobel in 1867. Several formulations of dynamite are still used and are available in a wide range of small- and medium-diameter cartridges of different lengths. Dynamite has good water resistance and provides a moderate to powerful charge.

Ammonium nitrate and fuel oil explosives were developed in the mid 1950s (*38*). They are safer and less expensive than dynamite but best suited to dry conditions and to large projects, where mechanical handling methods can be used to maximum advantage. ANFO in free-flowing form is normally not used under tightly controlled conditions because of the possibility of excessive concentration of explosive in cracks or voids intercepted by the boreholes.

TABLE 1
TYPICAL VALUES OF SPECIFIC CHARGE AND HOLE SPACING SUITABLE FOR BLASTING PLAIN AND REINFORCED CONCRETE (36)

Concrete Quality	Specific Charge lb/yd³	kg/m³	Hole Spacing in.	m
Plain concrete, poor quality	0.25-0.7	0.15-0.4	28-32	0.7 -0.8
Plain concrete, good quality	0.5 -0.7	0.3 -0.4	24-28	0.6 -0.7
Reinforced concrete, normal	0.7 -1.0	0.4 -0.6	16-20	0.4 -0.5
Reinforced concrete, heavy	1.0 -2.5	0.6 -1.5	12-20	0.3 -0.5
High strength, heavily reinforced concrete	2.5 -3.4	1.5 -2.0	10-20	0.25-0.5

Slurries are explosive chemicals mixed with water to form a gel or an emulsion. They can be formulated to be either sensitive to initiation by a detonator or nonsensitive, in which case a powerful primer is required to initiate the charge. Emulsions and water gels are available in small- and medium-diameter cartridges and in bulk. They offer performance and reliability approaching that of dynamite, without the volatility of nitroglycerine.

The fourth class of explosives consists of ANFO mixed with different percentages of a high-velocity explosive such as an emulsion. The blends can be formulated to provide differing degrees of velocity, pressure, density, and water resistance.

Commercial explosives in the four classes described above have a detonation speed in the range of 10,000 to 23,000 ft/sec (3 to 7 km/s). In the early 1970s, low-velocity explosives having subsonic detonation speeds, and usually less than 300 ft/sec (100 m/s), were developed in Japan. These explosives are claimed to break concrete with little noise or vibration and are suitable for use in urban areas (*29, 36*). However, no record of their use on North American bridges has been found.

Most blasting is done by delay initiation, which is the detonation of individual holes in a timed sequence. This controls the amount of vibration generated and influences the displacement and fragmentation pattern. Two types of initiator are used: electric and nonelectric. Conventional electric delay-blasting systems typically offer up to 30 delay periods. Some detonators have programmable delay intervals, though intervals of about 25 ms are commonly used. It has been found that short delay intervals result in better confinement of energy and better fragmentation. Electric initiation systems are cheap, simple, and reliable, and also have the advantage that they can be checked with a blaster's galvanometer before firing. Nonelectric systems consisting of plastic signal tubes can also be used to control row-to-row and hole-to-hole delays, but their use is usually limited to large applications. A list of available explosives, detonators, and related products is given in references *38* and *39*.

Blasting is most often used for the complete removal of structures, and there are case studies in Germany (*40*) of reinforced and prestressed concrete bridges spanning freeways being removed while the freeway was closed for a few hours in off-peak periods. There are also examples of using blasting to remove individual components and parts of components. In the case of a bridge in Kansas, a pier that had been damaged by a barge was demolished by blasting while the bridge was supported by falsework (*41*). As part of the reconstruction of the Dan Ryan Expressway in 1988, pieces taller than 30 ft (9.1 m) were fractured by explosives and the piers were then demolished using rig-mounted hammers (*6*). In Europe, mini-blasting is sometimes used (*35, 42*). The procedure consists of using carefully controlled blasting techniques for the removal of small concrete components such as curbs (*43*), or parts of components, such as pile caps (*44*). Some cracking was observed up to between 6 and 10 in. (150 and 250 mm) of the blasted face, depending on the hole size, spacing, and strength of the charge (*45*). The technique was considered feasible for the removal of concrete members having a thickness of 10 in. (250 mm) or greater. It also has been used for the removal of prestressed concrete, where the technique has the advantage of not exposing workers to the sudden release of the prestressing steel.

For underwater applications, an air curtain is sometimes used to protect aquatic life. Perforated pipe is placed on the river or seabed around the concrete to be removed. Compressed air is pumped into the pipe, and the bubbles rise to the surface, creating a "curtain" around the structure. It has been suggested that when the explosive is detonated, bubbles collapse and limit the spread of the shock wave, thereby reducing the fish kill. However, it may be that the air curtain is effective simply by creating a barrier that keeps fish away from the immediate vicinity of the blast.

Blasting is well suited to the removal of large volumes of concrete, especially in locations where there are no other structures nearby. In other cases, precautions must be taken to prevent excessive ground vibration or air blast damage such as window breakage. Precautions are also needed to stop flying debris, and strict site control must be maintained to ensure the safety of workers and the general public (*21*). Because of the dangers inherent in handling and using explosives, blasting is considered the most dangerous of the methods of demolition in common use. It is essential that only trained and experienced contractors be used.

SUMMATION

Wet-cutting diamond saw blades are often used to cut bridge decks into sections that can be removed by crane. This method of removal is sometimes used in conjunction with prefabricated deck panels when the work must be done at night and the bridge remain in service during the day. Dry-cutting diamond blades are also available, and are most often used where light weight and maneuverability are important. The most serious disadvantage of this method is the danger of cutting the top flanges of girders. A recent innovation in sawing technology has been the introduction of diamond wire saws, which are suited to cutting large members such as pier caps. Sawing can also be used in combination with drilling if it is necessary to cut an opening or, more frequently, to delineate the limit of removal before widening a deck.

Machine-mounted breakers are a common piece of equipment for the removal of all types of concrete component. The breakers are available in a wide range of sizes. Although production rates are high, there is considerable risk of damage to concrete left in place. Damage to girders has been a relatively frequent occurrence. Many agencies place restrictions on the size of breaker that can be used and their operation directly over girders and within a specified distance of the limit of removal. The whiphammer is a percussive tool consisting of a hydraulically operated hammer attached to a leaf spring. It is a relatively new piece of equipment, and the experience on bridges is limited.

Mechanical splitters are hydraulic tools that break concrete by inserting a wedge in holes in the concrete. The hole pattern is determined by a combination of experience and test breaks. Reinforcement must be cut by other means before the concrete can be removed. The technique has the advantages of no vibration, little dust, and the lack of damage to concrete left in place. Splitting can also be done using proprietary expansive chemicals, most of which are of Japanese origin.

The concrete crusher is another relatively new piece of equipment that removes concrete by applying opposing forces on either side of the concrete. It has been used successfully to remove both reinforced and prestressed concrete.

The older methods of using a ball and crane or blasting are still in use, especially for the complete removal of a structure outside urban areas. The major disadvantage of these methods is that it is difficult to prevent damage to concrete to be left in place. However, recent developments in mini-blasting suggest that this technology may be applicable for the removal of small concrete components or parts of components.

CHAPTER THREE

EQUIPMENT AND PROCEDURES FOR PARTIAL REMOVAL

INTRODUCTION

The objectives in removing part of a concrete member are to salvage the sound portions and to remove the required concrete quickly and economically and without damage to the concrete to be left in place.

The most common highway application is the removal of deteriorated concrete from bridge decks. In recent years, the need to remove corrosion-damaged concrete from other components such as pier caps, columns, and beams has increased. In these cases, contracts require the removal of all the deteriorated concrete; sometimes some of the sound concrete (depending on the removal criteria) is also removed. Two factors combine to make the operations expensive:

- Much of the work involves working in close proximity to the reinforcement.
- The precise quantity to be removed usually cannot be determined in advance, and therefore bid prices include a risk factor.

The other common examples of partial removal occur when a parapet or curb must be removed for a bridge widening or the addition of a safety barrier. In these cases, the quantity of concrete can be calculated from the plans and different equipment can be used. Often the removal can be done by the procedures described in Chapter 2, or only the final concrete removed by the techniques described in this chapter.

Other examples that include partial removal of concrete include the replacement of expansion joints and bearings and the removal of the surface of a bridge before the application of a skid-resistant overlay.

The techniques for partial removal divide conveniently into hand-held percussive tools, hydrodemolition, and thermal techniques.

HAND-HELD PERCUSSIVE TOOLS

Breakers

Hand-held percussive breakers, commonly known as jackhammers, are the most widely used tools for the removal of concrete from part of a concrete component before repair or modification. Originally powered only by compressed air, hand-held breakers are now available that are powered electrically, hydraulically, or with a two-cycle gasoline engine. The pneumatic hammers have changed little since their introduction about 90 years ago. They consist of a tool chuck that is connected to a piston that moves in a casing. The flow of compressed air acts on the piston, which punches the tool into the concrete, and the movement of the piston allows the air to exhaust. The pressure applied by the operator on the concrete causes the piston to return, and the cycle is repeated at a rate of more than 1000 blows/min. The method of operation of the hydraulic, electric, and gasoline breakers is very similar.

A wide variety of tools is available, but for concrete-removal operations, only chisels and the standard moil point normally are used. Chisels are supplied in various widths up to 3 in. (75 mm). A 1-in. (25-mm) chisel is most common in bridge work.

The procedures for removing concrete are straightforward. Where a member is to be patched, it is customary to sawcut around the perimeter of the patch to a depth greater than the size of the maximum aggregate in the repair material but less than the cover to the reinforcement. Where a member is to be overlaid, the sawcutting is usually unnecessary, and the edges of the area of removal are finished at approximately 45°. The concrete is removed with breakers, using the impact blows to shatter a little of the concrete at a time. The procedure is tedious and the quality of the work is strongly dependent on the care and attitude of the operator. The process has a number of disadvantages:

- All the deteriorated concrete may not be removed.
- The surface of the concrete remaining may be extensively microcracked by the blows from the breakers.
- Striking the reinforcement with the breakers may nick the bar and, of greater concern, may destroy the bond adjacent to the removal area.
- The procedure is slow, noisy, and dusty.

Production rates fall in a wide range and are influenced by the quality of the concrete, the ease of access, the amount of concrete that must be removed from around the reinforcing steel, and the motivation of the operator. Typical production rates of 5 ft^2/hr (0.5 m^2/hr) or 1 ft^3/hr (0.03 m^3/hr) have been quoted for a laborer with a 30-lb (14-kg) breaker working on a horizontal surface (*46, 47*), but these rates may differ by almost an order of magnitude, depending on the job conditions. On vertical surfaces, provision of access may be a significant cost factor and production rates are typically very low. An example of work on a high-level structure is shown in Figure 9.

Specifications for concrete removal are reasonably consistent from jurisdiction to jurisdiction, probably because many were adapted from a specification developed by Iowa in the mid 1970s for the placement of concrete overlays. Most specifications place a limit on the size of the breakers that are allowed to be used. The most common limits are no heavier than 30-lb (14-kg) hammers above the level of the reinforcement, as shown in Figure 10, and 15 lb (7 kg) around and below the reinforcement, as shown in Figure 11. These limits are by no means universal, and figures as high as 90 lb (41 kg) for hammers used above the steel and 30 lb (14 kg) below the reinforcement were reported in responses to the state-of-the-practice survey (Appendix A).

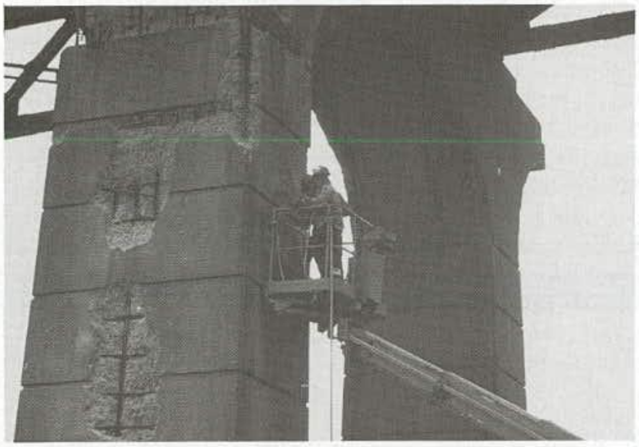


FIGURE 9 Use of hand-held breakers on a vertical surface.

FIGURE 10 Use of a jackhammer to remove concrete to the level of the reinforcement.

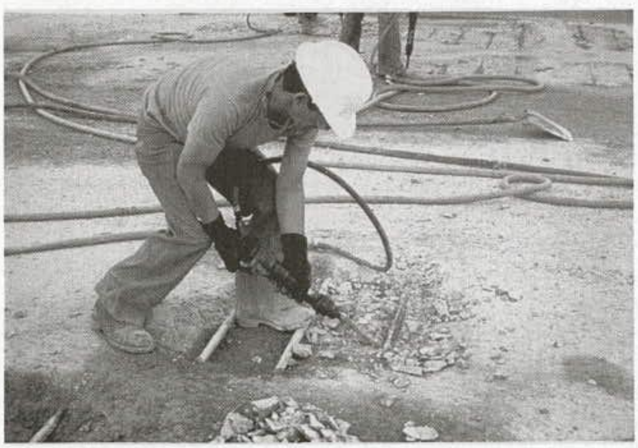


FIGURE 11 Use of a chipping hammer to remove concrete from around the reinforcement.

Some specifications state the limits as 30-lb (14-kg) and 15-lb (7-kg) "class" hammers, though no such classes exist in the industry and what is accepted in one jurisdiction as a 30-lb (14-kg) hammer is not necessarily accepted in another. Neither is there a clear distinction between a chipping hammer and a jackhammer except that chipping hammers are generally smaller and have a single D handle. Many specifications also limit the angle at which the hammers can be used, the most common being no more than 45° to the horizontal. The limits on hammer size and angle of operation are both intended to minimize damage to the concrete left in place.

It is interesting that there should be so much uniformity between specifications on a provision for which there is a poor engineering foundation. The limits on the weight of the hammers are intended to limit the maximum impact per blow, but there is little relationship between the weight of hammers and the energy delivered to the concrete. The features of hand-held breakers made by 12 manufacturers of pneumatic breakers, 7 manufacturers of hydraulic breakers, plus two electric and one gasoline-powered breaker have been summarized in one of the trade journals (*17*).

The pneumatic hammers ranged in weight from 20 to 90 lb (9 to 44 kg), delivered 900 to 2150 blows/min (most were around 1400), and operated at a pressure of 70 to 90 psi (480 to 620 kPa). The relationship between weight and energy per blow is different from manufacturer to manufacturer and ranges, for example, between 14.5 ft lb (20 J) for a 32-lb (14.5-kg) hammer to 50 ft lb (68 J) for a 35-lb (16-kg) hammer.

The hydraulic hammers ranged in weight from 27 to 80 lb (12 to 36 kg), delivered 1200 to 2500 blows/min, and operated at a pressure of 1000 to 2200 psi (7 to 15 MPa). Being lighter than pneumatic hammers, the energy-to-weight ratio is higher. For many hammers it is approximately 1 ft lb (1.4 J) per lb (450 g) weight. However, there is still a considerable difference between manufacturers, with, for example, a 54-lb (24-kg) hammer rated at 35 ft lb (47 J) and a 65-lb (29-kg) hammer rated at 100 ft lb (135 J).

Gasoline and electric hammers tend to have a lower energy output per unit weight of hammer than pneumatic hammers because of the weight of engine and electric motor, respectively. On the basis of limited information available, the relationship is approximately 0.5 ft lb (0.7 J) of the output energy per lb (450 g) of weight (*17, 48*). The electric hammers tend to be the smallest of the types available and are probably best suited for use where access is difficult.

In addition to the technical issues surrounding the use of hand-held percussive tools, there are also serious occupational health and safety implications. Workers who use hand-held power tools such as jackhammers and rock drills suffer injury to their hands. Pneumatic drills and air hammers were introduced at about the turn of the century, and by 1911 in Italy and 1918 in the United States, the relationship between vibration and "dead man's hand" or "vibration white finger" had already been described (*49*).

Occupational exposure to vibration is common in many industries, but people are more vulnerable in occupations where the vibration enters the body through the hands from hand-held tools. When people first expose their hands to prolonged vibration, they usually report tingling followed by numbness. After further exposure, usually several years, the fingers become swollen and inflexible. If they touch cold objects, or are exposed to a cold environment, the tips whiten. At first only the fingertips go white during an attack, but gradually the blanching spreads to the base of the fingers on both hands. After many years of exposure (about 10 to 15 years in the case of pneumatic drills), the thumbs also become white in an attack and the fingers turn blue. In extreme cases (fewer than 1 percent), ulcers form on the fingertips, leading in some cases to gangrene, in which the tissue dies because the reduced supply of blood provides insufficient nutrition. Long neglected, the disease is now known as hand-arm vibration syndrome (HAVS) and is receiving attention from researchers around the world. Figure 12 shows the advanced stages of HAVS.

Growing recognition of HAVS between 1970 and 1980 resulted in efforts to reduce vibration in all hand-held tools and research to discover how vibration damaged the hands and the relationship between the amount of vibration and the symptoms it produced. Although the cause is complex and can involve damage to arteries, nerves, bones, muscles, and tendons (*49*), in many severe cases, the vibration gradually reduces the diameter of the arteries to zero. Beginning in 1975, a succession of guidelines were produced by several organizations, but all suffer from the lack of a meaningful dose-response relationship. The development of HAVS and the length of the latency period depend on many interacting factors, including vibration level, hours of tool use per day, environmental conditions, type and design of the tool, the manner in which the tool is held, the vibration spectrum produced by the tool, the vibration tolerance of the worker, and tobacco and drug use by the worker (*50*). In 1989 the American Conference of Government Industrial Hygienists recommended that the vibration should not exceed an acceleration of 13 ft/s^2 (4 m/s^2) for a daily exposure lasting from 4 to 8 hr (*51*). This limit is impossible to meet with existing tool designs. Vibrations on pneumatic percussive tools have been measured at 125 to 1,000 ft/s^2 (38 to 305 m/s^2) on the handle and at 6,560 to 78,400 ft/s^2 (2,000 to 23,900 m/s^2) on the chisel. The vibrations can be even higher on tools with blunt chisels or those that have been poorly maintained. The addition of antivibration mounts to tools that have predominantly reciprocating forces, such as chain saws, has been very successful in reducing vibration levels. For tools driven by compressed air, reducing vibration is much more difficult because the predominant forces are impulsive. Although a number of manufacturers now produce tools with some form of vibration damping, these are not often used, sometimes because of the increased cost and weight, sometimes because users are not aware of the advantages, or even because of the masculine image that is associated with operating a machine that is noisy and vibrates a lot. Even a simple precaution such as wearing safety gloves, which absorb some vibration and keep the hands warm, is ignored. However, as workers and employers become more aware of HAVS, the days of the conventional chipping hammers and jackhammers in use today are numbered. Either they will be replaced by a new generation of low-vibration, percussive tools or other methods of concrete removal will be used.

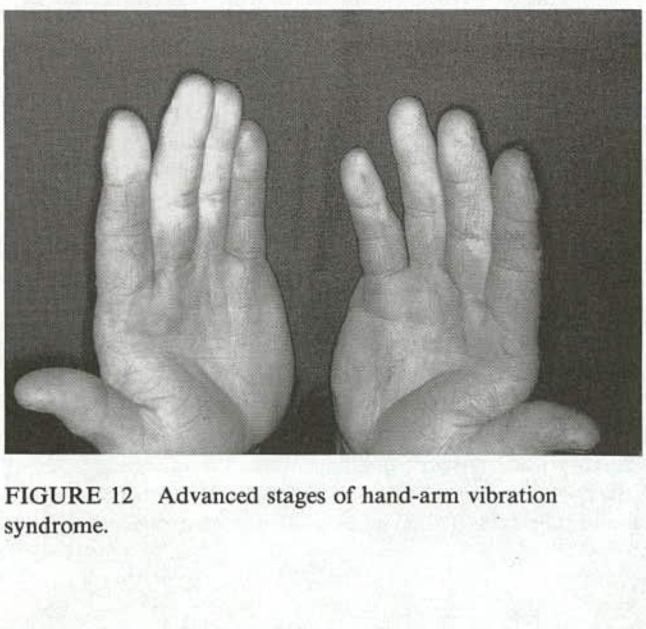


FIGURE 12 Advanced stages of hand-arm vibration syndrome.

Needle Scalers

Needle scalers are designed primarily for such applications as removing scale or paint from metal or cleaning weld seams. Most are pneumatic tools that, instead of a single point, have upward of 20 steel needles approximately ⅛ in. (3 mm) in diameter. Some models have needles of more than one size. The tools range in size from models weighing 3.5 lb (1.6 kg) and delivering 4850 blows/min to a model weighing 11 lb (5 kg) and delivering 2900 blows/min. The tools require approximately 5 cfm (0.1 m^3/min) of compressed air at 90 psi (620 kPa). They are also available as hydraulic tools delivering about 2100 blows/min.

Needle scalers are especially well suited for use on uneven surfaces, because the needles conform to the contour of the work. The main application for concrete work is the removal of small quantities of concrete in areas where access is difficult or where special care is required, such as in removing concrete adjacent to ducts containing prestressing steel or when working close to pretensioned strands. In such cases the light weight of the tool is a distinct advantage and the low production rates are acceptable. The tools can be fitted with a chisel point so that the concrete can be removed to almost the desired extent using the chisel, with only the final concrete being removed by the needles.

WATER JET REMOVAL

Water jets operating without abrasives and at lower pressures than used to cut concrete can be used for the partial removal of concrete. Most of the equipment used for this purpose operates in the range of 12,000 to 14,000 psi (83 to 97 MPa). At these pressures, the water does not cut the aggregate (*52*), and consequently the concrete is removed by cutting the matrix, thereby loosening aggregate particles, which are removed intact by the water stream. This means that the product of water jetting is a rough surface and that the profile is a function of the maximum size of the aggregate in the concrete.

Water jets consist of a relatively lightweight wand or lance connected by suitable hoses to a high-pressure pump and water supply. Some lances are fitted with a deflector to shield the operator from debris and rebounding water. These hand-held water jets are used most frequently on vertical surfaces and for small-scale applications on decks. Machine-mounted water jets are more suitable for large-scale deck applications, and these are described in the next section of this chapter.

The key to successful water jetting is to establish the correct stand-off distance for the nozzle, pressure, and volume of water being used, and this is largely a matter of experience (*53*). It is also important to ensure that the water is filtered effectively and that the size and length of hoses are compatible with the pump so as to maximize the energy available at the nozzle.

Water jets were used successfully to remove deteriorated concrete from the piers of 44 bridges during reconstruction of the Lodge Freeway. The working conditions were unpleasant, and it was reported that it was difficult to keep the operators dry and to protect them from flying debris (*54*). Although the risk of a disabling injury is less than when using water jets for cutting (because the pressures are less and no abrasives are used), their use from scaffolds or in cramped conditions is both difficult and fatiguing.

HYDRODEMOLITION

The term hydrodemolition evolves simply from the process of using water to demolish concrete. The equipment consists of the application of water jetting on a large scale. In practice, hydrodemolition is used mainly for surface preparation and the removal of deteriorated concrete from bridge decks as an alternative to scarifying and chipping.

Hydrodemolition is a relatively new technology that is still developing. Although the ability to use water to cut concrete had been known for many years, it was not until the late 1970s and early 1980s that prototype units were produced using water for the large-scale removal of concrete surfaces.

A number of advantages are claimed by the manufacturers of hydrodemolition equipment:

- The process is naturally selective and removes all the unsound concrete.
- The reinforcing steel is cleaned but not damaged, and bond to the concrete is not destroyed where the concrete is not removed.
- The process does not induce microcracks in the concrete left in place.
- No other surface preparation is required.
- There is no dust and little noise or vibration (though some users would dispute this claim).
- Hydrodemolition can be done in inclement weather (provided the temperature is above freezing).
- The process is rapid and costs are reasonable.

Hydrodemolition involves three separate mechanisms (*55*):

- direct impact
- increasing the pressure in cracks
- cavitation

Although the relative importance of the mechanisms has not fully been established, the properties of the concrete that correlate best with the amount of material removed are the permeability of the paste and the amount of cracking. A dense, homogenous concrete is relatively unaffected by hydrodemolition, whereas a concrete that has a high water-cement ratio paste or is cracked and laminated is easily removed. This means that the depth of removal increases if the concrete strength is low or the concrete is unsound and explains why hydrodemolition enables selective removal, partly as a function of the concrete strength and partly as a function of the degree of damage.

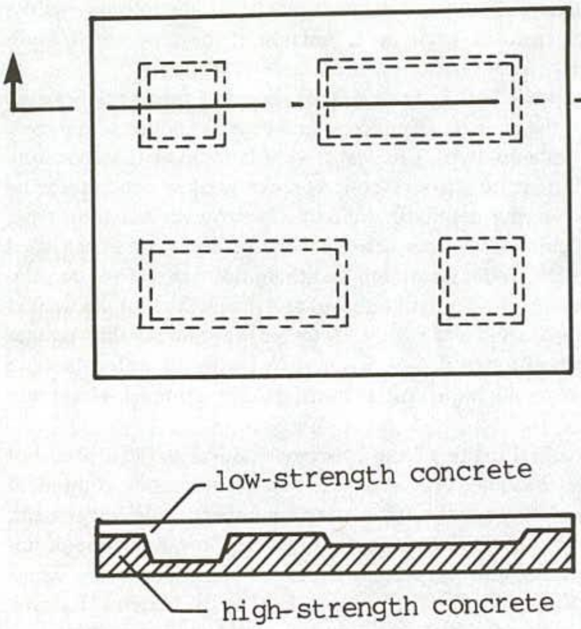
Tests carried out in Sweden (*56*) showed a direct relationship between the strength of concrete and depth of concrete removed by hydrodemolition. Test slabs were fabricated incorporating two different qualities of concrete, the weaker concrete being cast to varying depths in wells in the stronger concrete base. Hydrodemolishers from several manufacturers were then used on the slabs, and it was found that there was an excellent correlation between the depth of removal and the location of the weaker concrete, as shown in Figure 13. Other experiments showed that the depth of removal not only increased with the water pressure but that at high pressures the depth of removal was more uniform.

The actual depth of the concrete removal is influenced not only by the quality of concrete but by numerous equipment variables. The nozzles (size, shape, number, angle, movement, standoff) and the water supply (pressure, flow, and time of impact) are the most important factors.

A contract was awarded around 1980 by the Federal Highway Administration (FHWA) to design, build, and demonstrate a prototype hydrodemolisher using commercially available components wherever possible (*57*). The study included an examination of many of the nozzle parameters that determine its effectiveness in removing concrete, under a maximum water pressure of 12,000 psi (83 MPa). It was found that a straight jet-type nozzle was more effective than a fan jet-type nozzle. The production rate could be increased by increasing the number of nozzles, but a proportionally greater improvement resulted from rotating the nozzle. Removal rates were found to increase up to a rotational speed of 80 rpm and then decrease. The angle of the nozzle was also found to be important. Angles of 20° to 45° to the horizontal were considered acceptable, though the optimum was closer to 20°. A prototype unit was constructed and demonstrated successfully on a bridge deck in Virginia in October 1982. The project promoted the advancement of hydrodemolition technology and demonstrated the feasibility and cost-effectiveness for large-scale concrete removal. Further development of equipment for hydrodemolition was left to the private sector.

During the 1980s several hydrodemolishers were introduced into the North American marketplace by European and domestic manufacturers. Many of these machines are large, sophisticated pieces of equipment that can cost $500,000 or more. This means that hydrodemolition is only economic on larger projects, because of the high mobilization and operating costs. One manufacturer recommends production of 72,000 ft^2 (6,700 m^2) per machine per year as a minimum for ownership.

Most hydrodemolishers consist of two units, one stationary and the other mobile, as shown in Figure 14. The stationary unit includes the power supply (usually a large diesel engine), a water tank, filters, and the high-pressure pump. The filters are extremely important to minimize wear on the components. The mobile unit is often operated by remote control, and includes the nozzle head, which usually moves on a track across the front of the unit, the splashguard, and a second power supply. A typical cutting width is about 6 ft (1.8 m). Some manufacturers supply attachments to enable the unit to be used for soffit and vertical applications, as shown in Figure 15. Most units also have a manual lance that can be used for concrete removal in areas



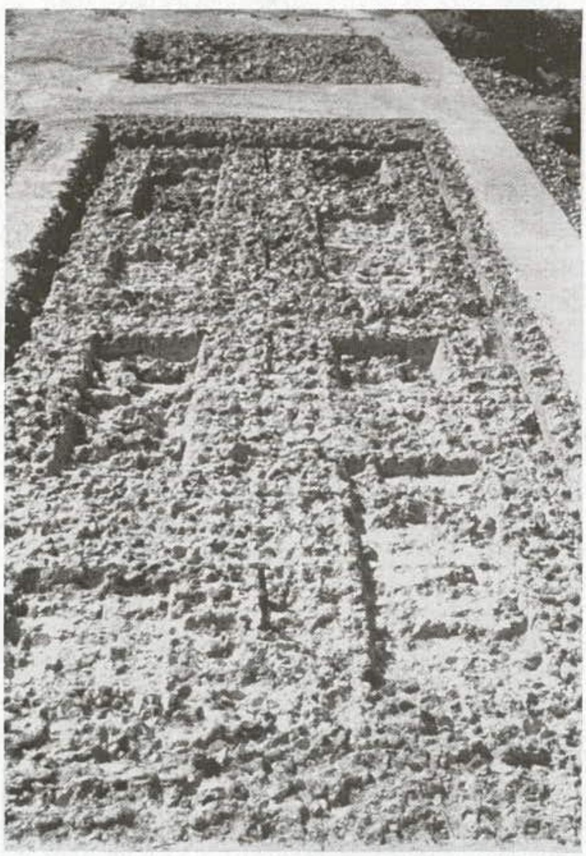


FIGURE 13 Use of hydrodemolition to remove weak concrete.

FIGURE 14 A commercial hydrodemolisher.

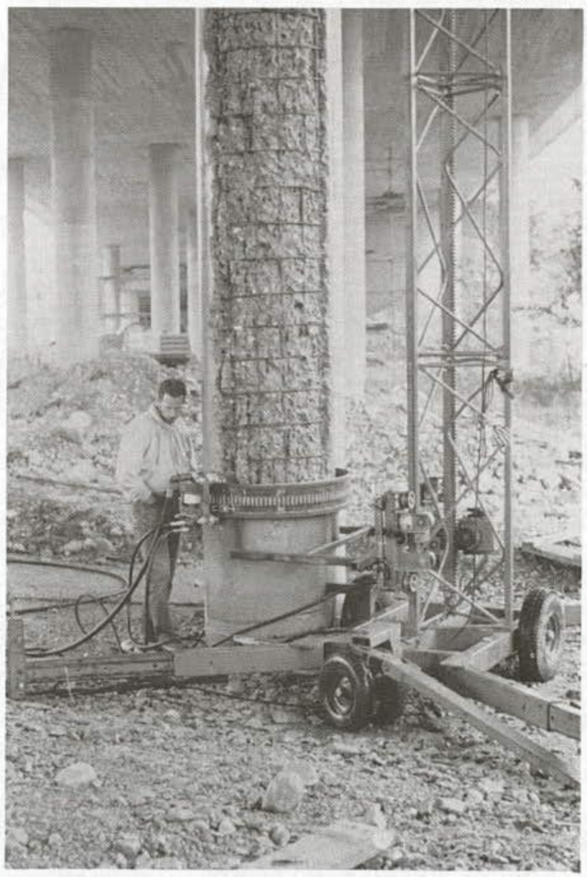


FIGURE 15 Use of a hydrodemolisher on a vertical surface.

that are inaccessible by the nozzles on the mobile unit and for final cleanup of the concrete surface.

The operating parameters and nozzle details differ from manufacturer to manufacturer (many of the details are patented or considered proprietary information). Most of the European equipment operates at less than 20,000 psi (140 MPa), but some of the domestic equipment operates at pressures as high as 35,000 psi (240 MPa). The advantages of using a higher pressure are that depth of removal is greater and more uniform and water consumption is reduced. For example, a widely used machine of Italian origin that operates at 13,000 psi (90 MPa) uses 66 gpm (250 L/min) of water, compared with a U.S. machine that operates at up to 35,000 psi (240 MPa) and uses as little as 13 gpm (49 L/min). The disadvantages are that capital, maintenance, and energy costs for the machine increase (*53*) and there is a danger of removing too much concrete (*34*).

The survey reported in Appendix A showed that hydrodemolition has been used in more than half of the jurisdictions responding, but more than two-thirds of these stated that the procedure was considered experimental. The vast majority of the experience with hydrodemolition has been on bridge decks. Of all the methods of concrete removal in use, the experience with hydrodemolition has been the most varied. Some respondents indicated that it is the preferred method of removal, whereas another found it ineffective. Others indicated that the experience to date had not been entirely satisfactory but expected future use to increase.

There have been several reports in technical journals of successful application of hydrodemolition (*34, 42, 46, 47, 58–63*) to concrete-repair projects in both the public and private sectors. Although some of the articles are based on information supplied by the equipment manufacturers, there is no doubt that hydrodemolition has been successful on some jobs in terms of preparing the concrete surface rapidly and at reasonable cost without the damage normally associated with the use of percussive tools. Production rates vary widely but should exceed 100 ft^2/hr (9 m^2/hr) (*56, 64*) on most jobs, and up to 300 ft^2/hr (28 m^2/hr) has been reported (*60, 62*). Because of the number of variables that affect the depth of cut, it is essential that the equipment be calibrated on site with respect to operating parameters such as water pressure, flow rate, and travel speed to achieve the desired results. There have been reports of hydrodemolishers breaking through the deck slab, but they were not sufficiently documented to determine whether it was the result of an inexperienced operator, whether the concrete was of very poor quality, or some other reason. Nevertheless the consequences can be serious on grade separations if protection is not provided to traffic passing below the deck. There is often a large amount of concrete removed, and cleanup is accomplished most satisfactorily using an industrial vacuum. It is important to clean up quickly after the hydrodemolisher, because if the water is allowed to evaporate, the fine particles stick to the concrete surface and are difficult to remove. The recommended procedure is to use a vacuum cleaner immediately behind the hydrodemolisher, flush the deck with clean water, and vacuum again. This both prevents the slurry sticking to the concrete and minimizes the formation of rust on any exposed reinforcing steel.

Where difficulties have been experienced, these generally fall into one of three categories:

- equipment breakdowns
- rebar shadows
- disposal of material

"Rebar shadows" refers to the situation in which the specifications require the removal of concrete from around the reinforcing steel but the concrete below the bars is not removed because it is shielded by the rebars from the water jets. The phenomenon does not occur with all machines and can sometimes be corrected by making a pass in the opposite direction. However, this defeats the objective of having a one-step process.

Environmental restrictions on the disposal of the concrete and slurry vary considerably from jurisdiction to jurisdiction. Although most agencies did not report this as a problem, there are cases in which restrictions have been placed on the pH and solids content of the runoff. The usual solution is to construct settling ponds so that only an acceptable effluent is discharged into the watercourse or storm sewer, but this may be impracticable on sites where it is not possible to seal the deck drains and expansion joints. Sometimes acid is used to buffer the high pH in the runoff. In extreme cases, all the solid material and water must be collected in holding tanks and removed from the site, though this could render the hydrodemolition prohibitively expensive.

The varied experience is perhaps a reflection of the inexperience that inevitably accompanies the introduction of new technology, and particularly one that involves sophisticated machinery working at high pressures. The process has a number of distinct advantages over conventional removal procedures, but although there is optimism that its use will increase, it has not yet reached its potential.

THERMAL TECHNIQUES

Oxyacetylene cutters are used routinely in combination with other methods in concrete-removal operations to cut exposed reinforcing bar (*19*) and prestressing steel (*65*). In the latter case it is essential that the structure be analyzed to ensure the safety of the workers and the structure when the prestressing forces are released, but burning through the strands presents no particular difficulties and can be less troublesome than sawing (*65*). The use of thermal techniques to cut concrete is far less common and requires equipment capable of generating much higher temperatures than a mixture of oxygen and acetylene. Although there are several candidate techniques that could be used, or are in the process of development, thermal techniques are used infrequently on ordinary concrete structures and only rarely on highway structures. Most applications tend to be very specialized, such as for the removal of shielding in nuclear plants or in buildings where access is restricted. However, thermal techniques are relatively new, and, hence, rapid advances in the technology are more likely than with traditional methods using saws and percussive tools.

Thermal processes can be divided into three groups (*66*):

- Thermal boring and cutting using high-temperature flame, plasma, or laser beam.
- Removal of the concrete cover by electrical heating of reinforcing bars.
- Removal of the concrete surface by direct application of heat.

The various techniques that can be used for each of these three processes are summarized in Table 2.

All the techniques listed in the first column of Table 2 are based on methods that generate very high temperatures to melt the concrete, but only the flame lances are in practical use. These techniques can be used for either complete or partial removal of concrete; the methods listed in the other two columns are used only where some of the concrete will be left in place.

Thermit Flame Lance

Thermal lances have been used to cut metals for many years, but the technology has been applied to cutting concrete only recently.

The lance consists of a seamless mild steel pipe, 0.5 to 0.6 in. (12 to 14 mm) inside diameter (*67*), containing iron alloy or aluminum alloy wires, filling approximately 75 percent of the pipe. Oxygen is passed between the wires and discharged from the tip of the pipe. To start the lance, the end is heated to red hot and the oxygen, which is supplied at low pressure, is ignited. The burning tip is then placed on the concrete and cutting is begun by exerting a gentle pressure. When the lance has penetrated 1 in. (25 mm) or more, the oxygen supply is increased to full pressure (115 to 200 psi or 0.8 to 1.4 MPa). The pipe and wire core burn at a temperature in excess of 5400°F (3000°C) and melt the concrete. Silica-based aggregate can generally be cut at a higher speed than limestone aggregate. Reinforcing steel does not present an obstacle and can, in fact, be cut faster than concrete because of the high temperatures generated when the steel reacts with oxygen.

Thermal cutting emits sparks up to 10 to 13 ft (2 to 3 m) from the concrete. Although these are no more dangerous than welding sparks, special precautions must be taken:

- The operator must be protected by heat-resistant clothing and the eyes and face shielded by a mask.
- Flammable materials in the work areas must be removed or, if that is not feasible, protected from the molten slag.
- Good ventilation is required.

The normal practice is to cut a series of adjacent holes about 2.5 to 4 in. (60 to 100 mm) in diameter in the concrete member and then lift out the cut segment. Where concrete is to be left in place, all the concrete that has been damaged by heating (corresponding roughly to that which has experienced temperatures in excess of 932°F or 500°C) must be removed, usually by mechanical means.

There is a wide variation in cutting speeds reported, from typical values of 2 to 3 in./min (50 to 75 mm/min) (*21*) to as high as 8 to 16 in./min (200 to 400 mm/min) (*66*). Cutting speed depends on the quality of the concrete, the type of aggregate, the amount of reinforcement, operator skill, and whether the molten slag can be discharged smoothly. When making a vertical cut, slag discharge is improved by cutting from the bottom upward.

The thermit lance has a number of advantages:

- The process generates no vibrations and has low noise levels.
- It can be used where access is difficult.
- The process is not hampered by embedded steel.
- It can be used underwater.

The major disadvantage is that costs are higher than with mechanical methods under normal conditions. Consequently, thermal lancing is most useful in unusually difficult situations (e.g., for the removal of very heavily reinforced, large sections where access is restricted).

TABLE 2

CLASSIFICATION OF THERMAL TECHNIQUES FOR CONCRETE REMOVAL (ADAPTED FROM 66)

Boring and Cutting Techniques	Heating of Reinforcing Steel	Heating of Concrete
*Thermit flame lance	*Direct electrical heating	*Direct flame
*Jet flame lance	*Induction electrical heating	*Microwave
*Plasma powder flame lance		*High frequency and high voltage
*Plasma jet		*Electric discharge
*Laser beam		
*Electron beam		
*Arc heating		

Jet Flame Lance

The jet flame lance uses flame at 5800°F to 6300°F (3200°C to 3500°C) from a mixture of kerosene and oxygen accelerated to supersonic speeds to cut concrete. The process has the same advantages as the thermit flame lance but has a higher cutting speed. It has also been found to give good results underwater (*68*). In addition to having the same disadvantages of generating fumes and the fire and safety risks presented by molten slag, the jet flame has a supersonic speed of Mach 5 to 6. This causes an impact wave resulting in a 100 to 110 dB noise that effectively precludes its use at many locations.

Other Thermal Cutting Techniques

The other thermal cutting techniques listed in the first column of Table 2 are all at the experimental stage and require further development to overcome problems such as high capital costs, large energy requirements, and slow cutting speeds. Details of these techniques and the status of their development are described in reference *66*.

Electric Heating of Reinforcing Steel

Electric heating of the reinforcing steel can be used to cause the concrete cover to delaminate so that it can be removed by mechanical means. The electric heating can be either direct or induced.

Experiments in Japan (*66*) have shown that direct heating of the reinforcement can be used to remove the concrete cover. Both ends of the reinforcing bars must be exposed, and simulated wall sections were connected to a 57.5 kW heater having a frequency of 400 Hz. Heating the reinforcing bars to 750°F to 930°F (400°C to 500°C) was found sufficient to crack the concrete, a process that took about 8 min for the specimens used. The process is reported to be effective but is likely to be used only for special applications.

In the case of induced heating, a large induction coil is placed on the surface of the concrete. An alternating field generates an eddy current in the reinforcing bars, and the resistance loss is used to heat and crack the concrete. This procedure has also been investigated in Japan (*69*), but compared with direct heating has the disadvantages that the induction heaters are expensive and power requirements are very high, especially for thick covers.

Direct Heating of the Concrete

Concrete can be broken by thermal strain; thus, direct heating of a concrete surface is one method of partially removing concrete or preparing a concrete surface for repair. Possible sources of heat are direct flame, microwave or high frequency, and high-voltage heating.

The use of direct flame was investigated in Europe as a means of cleaning a concrete surface (*70*). It was found that the thickness of the concrete layer removed was largely a function of the speed at which the burner was moved and the moisture content of the concrete. Higher moisture contents increased the efficiency of removal. At a burner speed of about 1.2 in./s (30 mm/s), the thickness of the concrete layer removed was an average of about 0.04 in. (1 mm). The flame cleaning was not found to damage the concrete or impair the bond to new concrete. No record was found of direct flame being used in routine operations for either concrete removal or surface preparation. A recent Organization for Economic Co-operation and Development report (*42*) discouraged the use of flame cleaning on the grounds that microcracks may develop in the concrete surface.

Microwave heating has been investigated in Japan using large industrial magnetrons in the 915 to 2450 mHz range (*71, 72*). The microwave energy polarizes the water molecules and heats the concrete from the surface inward, thereby inducing a thermal strain in the concrete. Experiments showed that concrete fractured at a depth of 0.4 in. (10 mm) when the temperature reached 340°F (170°C). The advantages of microwave heating are that it is easy to control and generates no noise (except when the concrete fractures) or vibration. However, there are serious disadvantages to be overcome before the method can be used in the field. These include ensuring the safety of personnel, the protection of communications from interference, and the availability of the high-output magnetrons required.

SUMMATION

Hand-held pneumatic breakers are the most common method of removing deteriorated concrete. Other breakers are hydraulically and, though much less common, gasoline- and electrically powered. Most agencies place a limit on the size of breakers used in order to limit the damage to the concrete that remains in place. This approach has questionable validity because the weight of the hammer has little relationship to the energy per blow, which varies with both the power source of the breaker and, even for breakers of the same type, from manufacturer to manufacturer.

The capital investment in breakers is small and they are widely available. However, they have the disadvantages of being noisy, slow, and dirty. The surface of the concrete remaining is often damaged and the quality of the work is strongly influenced by the skill and attitude of the operator. In addition, the use of breakers over a period of several years causes HAVS ("white finger"). As workers and employers become more aware of the disease, conventional breakers can be expected to be replaced by a new generation of low-vibration percussive tools, or other methods of removal will be used.

Hydrodemolition uses water at pressures in the range of 13,000 to 35,000 psi (90 to 240 MPa) to remove concrete. The equipment is large and sophisticated and can cost upward of $500,000. The process has the advantages of being rapid and removing all the unsound concrete with no damage to the reinforcement or the concrete left in place. The technology has only been used in North America since the mid 1980s, with the result that most uses have been considered experimental. The experience has ranged from very successful at some sites to cases in which its use was terminated because it was found to be ineffective and slow. This varied experience appears to be a consequence of the introduction of new technology. Although the process has several advantages and there is optimism that its use will increase, hydrodemolition has not yet reached its potential.

There are several thermal processes that can be used to remove concrete, but only the thermit flame lance is in practical use. The process has the advantages of generating no vibration and little noise, not being hampered by embedded steel, and being capable of being used underwater. However, the process is relatively expensive and its use is usually limited to difficult situations, such as the removal of heavily reinforced sections in locations where access is restricted.

CHAPTER FOUR

EQUIPMENT AND PROCEDURES FOR SURFACE PREPARATION

GENERAL PRINCIPLES

Two main factors govern the bond between new and old concrete:

- The strength and integrity of the old base concrete.
- The cleanliness of the old surface.

Contrary to popular opinion, a rough concrete surface is not essential to a successful repair.

Laboratory data and field work have shown that bond strengths, as determined by a shear test, may be 400 psi (2.8 MPa) or more but that strengths of 200 psi (1.4 MPa) or less may be adequate when patching or resurfacing concrete pavements (*73*). Calculation indicates, for a typical girder spacing, the horizontal shear at the interface between a 7-in. (180-mm)-thick uncracked slab and a 2-in. (50-mm)-thick overlay to be 64 psi (440 kPa) under an AASHTO H20 wheel load plus impact (*74*). Elsewhere, the bond strength of thin (up to 0.5 in. or 13 mm) mortar patches in a concrete pavement was investigated (*75*). Measurements were made in direct tension using a hydraulic "pull-off" apparatus. Bond strengths as low as 40 psi (280 kPa) were obtained on patches that had performed satisfactorily under traffic for more than eight years. This is not to suggest that bond strength is unimportant but to emphasize that when a clean, sound surface is prepared, bond will not be likely to affect the performance of the repair, providing that the new concrete is properly proportioned, placed, and cured.

The most thorough investigation of the factors affecting the bond between new and old concretes was undertaken by the Portland Cement Association (PCA) in the early 1950s as part of a study on concrete pavement patching and resurfacing (*73*). The investigation included a series of tests specifically designed to determine the influence on bond of the surface roughness of the base. Surfaces with various degrees of roughness were prepared using an electric chisel, a scarifier, and by etching with hydrochloric acid. The results showed that surface roughness influenced the bond, but that the effect was neither great nor consistent. It was concluded that there was little to be gained by roughening a sound surface to an extent greater than that produced by acid etching. Although this method of surface preparation is no longer used on highway structures, a comparable texture would result from abrasive or water blasting. The study concluded:

> . . .mechanical cleaning was essential if a weak or deteriorated surface layer existed on the old concrete. No great benefit was derived from intensive mechanical roughening of the old surface provided it was clean and sound.

The findings of the PCA study were confirmed in a series of laboratory tests carried out at the Texas Transportation Institute around 1970 (*76*). The conclusions emphasized the need for a clean, sound substrate and the importance of removing all dust before applying the bonding agent. The results also showed that a sandblasted, dry surface produced better bond than did a chipped, dry surface. In another series of tests, the specimens were soaked in engine oil before the surfaces were prepared for overlay. It was found that even after brushing, the bond strength was only 60 psi (400 kPa), but that sandblasting or chipping resulted in bond strengths of 330 psi (2.3 MPa), which was about 60 percent of the bond strength of specimens free from oil.

A more recent investigation showed no significant difference in the shear bond strength of a concrete overlay to a milled and to a sandblasted concrete pavement (*77*).

Another study (*78*) examined the effects of surface preparation on the horizontal shear between an existing deck and a structural concrete overlay under heavy loads. Lightly blasted slabs, scarified slabs, and those that were lightly sandblasted followed by lubrication with form oil were overlaid and compared with a monolithic slab. Specimens were also fabricated with dowel reinforcement across the shear plane for each of the three methods of surface preparation. All the slabs were loaded to failure in flexure. The results showed that the lubricated specimens exhibited early separation at the bond line and that the overlay and the base behaved as independent slabs. The performance of the remaining specimens was very similar to the monolithic slab, and the dowel reinforcement had no significant effect on the crack pattern development or the ultimate capacity.

One of the major difficulties in contract administration is that the terms "clean" and "sound" are qualitative and have a wide range of interpretation. Use of the terms immediately gives rise to the questions "How clean is clean?" and "How sound is sound?" Although there are no easy answers, useful guidance on the subject is given in reference *79*. Although the subject of the paper was the preparation of concrete surfaces for coatings (e.g., decorative paints, waterproof coatings, and protective polymer barriers), many of the principles are applicable to repairs involving the application of portland cement concrete.

The paper states that "clean" means there shall be no foreign matter such as dust, dirt, grease, or oil on the surface. A simple, practical test for dust is to wipe a dark cloth across the concrete surface; there should be no evidence of white powder on the cloth. Dust prevents the bonding grout from wetting and penetrating the concrete surface. Oily conditions exist if water sprinkled on the surface stands in droplets without spreading out immediately. Although the water test is useful in some cases, it is practically impossible to determine the presence of some release agents, curing compounds, or surface sealers that contain oils, waxes, greases, or resins using a simple field test. The best approach is to use a method of surface preparation that exposes a fresh concrete surface.

A "sound" surface is one that is free from laitance and has sufficient strength to resist stress that may be exerted by the repair material (e.g., from shrinkage during curing or cooling after application) or from structural and environmental loading. Laitance is the milky-colored skin of high water-cement ratio paste that results from the bleeding of concrete. The laitance layer is weak and poorly adhered to the concrete. It can be detected by scraping the surface with a knife blade. If a fine, white powder is produced, the presence of laitance is confirmed. The strength of concrete near the surface can be evaluated by a pull-out test. In this test a core hole, usually 2 in. (50 mm) in diameter, is drilled no more than 1 in. (25 mm) deep and a pipe cap bonded to the concrete with epoxy resin. After curing, the pipe cap is attached to a hydraulic jack, with care taken not to induce an eccentric load on the cap. There is no universally accepted figure as to what the minimum strength should be. Many manufacturers of repair materials specify not less than 100 psi (7 MPa), and some go as high as 200 psi (14 MPa), though the earlier discussions indicate these figures may be conservative.

Many coatings require that the surface be dry at the time the coating is applied, and this is also true of most of the polymer-based repair materials used in the highway industry. "Dry" is usually taken to mean that there is no free water on the surface of the concrete. A crude test is to drag one's fingers over the surface and check that no moisture is picked up. A better method is to press an absorbent paper tightly against the concrete. Where the moisture content of the new concrete is of concern, a polyethylene sheet can be taped to the concrete surface and examined for visible drops of moisture collecting under the sheet. To be valid, however, the sheet should be exposed to the same conditions of sunlight, temperature, humidity, and atmospheric pressure as will exist when the repair material is applied and left in place for as long as the repair material takes to cure. Because this is virtually impossible to accomplish in practice, the test gives no more than an indication of the moisture content of the concrete.

Another aspect of the strength of the concrete substrate that has only recently received attention is that the concrete surface can be damaged by some methods of concrete removal and surface preparation. This is particularly true of percussive tools and scarifiers, which can fracture but not remove particles of aggregate and paste and leave a surface that is extensively microcracked. An investigation has been reported (*80*) in which the effects of pneumatic hammers and hydrodemolition were compared by in-place bond tests of concrete overlays and microscopic examination of the concrete beneath the bond-line. Bond strengths where the pneumatic hammers were used ranged from 45 to 250 psi (0.3 to 1.7 MPa) but with the majority of the test results around 100 psi (7 MPa). In most cases, there was a damaged or "bruised" area with numerous microcracks immediately below the bond line. This zone was found to be as much as $\frac{3}{8}$ in. (10 mm), depending on the size of the hammer and the quality of the concrete. Bond strengths where hydrodemolition was used ranged from 103 to 278 psi (0.7 to 1.9 MPa), with an average of 200 psi (1.4 MPa). Only isolated microcracks were observed below the bond line. Unfortunately, the data were taken from several widely separated job sites, so the methods of surface preparation were not the only variables. Other tests (*64*) on a full-scale bridge deck panel showed that the shear bond of low-slump and latex-modified concrete overlays applied to a surface prepared by a hydrodemolisher were comparable to the shear strength of the base concrete.

In a laboratory study in Sweden (*81*), pull-off tests were conducted on concrete overlays placed on surfaces prepared by water jetting and by pneumatic breakers. The mean strength of the slabs with the water-jetted surfaces was 290 psi (2 MPa), which was approximately the strength of the base concrete. The mean strength of the slabs with the chipped surfaces was about 145 psi (1 MPa). The difference was ascribed to the fact that the chipping induced microcracks in the surface of the concrete.

The results of the two studies (*76, 78*) in which the surface was contaminated with oil illustrate the detrimental effects of oil on bond strength. It has also been noted that it is difficult to detect the presence of some release agents, curing compounds, and surface sealers, so that it is prudent to expose a fresh concrete surface. There is another reason for so doing. Most existing structures, particularly older structures, have a surface layer of carbonated concrete, and this is often overlooked. Carbonation of concrete is the result of the chemical reaction of carbon dioxide and other acidic gases in the air (which form weak acids in solution) and the cement paste. The reaction increases the porosity of the paste and produces a weak surface layer. The depth of carbonation follows a square-root time law and is largely a function of the quality of the concrete and the humidity of the service environment. For good-quality concrete, the rate of carbonation is low, typically no more than about 0.04 in. (1 mm) per year, but for an old structure, this can mean that a significant depth of concrete should be removed before conventional methods of rehabilitation. The actual depth of carbonation can be measured by exposing a fresh surface to a 2 percent solution of phenolphthalein in ethanol (*82*).

In summary, the method of surface preparation to be used in a rehabilitation contract must take into account the effects of contamination and carbonation of concrete. It is prudent to specify a method that removes the carbonated layer and exposes a fresh concrete surface. The most important requirements for the surface are that it be clean and sound; the roughness of the surface is of much less importance.

SCABBLERS

Although the terminology is not always consistent, even within the industry, the essential difference between scabblers and scarifiers is that scabblers are percussive tools, whereas scarifiers use a milling action. Scabblers were developed from rock drills and use compressed air to hammer piston-mounted bits that are about 2 in. (50 mm) in diameter at a rate of 1600 to 2000 blows/min. They tend to roughen the concrete surface more than abrasive blasting, and the finished surface is comparable to that produced by a scarifier. Units range from single-head, hand-held devices suitable for use on vertical and inclined surfaces to self-propelled, multiple-head machines, such as those shown in Figure 16, suitable for large horizontal surfaces.

When self-propelled scabblers are used only for cleaning (to remove approximately $\frac{1}{32}$ in. or 0.8 mm of concrete), the performance and production rates are similar to those of shotblasters. The depth of penetration and the roughness of the finished surface is controlled by the size of the points on the bits. Bits are available that will remove up to $\frac{1}{4}$ in. (6 mm) at a single

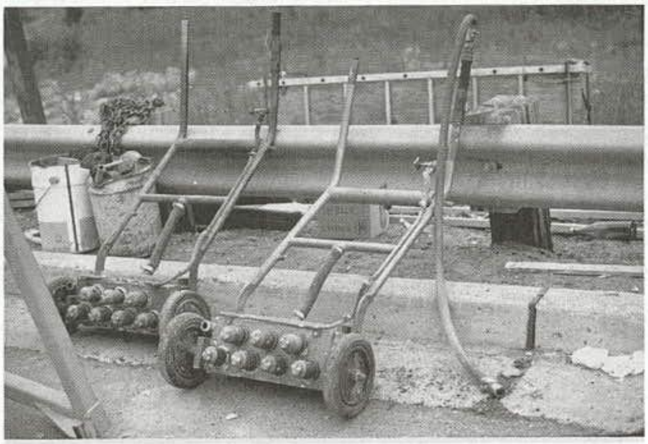


FIGURE 16 Multiple-head scabblers.

pass. Most bits have five to nine points. The tips are constructed from tungsten carbide, and the bits have an average working life of 80 hr. Production rates are strongly influenced by the quality of the concrete and the depth of removal. The depth of removal is determined by the length of time the scabbler remains in one position. A typical rate for a machine with a 12-in. (300-mm) working width is 45 to 80 ft^2/hr (4.2 to 7.4 m^2/hr) to remove $\frac{1}{8}$ in. (3 mm) of concrete (*83*).

The push or self-propelled scabblers have from 2 to 11 bits and a working width of 4 to 19 in. (100 to 480 mm). They require an air compressor that can deliver 100 to 300 ft^3 (2.8 to 8.5 m^3) of air per minute at a pressure of 90 psi (620 kPa). The large units cannot remove concrete immediately adjacent to walls or obstructions, and hand-held units are used in these situations.

Hand-held scabblers usually consist of only one bit and therefore have smaller air requirements and lower productivity. Typical figures are 20 to 35 ft^3/min (0.6 to 1.0 m^3/min) at 80 psi (550 kPa) and production rates of 25 to 50 ft^2/hr (2.3 to 4.6 m^2/hr), depending on the application (*83*). Scabbling operations are noisy and are dirty unless a vacuum system is used. Wetting the surface helps to control dust, but the fine particles adhere to the finished surface and normally require more than an air blast to remove them.

SCARIFIERS

Scarifiers remove concrete by applying a rotating cutting wheel to the surface, and are sometimes called planers or milling machines. In some of the early models, the cutting head was held against the concrete surface by hydraulic pressure and was rotated by the forward motion of the machine. However, in most models the cutting head rotates independently, usually in the direction to produce an upward cutting action on the concrete. Scarifiers range in size from walk-behind units that have a 2-in. (50-mm) cutting path and are designed primarily for the removal of pavement markings and surface coatings to track-mounted units that weigh in excess of 100,000 lb and have a cutting head up to 14 ft (4.3 m) wide (*84*). These large units are designed for use on pavement, and are often too large for use on bridge decks. The smaller units may be powered by compressed air, gasoline,

FIGURE 17 A large scarifier with a conveyor to remove scarified concrete.

FIGURE 18 A medium-sized scarifier head.

or electric motors. The large units use diesel engines up to 1000 hp. Even the very small units cannot be used on vertical surfaces.

Scarifiers are widely used in bridge rehabilitation contracts, especially to prepare the concrete surface before the application of a concrete overlay. The optimum size for a scarifier for bridge work is one with a cutting head of 12 to 72 in. (0.3 to 1.8 m) and capable of removing $\frac{1}{4}$ in. (6 mm) of concrete at a single pass. A large unit is illustrated in Figure 17 and a medium-sized cutting head in Figure 18. Although the first impression would be that the larger machines would be more efficient, this is often not the case. The single biggest problem in using a scarifier on a bridge deck is in the areas of low cover, where the scarifier may rip out the reinforcing bars, as shown in Figure 19, and the unit may be damaged. Other difficulties are in finishing close to curbs and drains and in avoiding spalling unarmored joints. Skew joints (armored and unarmored) are a particular problem with wide cutting heads, because large areas must be finished with a smaller unit or by hand. In such circumstances a smaller, more maneuverable machine that can avoid local areas of low cover, cut close to curbs and embedded hardware, and even be

FIGURE 19 Effect of using a scarifier in an area of low cover.

turned to cut parallel to skew joints may be the best choice. Several manufacturers make units that are suitable for use on bridge decks.

The depth of a cut can be more easily controlled with a scarifier than a scabbler because the cutting head can be adjusted to a reference position, either on the machine or, for the large units, a profile line. The surface roughness is determined by the spacing and shape of the teeth on the cutting head. Many of the smaller units have interchangeable teeth for removing various surfacings, for cleaning, and for light or heavy milling. The teeth, which usually have tungsten carbide tips, wear out and must be replaced, sometimes after only a few hours' use.

Production rates for scarifiers depend on the strength of the concrete, the type of aggregate, the depth of removal, and the number and nature of obstructions. The rates also vary widely with the size of the machine, but a typical figure for the machines used in bridge deck work would be on the order of 500 to 1000 ft^2/hr (93 m^2/hr). Scarifiers are noisy, and some machines may create a lot of vibration. The larger machines are equipped with water tanks for dust control and conveyor systems for loading the scarified material directly into trucks. As noted for scabblers, the use of water for dust control can result in a tightly adhering layer of dust that is difficult to remove.

BLAST CLEANING

Air Blasting

Air blasting is normally used only as a final cleaning to remove dust and loose particles immediately before the application of the repair material. The most important considerations are:

- Using oil-free air by ensuring that the equipment supplying compressed air is equipped with efficient oil and water traps.
- Proceeding in an orderly fashion, with due consideration of the wind direction and the sequence of construction, to ensure that dust is not blown over areas that have been cleaned.

Air blasting is suitable only for removing loose particles, and will not remove material adhering to the concrete surface.

Abrasive Blasting

Abrasive blasting can be used to remove laitance or clean an uncontaminated surface, but is more commonly used as the final method of surface preparation following chipping, scabbling, or scarifying. The abrasive blasting not only removes dust from the surface but also many of the particles that were cracked but not removed by previous operations. One of the major difficulties in contracting for abrasive blasting is that it is not possible to prepare an end-result specification for concrete in the same way that it is for steel by specifying an anchor profile for depth and comparison with standardized photographs for cleanliness. As a result, method specifications are usually used, and the quality of abrasive blasting can vary enormously from contract to contract. The most common abrasives are "sand" and steel shot.

Sandblasting

Natural sand was used for many years for sandblasting, but its use has largely been discontinued because of environmental and health restrictions on silica in the workplace. Further, most natural sands are not ideal abrasives because the particles are too soft and rounded. Synthetic sands (usually crushed blast furnace slag) are now in common use. The abrasive for sandblasting concrete must be coarser than for sandblasting metal surfaces. An 8- to 10-mesh sand composed of angular particles is recommended (*83*).

Sandblasting machines are relatively simple. The abrasive is fed from a storage hopper into a stream of compressed air that then ejects the abrasive at high speed from a nozzle. The finished surface is largely determined by the type, volume, and speed of the abrasive and the shape of the nozzle, as well as the quality of the concrete and of the aggregate.

Dust is the major problem when sandblasting, and workers must wear protective helmets as shown in Figure 20. When using silica sand in manual blasting operations, Occupational Safety and Health Administration standards require a continuous-flow air-line respirator constructed so that it will cover the wearer's head, neck, and shoulders to protect against rebounding abrasive. Dust-filter respirators are not considered adequate protection. Cleanup and disposal of the sand and abraded concrete can

FIGURE 20 A typical sandblasting operation.

also present difficulties, both in physically picking up the sand and satisfying environmental restrictions on dumping. Brooms and shovels are still used, but industrial vacuums are quicker and more effective.

Wet sandblasting, in which water is injected into the abrasive stream, is sometimes used and has a number of advantages, including dust control, use of less abrasive, and the ability to wash the surface for the final cleanup. The disadvantages are the availability of clean water at some sites and the fact that collection and disposal of the spent materials are more difficult.

Sandblasting is widely used in bridge rehabilitation because of the widespread availability of the equipment and the low capital investment. A major advantage is that it is one of the few methods that can be used to prepare vertical and steeply inclined surfaces.

Shotblasting

The abrasive used in shotblasting machines is steel shot. The typical machine, such as that illustrated in Figure 21, is a self-propelled unit in which the shot is propelled by a rotating wheel, hits the concrete surface, and rebounds into a recovery unit. A vacuum system collects dust and shot, separating and recycling the usable shot and storing the abraded material.

Both push-type manual models and self-propelled riding shotblasters are available (*70*). Self-propelled units are powered by gas, propane, or electric motors ranging from 10 to 100 hp. The large units will clean to within 1 to 2 in. (20 to 50 mm) of a vertical surface, the smaller units to within ½ in. (13 mm). Shotblasters have been modified for specialty applications such as cleaning the hulls of ships, but it is not known of any applications to vertical surfaces of concrete.

The depth of cut is controlled by the size of the abrasive, the amount of abrasive, and the speed of the machine. Machines that provide cleaning path widths ranging from 6 to 20 in. (150 to 500 mm) are manufactured. The largest available shot, 0.046 in. (1.2 mm) in diameter, is usually used on concrete. The major operating costs are those of replacing the throwing wheel frequently and replacing the shot as it gradually pulverizes.

The advantages of shotblasting are good dust control, little vibration, and lack of separate cleanup. Because the shot is standardized and there are few manufacturers of the machines, shotblasting tends to result in a much more consistent finished surface than sandblasting. Shotblasting has been used quite extensively in the private sector but has not often been used on highway bridges. The reasons appear to be that it is less available and more expensive than sandblasting and that, in bridge work, abrasive blasting usually follows scarification and the removal of delaminated concrete. This presents a rough concrete surface and exposed reinforcement, for which the small wheels on the machines are ill-suited and the effectiveness of the shot recovery system is reduced.

Waterblasting

Waterblasting, as distinct from hydrodemolition and water jetting, is a method of surface preparation that has the same objectives as abrasive blasting (i.e., to remove the surface layer of the concrete and leave a clean surface suitable for application of the repair material). Water blasters are hand-held, high-pressure water jets, as illustrated in Figure 22, for which the pressure is supplied by a pump. The depth of cut is controlled by the volume and pressure of the water and the shape of the nozzle. Waterblasting has been found to be very effective following chipping, scabbling, or scarifying, because the water penetrates cracks in the surface and removes the affected particles. The other big advantage over abrasive blasting is that there is no dust. The disadvantages are that production rates are lower than abrasive blasting, it is less effective in cleaning corroded steel, and the water leaves exposed steel with a fresh oxide film. Large quantities of clean water are required. Removing the water from depressions in a deck surface is difficult without a vacuum, and collection and disposal of the runoff can present major difficulties at some sites. Waterblasting can be used on vertical surfaces provided that the safety of the operator is not compromised.

CHEMICAL CLEANING

Acid etching used to be a common method of removing laitance and dirt from concrete (*1, 73*). The process of applying

FIGURE 21 A commercial shotblasting machine.

FIGURE 22 A waterblasting operation.

the acid is made easier by prewetting the concrete. The acid is then vigorously scrubbed on the surface. After the foaming action has ceased, typically in 3 to 5 min, the surface is flushed with water while still being scrubbed to remove loosened particles and the products of the reaction between the acid and the cement paste. The flushing is important to remove all the acid, and the surface of the concrete should be checked with litmus paper (*79*). Ammonia and caustic soda have also been used to neutralize the acid (*1*).

Hydrochloric acid has most commonly been used. Recommended application rates vary, but a 10 percent solution applied at the rate of 1 gal to 4 yd^2 (0.9 L to m^2) is typical (*79*). A 15 percent solution of phosphoric acid can be used instead of the hydrochloric acid, and this is preferred because it does not contain any chloride ions.

Acid etching is effective in removing laitance and dirt, provided that additional applications are made, if necessary, but oil drippings are only partially removed. Oil, grease, and fat may be removed by chemical cleaning with detergents, caustic soda, or trisodium phosphate. A vigorous scrubbing action should accompany the washing and the flushing procedures to remove all traces of contamination and prevent loosened oils from being deposited on the surface again. In cases where the concrete has been exposed to oil, grease, or fat for a long period of time, even careful chemical cleaning may not be adequate (*79*). In such cases removal of the affected concrete is necessary.

There are a number of serious drawbacks to chemical cleaning. The major objections are that it is difficult to control (especially on vertical surfaces), workers are exposed to hazardous chemicals, it is difficult to ensure that all contaminants and chemicals have been removed, and it is even more difficult to collect and dispose of runoff in an environmentally acceptable manner. As a result, chemical cleaning, and particularly acid etching, is now used in the concrete industry only when there is no alternative, and this is rarely the case in highway construction.

SUMMATION

The main objectives in preparing a surface for repair are that the base concrete be clean and sound; the roughness of the surface has little effect on bond strength. Unfortunately "clean" and "sound" are qualitative terms subject to wide interpretation in contracts. Clean means that there shall be no foreign matter such as dust, dirt, grease, or oil on the surface. Sound means that the surface is free from laitance and has sufficient strength to resist stress exerted by the repair material or from structural and environmental loading.

Mechanical equipment such as scabblers or scarifiers is used when the surface of the concrete is removed. Scabblers are percussive tools suitable for removing no more than ¼ in. (6 mm) of concrete, and usually less, from relatively small areas. Scarifiers use a rotating cutter to remove ¼ in. (6 mm) of concrete or more at a single pass. The machines are available in a range of sizes. The optimum size for bridge deck applications is a cutting head of 12 to 72 in. (0.3 to 1.8 m). Scabblers and scarifiers are noisy and create a lot of dust, and the large scarifiers can create considerable vibration. They are, however, capable of high production rates and are the most common type of equipment for surface removal.

Blast cleaning is normally used as the final method of surface preparation. It is often used after scabbling or scarifying to remove damaged particles and any tightly adhering dust resulting from using water for dust control. Abrasive blasting uses "sand" or steel shot. The use of natural sand has largely been discontinued because of restrictions on silica in the workplace. Manufactured sands are now used. Shotblasting is done with a machine that propels the shot, collects the rebounding material, separates it, and recycles the usable shot. The major disadvantage on bridges is that its use is limited to decks and the surface is often too rough. Abrasive blasting is very common, and the equipment is inexpensive and widely available. It is often the only method of surface preparation that is practical on vertical and steeply inclined surfaces. The major disadvantages are that the quality of work is operator-dependent, it is dusty, and cleanup can be difficult.

Water blasting is an alternative to abrasive blasting and is growing in popularity. There is no dust and fewer problems in cleanup. However, it is more expensive and less effective in cleaning corroded steel.

Chemical cleaning was once a common method of surface preparation but is now rarely, if ever, used in the highway industry.

CHAPTER FIVE

CONTRACT PREPARATION AND EXECUTION

INTRODUCTION

Contracts are most likely to be completed on time and within budget if there are no changes in the quantity or nature of the work after the contract has been awarded. This requires that the agency define both the quantity and quality of the work in a set of unambiguous contract documents. For work such as a deck widening or a joint replacement, the quantity of concrete to be removed can be calculated from the plans. However, when repairing corrosion-damaged members, it is extremely difficult to define the quantity of concrete to be removed. Normal practice is to carry out a condition survey (*82*), but, even with a thorough survey, estimating removal quantities is difficult for three reasons:

- The results of the survey must be interpolated between grid points.
- Much of the deterioration is hidden.
- The deterioration continues between the times of survey and construction, but the rate of deterioration is not known.

The problem is further complicated by the fact that it is expensive to remove concrete and difficult to measure for payment. This has led to jurisdictions taking different approaches to the definition of bid items and methods of payment. The purpose of this chapter is to describe the several approaches to contract preparation and execution for dealing specifically with corrosion-damaged concrete.

CRITERIA FOR CONCRETE REMOVAL

When bridge deck overlays were first used in the mid 1970s, the normal practice was to scarify ¼ in. (6 mm) of concrete from the entire deck surface and remove all delaminated or deteriorated concrete (*85*). It was known that the only way to be certain of a "permanent" repair was to remove all the concrete that contained chlorides in excess of the corrosion threshold value and prevent deicing salts that are applied later from gaining access to the reinforcing steel (*86, 87*). It was also recognized that application of such criteria would result in deck replacement in many cases. Further, some methods of rehabilitation appeared to be performing well, and, in 1976, the FHWA permitted the use, in federal-aid work, of experimental cost-effective reconstruction in which not all the chloride-contaminated concrete was removed if it was otherwise sound (*1*).

As more jurisdictions began to construct concrete overlays, there was the inevitable trend to more detailed requirements in specification and a divergence in content. The question of how to deal with corroded rebars arose, and, because the removal of concrete from around the reinforcing bars is much more expensive than from above the bars, most jurisdictions opted to remove no more concrete than necessary. This led to specifications that did not require the removal of concrete from around the steel except under specific conditions such as:

- The bond to the reinforcement was broken.
- More than half the perimeter of the bar was exposed.
- The bars were heavily corroded.

As agencies monitored the performance of concrete overlays and it became clear that corrosion was continuing in the underlying deck concrete, there was growing recognition that application of the above criteria could be a major contributing factor to continuing corrosion. Because delaminations usually originate at the level of the top reinforcement, the top surfaces of many bars were exposed following concrete-removal operations. After repairs, the lower portions of the bars were embedded in chloride-contaminated concrete and the upper portions in chloride-free concrete, thereby promoting continued corrosion.

A number of agencies modified the removal criteria to require concrete to be removed from around all the reinforcing bars that were exposed. Other jurisdictions adopted removal criteria based on half-cell potential measurements. The usual criterion was to remove concrete from all areas more negative than −350mV (CSE) on the premise that if concrete were removed from all the areas of active corrosion, there would be no corrosion in the rehabilitated deck. Although the approach had the advantage that, for exposed deck surfaces, it was much easier to define the areas of removal involved, the argument that corrosion was arrested was flawed. Differences in potential between portions of bar embedded in the original and repair concretes, or chlorides remaining in rust on the bars, were each sufficient to initiate further corrosion.

Some jurisdictions went one step further and adopted a criterion that required the removal of concrete below the level of the reinforcement in areas of unsound concrete and active half-cell potentials. An example of this was New York, for which the removal criteria were as follows (*2*):

- Remove spalled, debonded, or otherwise damaged concrete to a depth required to expose a sound surface, but to at least 1 in. or below the bottom of any exposed reinforcing steel (so-called deep removal).
- Remove all concrete associated with sites at which the half-cell potential is more negative than −350 mV (CSE) to the same depth as above.
- Scarify all other concrete surfaces to a depth of ¼ to ½ in.
- Sandblast steel reinforcement to remove all but firmly bonded rust.
- Sandblast newly exposed concrete surfaces to eliminate microfractures.

It should be noted that the above criteria do not result in the removal of all the chloride-contaminated concrete.

An investigation in New York (*2*) in 1985 of overlays constructed in the period 1979 to 1981 revealed relatively little corrosion activity, and, except for delamination associated with joints, the delamination was confined to deck areas that had been scarified. There was no delamination in areas excavated to beneath the reinforcement. It was also found that there was significantly less corrosion activity (as determined by half-cell potential measurements) associated with areas of deep removal than with scarified areas. It was concluded that the deep concrete removal resulted in superior performance. The service life of dense overlays following the then-current practice of removing concrete from below the reinforcement over about half the deck surface was estimated to be 25 years, but if the entire surface were subjected to deep removal, the estimated service life was increased to 40 years.

A study in the United Kingdom (*3*) examined the influence of steel condition on the durability of repairs. The effect of three cleaning procedures (i.e., manual brushing, power wire brushing, and grit blasting) on continued corrosion after repairs was investigated. Three steel conditions were examined: uniformly corroded steel, locally corroded with coarse pitting, and locally corroded with clusters of fine pits. The uniformly corroded bars were produced by exposing bars to industrial and marine atmospheres for six months before embedment in the concrete. The other bars were taken from a bridge under repair. Two concrete mixes were used, one with no added chlorides and the other with 0.5 percent chloride ion by mass of cement.

It was found that even in the chloride-free concrete, the manual and powered wire brushing were not effective in cleaning locally corroded steel and did not prevent corrosion from continuing in a repair. It was suggested that the corrosion was probably caused by the high chloride content of the magnetite deposits within the pits. Grit blasting was effective in three out of four cases for steel with coarse pits but not for steel with fine pits. It should also be remembered that the quality of the grit blasting was higher than would be possible in a structure where it is difficult to blast and inspect the lower surface of exposed reinforcement. For concrete with added chloride, none of the cleaning treatments prevented further corrosion. This was anticipated, because cleaned, pitted steel has numerous sites where the initiation of corrosion is favored. The results emphasize the importance of preventing the ingress of chlorides into new concrete. It was suggested that the safest practice to avoid further corrosion would be to cut out and replace all pitted reinforcement, though this is rarely practical.

The criteria for concrete removal vary widely from agency to agency. There has been a trend over the years to remove a greater amount of concrete, and it has been shown that this leads to a projected longer service life of the repair. Unfortunately, this also increases the cost of repair substantially, and it is therefore important to compare the cost-effectiveness of the repair with that of replacement. This does not mean that repairs that remove only the deteriorated concrete are not cost-effective, because, in some circumstances, this method of repair can extend service life at an economical cost. Ideally, a financial analysis could be conducted to compare the costs of several removal criteria with the projected service life data so that the most cost-effective solution could be determined. This is not possible with the current state of knowledge, because, although the unit costs of removal can usually be estimated reliably, the quantities are often uncertain and there are so many factors that affect service life that, though predictive methods are improving, they are still little more than an educated guess.

QUANTITIES AND METHODS OF PAYMENT

In response to the survey (Appendix A), several agencies reported that it is very difficult to estimate the quantity of concrete to be removed and that overruns occur routinely. It is not uncommon to find after the contractor begins work that the deterioration is much greater than anticipated. Not only does this increase costs, but even the method of repair may have to be changed, resulting in delays and complicating the administration of the contract.

When the quantity of concrete to be removed can be specified on the plans, it is usually bid as a lump sum. This is common for widenings or joint replacement, but some agencies also bid removal of deteriorated concrete as a lump-sum item. Unless a criterion such as "the removal of all concrete to below the level of the reinforcement" or "removal from areas of high potential according to a plan included in the contract documents" is used (in which cases the quantity can be calculated if the concrete cover is known), contractors must include a substantial risk factor in the bid price. This means that payment is unlikely to be equitable to both parties. If the removal quantity is greater than anticipated, not only does the contractor lose money but also the quality of the work is likely to be compromised. Furthermore, if a lump-sum payment is used and the site conditions require changes in the contract, there is no basis to establish a negotiated price for the new work.

The method used by most agencies for the removal of concrete from corrosion-damaged structures is to specify several classes of removal and bid each class as a price per unit area based on an estimated quantity of work. Payment is then made by measuring the area of each class of removal in the field. Responses to the survey showed that several states use four classes of removal for bridge decks:

- Class 1: Scarify to a depth of ¼ in. (6 mm).
- Class 2: Remove concrete to the top mat of reinforcing bars.
- Class 3: Remove concrete to ¾ in. (20 mm) below the top mat of reinforcing steel.
- Class 4: Perform full-depth repair.

Some states recognize only three classes by combining Classes 2 and 3. A small number of agencies use volumetric measurement for payment, though this is usually established by measuring the quantity of concrete placed in the repair. Because the unit prices for this work are high and the quantities small, considerable errors can be introduced, particularly if concrete is wasted. The alternative method of measuring the area and calculating the average depth of removal by taking measurements on a fairly small grid is tedious. A recent innovation has been the introduction of total survey station technology, which uses a laser and automated data processing to calculate the quantity of concrete removed quickly and accurately. More widespread availability and use of the equipment may lead to a shift from payment for concrete removal by area to payment by volume, which is a better measure of the work involved.

The method of specifying concrete-removal quantities for other than decks is not well established because of the relatively small amount of work that has been done on other components. The most common approach appears to be to bid unit prices for several classes of removal that are defined in relation to the position of the reinforcement in much the same way as Classes 2 and 3 do for decks. When the costs of access to the work area are high (e.g., where scaffolding is required around a pier cap) it is not uncommon to include a separate bid item to cover the contractor's mobilization costs. This is a prudent approach, especially when mobilization costs are high and quantities of removal small, because otherwise the unit prices are high and small changes in quantity result in payments that bear little relationship to the costs involved.

An alternative approach to payment for concrete removal in situations where the quantities involved are uncertain is to bid the item by "crew hour." Under the crew hour system, the contractor quotes the price per hour for supplying a specified number of operators and pieces of equipment for the estimated number of hours required to remove concrete. This approach falls between unit price bids and force account procedures insofar as it promotes competitive bidding with little risk to the contractor. The major disadvantage of the crew hour system is that it is difficult to motivate the contractor to achieve high production rates. It is interesting to note that in Ontario, crew hour production rates dropped dramatically between 1980, when the system was introduced, and 1988. The reduction was ascribed to fewer inspectors, the lack of experienced operators available to the contractors, and the absence of any incentive to achieve higher output. There are also difficulties in establishing payment rates when the crew is incomplete (e.g., when one member is sick or a piece of equipment breaks down) and in keeping accurate records if the crew or equipment is involved in several activities during the course of a day. The result is that the agency's inspector spends a lot of time in record-keeping at the expense of inspecting the quality of the work.

The major problem for agencies in preparing contract documents is to estimate the quantity of concrete removal accurately. Most agencies responding to the survey indicated that the quantities are calculated from condition survey reports, though how this was done was not specified. Given the amount of uncertainty surrounding even the best condition survey, a considerable amount of engineering judgment must be applied, and the process is as much an art as it is a science. The difficulties arise because the condition survey data are often incomplete and the deterioration continues between the time of the survey and construction. Although the increase in the area of deterioration can be taken into account by applying a factor to the suspected area of deterioration, the figure used is often arbitrary and subject to considerable error if there are delays in awarding the contract.

The major problem for a contractor preparing bid prices is that the quality of the concrete is often unknown, and this has a substantial effect on production rates. Lump-sum bids for removing deteriorated concrete carry a high risk. When the bid item is based on unit area or unit volume, experience in similar work is invaluable.

There are no easy answers to the difficulties of preparing contract documents and bidding for concrete-removal work. The most reasonable solution appears to be to include a unit price for each class of removal likely to be encountered, with a separate lump-sum item for additional costs that can be clearly identified. Using this approach, the interests of both agency and contractor are protected.

CHAPTER SIX

CURRENT AND FUTURE RESEARCH

CURRENT RESEARCH

Much of the current research on concrete highway structures is included in the technical research area "Bridge Protection" of the Strategic Highway Research Program (SHRP). This program will result in the expenditure of approximately $10 million over a five-year period (1988 to 1993) to address the problems of corrosion in existing concrete bridges (*88*). Two contracts, C-101 and C-103, have a direct influence on the removal of concrete from bridges.

Contract C-101, "Assessment of Physical Condition of Concrete Bridge Components," was awarded to Pennsylvania State University in August 1988. The contract has a value of $2,300,000 and a completion date of January 1992. The project consists of a diverse group of tasks to develop nondestructive testing techniques for evaluating the condition of concrete bridges. Three of these tasks—the measurement of the rate of corrosion of embedded steel, the detection of deterioration in asphalt-covered decks, and the detection of delamination in concrete components other than decks—can be expected to have an impact on concrete-removal criteria. A criterion based on rate of corrosion is more valid than one based on potential measurements, and the use of a rate-of-corrosion device on rehabilitated bridges would lead to both a better understanding of the effect of the amount of removal on continuing corrosion and better predictions of service life. The other two tasks can be expected to result in methods that will give more reliable information on the extent of deterioration in bridges, thereby permitting better estimation of removal quantities, fewer cost overruns, and better adherence to work schedules.

Contract C-103, "Concrete Bridge Protection and Rehabilitation—Chemical and Physical Techniques," was awarded to Virginia Polytechnic Institute and State University in September 1988. The value of the contract is $2,700,000 and the completion date is March 31, 1993. The project addresses conventional and chemical means of repairing corroded bridges. One of the tasks is specifically to evaluate concrete-removal and surface-preparation techniques. It is not intended that the project will involve equipment development, but rather that the product will be nonproprietary specifications for rapid and economical methods of concrete removal and surface preparation. Another task involves the development of methods that can be used to prevent corrosion damage in salt-contaminated components without the need for concrete removal. This task includes an assessment of such techniques as sealers, inhibitors, chloride, and oxygen scavengers, and if successful, would lead to a substantial reduction in the amount of concrete now being removed.

The other major area in which research and development is being undertaken is in the private sector by equipment manufacturers in North America. By its very nature, this work is proprietary and the results only become known as new products are introduced to the marketplace.

FUTURE RESEARCH

Many of the future research needs follow from the discussion of the disadvantages of the existing practices in Chapters 2 to 5. Although there have been a number of developments in recent years, many of the methods now in use have remained unchanged for decades. Concrete removal is difficult, tedious, costly, and often hazardous. Furthermore, removal operations often control the progress of rehabilitation work and have a strong influence on the quality of the final product. Consequently, there is considerable scope for improving the existing technology.

The generic requirements for concrete-removal procedures are as follows:

- lack of damage to the concrete, reinforcing steel, or other components left in place;
- control of depth of removal;
- ability to remove concrete from around reinforcing steel;
- cleaning of reinforcing steel;
- rapidity, reliability, and inexpensiveness;
- safety; and
- environmental acceptability.

In addition, the procedures should have the following attributes:

- freedom from vibration,
- a minimum of cleanup required, and
- few restrictions by weather.

Some manufacturers may claim that their equipment already satisfies the preceding requirements, whereas agencies may argue that none of the existing procedures are completely satisfactory. Because the requirements are qualitative, the debate is unending, and it may even be unrealistic to expect a single piece of equipment to satisfy all the requirements under all job conditions (decks and substructures, for example). It would therefore be useful to define the limitations of any new procedures so that equipment and procedures could be carefully matched to specific job conditions.

In addition to the considerable research associated with the development of equipment and procedures to satisfy the generic requirements, a number of smaller and more specific tasks can be identified:

- Methods of identifying areas of deteriorated concrete are needed. Although some research is already under way, it is important to recognize the limitations imposed by the highway industry, which has not embraced high technology to the same degree as many other industries (*89*). The sheer number of bridges and limited budgets discourage the use of investigative techniques that are costly or time-consuming. Procedures must also be compatible with the expertise available in highway agencies, or the service must be readily available from specialized contractors at reasonable cost and the output must be expressed in common civil engineering terms.

- Research is needed on methods of contract preparation and administration. This is a neglected area, and the objective would be to develop innovative approaches that reward the contractor for initiative, speed of construction, and quality of workmanship while protecting the interests of the owner and the public.
- As part of the quality assurance process, quick and reliable methods are needed by the inspector to ensure that all the unsound concrete has been removed and the surface is not damaged.
- Much of the research to date, including that planned within SHRP, has concentrated on removing concrete from reinforced concrete structures. Work is also required to examine the additional complexities in removing concrete from prestressed concrete.
- The subject of service life prediction is an emerging technology with potentially large benefits. Studies are needed to relate the effect of concrete removal to service life of rehabilitated structures, thereby identifying the concrete-removal criterion associated with the most cost-effective method of rehabilitation.

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APPENDIX A
SURVEY OF CURRENT PRACTICE

To determine the current state of the practice in removing concrete from bridge structures, a survey form was mailed in December 1988. Replies were received from 42 states and six Canadian provinces. The responses are summarized in Table A-1 and observations on the responses are given below. It should be noted that the survey was made early in the process of preparing this synthesis, and slightly different terminology was used in the survey form than in the synthesis. The terminology used in Appendix A (except for that in the survey form) is consistent with the body of the synthesis.

Many states supplied a considerable amount of information that, although not amenable to treatment in a summary response, has been included in the text of the synthesis.

PARTIAL REMOVAL OF CONCRETE COMPONENTS

For the purpose of the survey, partial removal was defined as removal of deteriorated concrete before repair (e.g., by patching or overlay). However, partial removal is not limited to the removal of deteriorated concrete and includes, for example, the removal of curbs before widening of a deck or the removal of the surface concrete from a deck slab before construction of an overlay to restore skid resistance. Consequently, comparisons between the procedures reported in Table A-1 must be made carefully, because the applications may be quite different.

The most common method of removing concrete before patching a deck is to delineate the perimeter of a patch with a sawcut typically 3/4 to 1 in. in depth (20 to 25 mm) and remove the concrete with hand-held breakers. The sawcut prevents overbreak and provides a good surface for bonding, as well as eliminating feather edges to the patch. Of the different types of breaker available, pneumatically powered breakers are by far the most common. Most agencies limit the size of the breakers that can be used. The most common limits are a maximum of 30-lb-class jackhammers above the reinforcement and 15-lb-class chipping hammers around and below the reinforcement. Several specifications include the restriction that hammers be used at an angle of no greater than 45° to the deck surface, with the intention of preventing damage to the concrete remaining in place.

Hand-held breakers are also the most commonly used method of removing concrete from substructure components, though more agencies permit the use of rig-mounted breakers for partial removal of concrete from substructure components than from decks. Overbreak was reported to be a common problem on both decks and substructure components when percussive tools in general were used, and with rig-mounted breakers in particular.

Several agencies have used water blasting and hydrodemolition to remove concrete from decks, though the experience has been mixed. One agency (New Hampshire) reported that in the single experimental use, water blasting was found to be ineffective and slow. Others (Alabama, Colorado, Illinois) reported that it was difficult to control the depth of removal. Vermont reported delays because of mechanical breakdowns. Conversely, several agencies indicated that hydrodemolition either is now, or is anticipated to be, the preferred method of removing concrete from decks before overlay. Most specifications do not place limitations on size of equipment but state that it shall be capable of removing the specified amount of concrete without damage to the rest of the structure.

A number of states commented that one of the most difficult problems in the field is to prepare the longitudinal joint before widening the bridge. The joint should be at the location shown on the plans, have a vertical face, and the reinforcing steel protruding from the joint (for use as the lap bars) should not be damaged. The most common procedure is to make a full-depth sawcut at a distance of the lap length from the joint and a second sawcut slightly less than the depth of the concrete cover along the line of the joint. The concrete is then removed from around the bars back to the joint using breakers. Using this procedure it is very difficult to avoid damage to the reinforcing steel and to provide a vertical surface to the joint, because the bottom edge of the joint is not well defined. This problem has been addressed in the Arkansas specification, which contains the following requirements:

> When removing a portion of the structure for widening, particular care should be used in removing the deck slab and curbs so as to secure straight line cuts and vertical faces. A 1" deep slot shall be sawed in the top of the slab and 1" round holes extending from the top of the slab to within 2" of the bottom side, shall be drilled at 8" centers along the cut line. In addition, a plane of weakness approximately 1" deep shall be sawed or cut with chisels at the cut line on the underside of the slab.

COMPLETE REMOVAL OF CONCRETE COMPONENTS

For reasons of both economy and efficiency, there is naturally a tendency to use much larger equipment for the complete removal of concrete than for partial removal and a preference not to restrict unduly the contractor's operations. Most agencies, therefore, allow contractors a choice of equipment but protect the interests of the bridge owner by making the contractor responsible for any damage to those parts of the structure that will be reused. This is done by a statement in specifications or special provisions, of which the one from Tennessee is typical:

> Concrete removal on structures being repaired or reconstructed shall be performed by means that do not damage either the reinforcing steel or structural steel that will be retained in the renovated structure. The removal of the concrete also shall be accomplished without damage to the concrete beyond the limits of the area designated for removal.
>
> Any concrete removal procedure that causes damage to the reinforcing steel, structural steel or to the concrete beyond the limits of the concrete area designated for removal shall be discontinued immediately, and the Contractor shall not proceed with further removal of the concrete until the Engineer approves his equipment and method of removal.
>
> Any damage caused by the Contractor to the reinforcing steel, structural steel or to the concrete beyond the limits designated for removal shall be repaired by the Contractor at his own expense.

Although most agencies would prefer an end-result specification, experience has shown that it is often very difficult to detect damage to concrete and steel that is left in place and even more difficult to effect satisfactory repairs. Consequently, several agencies now place restrictions on the equipment which can be used for certain applications.

The most common damage that was reported was sawcuts in the top flanges of the steel floor beams and girders when full-depth sawing was used to remove bridge decks. When reference was made to a repair method, the procedure was to weld the girder and grind the weld flush with the top flange. Because it is better to avoid such damage, and because it is difficult to ensure the repair is satisfactory, some agencies have prohibited full-depth sawcuts over structural steelwork in contact with the deck soffit. The most detailed requirements are contained in special provisions developed by Maryland that limit full-depth sawing to within 2 in. (50 mm) of structural steel:

> A large tractor saw (6' ±) may be utilized in deck removal with the following restrictions:
>
> (a) Before any sawing is commenced, the outlines of the top flanges or cover plates of all stringers and floor beams are to be drawn on the bridge deck and 1" ± diameter pilot holes made outside these lines to confirm the width of the flanges.
>
> (b) All sawing must be confined to the areas between flange edges minus 4" (2" ± each side).
>
> (c) Longitudinal cuts for bridges, where material is to be removed with cranes on the structure, shall progress no further than the position of the crane when removing any section of deck between transverse cuts.
>
> (d) Only hand-held, maximum 90 lb. pavement breakers may be used within the flange areas where existing stringers have spirals and/or studs. Hand saws may be used in the flange areas where there are no existing spirals or studs, if the operation is observed and approved by the Engineer, and then only to a depth not penetrating the lower reinforcing steel mat. The Engineer has the right to terminate hand sawing over the flanges any time he feels the bridge integrity is in jeopardy.

The second-most-common form of damage reported was to the top flanges of steel and concrete girders by rig-mounted breakers. This has led a number of agencies to prohibit or place restrictions on the use of rig-mounted breakers. For example, Alabama does not allow rig-mounted breakers where reinforcement or girders will be reused. Illinois limits breakers to those having a rated striking energy of no more than 1200 ft lb. Maryland limits rig-mounted breakers to within 6 in. (150 mm) on each side of the edges of flanges. Hand-held hammers no heavier than 90 lb are used to remove the remaining concrete. Ontario restricts the size of breakers to those having a striking energy of 440 ft lb. (600 J) and also prohibits rig-mounted breakers within 12 in. (300 mm) of concrete to remain in place. The final 12 in. (300 mm) must be removed with hand-held hammers no heavier than 30 lb (14 kg).

The whiphammer has been used by only a few agencies and most have experienced damage to beams and excessive vibration.

Many agencies reported using a wrecking ball as a standard procedure in deck removal, but there were no comments with respect to limitations on the size of the ball. Four agencies (Kansas, Texas, Wisconsin, and Wyoming) commented on instances of damage that has occurred, but in two cases it was unclear whether it was only the deck that was being removed. Iowa does not permit the use of a drop hammer when beams are to be reused. Wrecking balls and blasting were commonly used in the removal of substructure components, and only Arkansas reported damage from blasting. Newer techniques such as splitting or the use of hydraulic cutters or nibblers have been used infrequently and on an experimental basis. Florida reported that chemical splitting had not been successful on a number of occasions, and the cause was thought to be deficiencies in the materials.

SURFACE PREPARATION

The procedure in use for surface preparation following removal and before the repair of decks or substructure components is much more uniform than for concrete removal. For decks, scarifiers are most commonly used, followed by abrasive or water blasting, though abrasive blasting is still the most common. Occasionally scabblers are used instead of a scarifier, especially on smaller jobs. The only problems reported were when scarifiers damage reinforcing steel and that they will sometimes cause overbreak at joints and cracks in the concrete. Mechanical cleaning is rarely used on substructure components, and blast cleaning is usually the only surface preparation.

QUANTITIES AND PAYMENT

Several agencies reported that it is very difficult to estimate the quantity of concrete to be removed for the purpose of contract documents and that overruns are common, especially on decks that have a bituminous surface. Most agencies calculate removal quantities from condition survey reports, although the precise manner in which this is done was not specified.

When the quantity of concrete to be removed can be specified on the plans, it is usually bid as a lump-sum item. This is common for widenings or deck removal but is sometimes also used for the removal of deteriorated concrete. The disadvantage of using a lump-sum bid for the removal of deteriorated concrete is that if site conditions require that the plan quantities be changed, there is no basis for a negotiated price. The method used by most agencies for the removal of deteriorated concrete is to specify several classes of removal and bid each class as an estimated area in square yards of square feet. Payment is then made on the basis of the area of each class as measured in the field. Practices vary widely from agency to agency, although the use of four classes of removal is not uncommon for bridge decks:

Class 1: Scarify to a depth of 1/4 in. (6 mm)

Class 2: Remove concrete to the top mat of reinforcing bars

Class 3: Remove concrete to 3/4 in. (20 mm) below the top mat of reinforcing steel

Class 4: Perform full-depth repair

Some agencies recognize only three classes of removal by combining Classes 2 and 3 above. Several respondents commented that it is not uncommon to break through a deck in areas of deteriorated concrete so that the bid quantity of full-depth repair is overrun considerably. A small number of agencies use a volumetric measurement for payment (usually determined by measuring the quantity of concrete placed in the repair) and one (Delaware) uses a bid quantity of yd^2/in. of concrete removed.

TABLE A-1
SUMMARY OF RESPONSES TO THE SURVEY

Agency	Complete Removal												Partial Removal														Surface Preparation							
	Deck						Substructure						Deck						Substructure								Deck				Substructure			
	Hand-Held Breaker	Rig-Mounted Breaker	Sawing	Splitting	Ball and Crane	Blasting	Hand-Held Breaker	Rig-Mounted Breaker	Sawing	Splitting	Ball and Crane	Blasting	Hand-Held Breaker	Rig-Mounted Breaker	Water Jet	Sawing	Splitting	Crushers	Hand-Held Breaker	Rig-Mounted Breaker	Water Jet	Sawing	Splitting	Crushers	Ball and Crane	Blasting	Scarifiers	Scabblers	Abrasive Blasting	Water Blasting	Scarifiers	Scabblers	Abrasive Blasting	Water Blasting
Alabama	S	S					S	S					S	S	E	S			S	S			E											
Alaska	No applicable work																																	
Arkansas	S	S	S				S	S				S	S	S		S			S	S						S	S	S	S					
Colorado	S	S	S		S		S	S			S		S		E	S			S	S					S		S							
Connecticut	S		S				S						S		E				S								S			E		S		
Delaware	S		S		S		S	S	S		S		S			S			S	S		S					S							
Florida	S	S	S	E		E	S	S	S	E		E	S	S		S			S	S		S					S		S	S	S		S	S
Hawaii	No applicable work																																	
Idaho	S												S		E			E	S								S		S	S				
Illinois	S	S	S				S	S	S	S	S		S		S	S			S	S		S	S				S			S				
Iowa	S				S		S				S		S						S			S			S		S	S						
Kansas		S	S		S	S		S			S	S	S		S				S		S	S				S	S		S	S			S	S
Kentucky	S	S	S				S	S			S	S	S	S					S	S							S		S				S	
Louisiana	S		S				S						S						S			S					S		E	E				
Maine	S	S					S	S					S						S									E	S			E	S	
Maryland	S	S	S				S	S					S			S			S	S							S							
Michigan	S	S	S				S		S				S		E	S			S		E	S					S		S	S			S	S
Minnesota		S	S		E			S		E	E		S	S	E				S	S							S	S	S			E	S	
Mississippi													S		E														S	S				
Missouri			S										S	S	S	S			S	S		S					S							
Montana	S	S	S					S				S			E		S		S		E		E	S	S			S		E			S	
Nebraska		S			S	S		S			S	S	S						S								S		S				S	
New Hampshire		S	S					S					S		S	S			S		S	S							S	S			S	S
New Jersey	S	S	S				S						S		E	S			S		E	S					S		S	E			S	E
New York	S		S										S		E	S			S	S		S	S							S				
North Carolina	S	S	S		S		S	S	S		S	S	S						S			S					S	S	S					
North Dakota	S	S	S				S					S	S		E				S								S		E					
Ohio			S		S	S					S	S	S	S					S	S							S		S	E				
Oklahoma	S	S						S					S		S				S								S		S	E			S	
Oregon	S	S									S	S	S		E													S	S					

TABLE A-1 (continued)

	Complete Removal												Partial Removal														Surface Preparation							
	Deck						Substructure						Deck						Substructure								Deck				Substructure			
Agency	Hand-Held Breaker	Rig-Mounted Breaker	Sawing	Splitting	Ball and Crane	Blasting	Hand-Held Breaker	Rig-Mounted Breaker	Sawing	Splitting	Ball and Crane	Blasting	Hand-Held Breaker	Rig-Mounted Breaker	Water Jet	Sawing	Splitting	Crushers	Hand-Held Breaker	Rig-Mounted Breaker	Water Jet	Sawing	Splitting	Crushers	Ball and Crane	Blasting	Scarifiers	Scabblers	Abrasive Blasting	Water Blasting	Scarifiers	Scabblers	Abrasive Blasting	Water Blasting
Pennsylvania	S	S	S				S	S	S		S	S	S	S	S	S		S	S	S		S			S		S	S	S	S			S	S
Rhode Island	S	S			S			S			S	S	S	S	E	S		S	S	S	E			S					S	E			S	E
South Carolina		S											S						S								S	S	S					
South Dakota	S	S	S				S	S		E	S	S	S		E	S			S			S					S		S	E			S	
Tennessee	S	S					S	S				S	S		E	S			S			S					S		S		S		S	
Texas	S	S	S		S		S	S			S		S		S	S			S		S	S					S		S	S			S	S
Vermont		S	S					S				S	S	S	S	S			S	S									S	S			S	
Virginia		S	S		S			S	S	S	S	S	S	S	E	S			S	S	E	S	E			S	S		E	E			E	
Washington	S	S	S				S	S	S	S			S		S	S			S			S	S				S	S	S	S		S	S	S
West Virginia	S	S			S		S	S		E	S		S						S				E				S							
Wisconsin	S	S	S		S			S		S	S	S	S			S			S	S		S					S	S	S	S	S		S	
Wyoming		S	S		S	S					S	S	S			S			S								S							
Alberta	S	S						S					S		E	S	E		S	S							S	S	S	E				
Manitoba		S	E					S				S	S			S				S							S	S	S	E				
New Brunswick	S											S	S			S			S			S						E	S				S	
Ontario	S	S	S	S			S	S	S	S			S		E	S			S			S					S	S	S	E			S	
Saskatchewan													S	S		S													S					

S - Standard Procedure
E - Experimental Use
Blank - Not Used

SURVEY FORM

1. REMOVAL PROCEDURES

Which of the following equipment or procedures have been used in the past three years to remove concrete from a) decks, b) substructure components?

	Decks		Substructures	
	partial removal	complete removal	partial removal	complete removal
Hand-held hammers - electric hydraulic pneumatic gasoline				
Boom-mounted breakers - hydraulic pneumatic				
Water Jet Water Jet plus abrasives				
Sawing - diamond blade diamond wire				
pressure bursting - mechanical chemical				
Hydraulic nibblers Ball and crane blasting				
others (please specify)				

Please indicate in the appropriate boxes an "E" for those used experimentally and an "S" for those considered standard procedures.

Note: i) partial removal means removal of deteriorated concrete prior to repair e.g. by patchinng or overlay;
ii) complete removal means removal of the component but not demolition of the entire structure e.g. deck replacement.

2. LIMITATIONS

a) List the restrictions placed on the above methods e.g. size of equipment, noise controls.

b) Specify any problems encountered e.g. overbreak, insufficient removal, equipment reliability, disposal of detritus.

c) Have any of the methods been found to damage other parts of the structure (for complete removal) or damage the concrete left in place (for partial removal)? Please specify the nature and consequences of damage.

3. QUANTITIES AND PAYMENTS

a) How are the area and depth of concrete for partial removal calculated?

b) What is unit for bid purposes?

c) How is the quantity measured in the field?

d) What has been the experience with over or under-runs?

e) Are typical production rates and unit prices available for methods used? Please summarize.

4. SURFACE PREPARATION FOLLOWING REMOVAL

Which of the following have been used in the past three years to prepare a surface for new concrete?

	Decks	Substructures
scarifiers scabblers abrasive blasting water blasting other (please specify)		

Please indicate experimental (E) or standard (S) procedures.

5. ADDITIONAL INFORMATION

a) Are specifications, special provisions or reports available in connection with any of the questions? Please reference or provide copies.

b) What are the preferred methods of concrete removal? Why?

c) May we contact you if clarification is required? Please give name of person to call and phone number.

d) Any other comments?

Your response is much appreciated. All responses will be tabulated and summarized in the NCHRP Synthesis Report "Bridge-Concrete Removal Practices"

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