# Removal and Reuse of Hardened Concrete

## Reported by ACI Committee 555


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*This report presents information on removal and reuse of hardened concrete. Guidance for assessment of concrete structures for complete or partial demolition is provided. The applicability, advantages, limitations, and safety considerations of various types of concrete removal methods, including hand tools, hand-operated power tools, vehicle-mounted equipment, explosive blasting, drills and saws, nonexplosive demolition agents, mechanical splitters, heating and thermal tools, and hydrodemolition (water-jet blasting), are provided. The available surface removal systems, their probable applications, and advantages and disadvantages of various types of surface removal systems are discussed. Considerations for evaluating and processing waste concrete for production of aggregates suitable for reuses in concrete construction are presented.*



**Keywords:** aggregates; concrete removal; condition survey; demolition; diamond saw; drop hammer; explosive blasting; hardened concrete; hydrodemolition; impact breaker; jet-flame cutter; mechanical splter; mixture proportion; nonexplosive demolition agent; recycled aggregates; recycled concrete; rotating cutter head; spring-action breaker; thermal lance; water-jet blasting; wrecking ball.


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## CHAPTER 1—INTRODUCTION

### 1.1—Scope

This report provides available information on concrete removal methods with detailed discussions on surface removal. Reuse of removed concrete as concrete aggregate is also addressed. The type and kind of concrete and its location within a structure directly affect the removal methods to be used. Selection of proper tools and equipment are critical for a cost-effective and safe concrete removal project.

### 1.2—Objective

Driven by cost, need, and limited resources, the technology for concrete removal and reuse is rapidly advancing. Partial removal of critical structural components for repair rather than replacement, geographical constraints, access to structures planned for removal, environmental regulations, and worker and structure safety will continue to effect an evolution of developing methods and equipment.

With safety as a foremost consideration, thorough planning is essential when engaged in a removal project. The scope and type of concrete to be removed should be evaluated and examined in detail to determine the most advantageous system(s). This report provides information on selecting the most appropriate systems.

Concrete reuse is primarily related to a project's location. For example, limited availability of materials in a particular region may result in a cost-effective use of equipment and manpower to remove nearby concrete structures with the intent of reusing the removed materials as a roadway base or as coarse aggregate for concrete. This report is confined to the evaluation and processing of hardened concrete used as concrete coarse aggregates.

Work continues in a number of countries to improve equipment and methods, including the use of robotics. Proceedings from the RILEM Symposium held in October 1993 in Odense, Denmark, and other RILEM publications provide additional information. These publications include: *Demolition and Reuse of Concrete and Masonry* (Kasai 1988), *Demolition and Reuse of Concrete and Masonry* (Lauritzen 1993), "Disaster Planning, Structural Assessment, Demolition and Recycling" (De Pauw and Lauritzen 1993), "Recycling of Demolished Concrete and Masonry" (Hansen 1992), and "Specification for Concrete With Recycled Aggregates" (RILEM Technical Committee 121 1993). The Strategic Highway Research Program (SHRP) in the United States studied problems that have an influence on the removal of concrete for bridges (Vorster et al. 1992).

## CHAPTER 2—KINDS OF CONCRETE AND DEGREE OF REMOVAL

### 2.1—Introduction

This chapter addresses complete and partial removal from different types of structures and assessment of structure considering safety, stability, cost, constructibility, and environmental impact. The complete or partial removal of prestressed, reinforced, and unreinforced concrete structures should be assessed by a competent team experienced in all phases of the concrete removal operation.

One should identify sound concrete and examine what effect the removal may have on remaining concrete and reinforcement when partial removal is undertaken. Most importantly, concrete removal or demolition should be performed under appropriate supervision, regardless of the project size.

### 2.2—Assessment of concrete structures for complete or partial demolition

**2.2.1** *General considerations*—Guidance on performing a condition survey of concrete structures is covered extensively in ACI 201.1R. Listed below are other general items to consider before either partial or complete concrete removal. If the decision to remove concrete is based on economic or reasons other than concrete deterioration, a detailed condition survey might not be necessary.

**2.2.1.1** *Safety*—A predemolition survey should be performed to determine if the planned work could cause any structure to collapse. Before to starting work, a survey of the job site should be made to determine the hazards and the safeguards necessary to ensure that work is performed safely. Continually check for hazards due to weakening of the structure.

**2.2.1.2** *Environmental impact*—A work plan requiring the removal of a structure, either partially or totally, should address the impact on the surrounding environment. Impacts on the environment include: neighboring tenants and surrounding structures; noise pollution; dust pollution; water runoffs due to work, storms, or both; and other environmental factors such as asbestos and hazardous chemicals. An inventory of potential environmental impacts should be developed and used as a checklist during concrete removal operations.

**2.2.1.3** *Plans provided or drawn for assessment documentation*—During the condition survey of the concrete structure, prepare drawings or sketches that reflect existing conditions. These drawings or sketches become part of the condition survey report to provide preremoval documentation.

**2.2.1.4** *Complete set of structural and architectural drawings*—In performing a condition survey of concrete structures, the use of as-built structural and architectural drawings is strongly recommended for work plan development. The drawings can be reviewed and evaluated for assessing existing conditions, areas of distress or potential hazards, development of work plans, and concrete removal operations. With accurate and thorough drawings, a work plan can be developed safely and effectively, while minimizing environmental impacts and costly errors. If original drawings are not available or if modifications appear to have been made, spot destructive exploration may need to be done to ascertain reinforcement location, size, and condition.

**2.2.1.5** *Budgetary and logistic constraints*—Budgetary and logistic constraints should be identified and incorporated into the work plan.

**2.2.2** *Evaluation of concrete*

**2.2.2.1** *Field documentation (visual examination)*—Refer to ACI 201.1R to develop a checklist for field documentation of the structure. ACI 201.1R provides information on examination of uniformity and rating of distress manifestations.

**2.2.2.2** *Detailed examination*

*(i) Petrography*—The usefulness of any petrographic examination procedure on the objectives of the investigation, proposed or underway, can be determined by a discussion with an experienced petrographer. ASTM C 457 can be used to develop data that will explain why freezing-and-thawing-related damage has occurred. ASTM C 856 gives the following purposes for petrographic examination of concrete:

- Determine, in detail, the condition of concrete in a structure;
- Determine inferior quality, distress, or deterioration of concrete in a structure;
- Determine whether alkali-silica or alkali-carbonate reaction, or cement-aggregate reaction, or reactions between contaminants and the matrix have taken place, and their effects upon the concrete;
- Determine whether the concrete has been subjected to and affected by sulfate attack, other chemical attack, early freezing, or to other harmful effects of freezing and thawing; and
- Determine whether concrete subjected to fire is essentially undamaged or moderately or seriously damaged.

*(ii) Nondestructive testing (NDT)*—There are numerous nondestructive test methods for estimating strength of concrete, a few of which are listed as follows:

a) Surface hardness methods;

b) Penetration resistance techniques;

c) Pullout tests; and

d) Ultrasonic pulse velocity method.

There are also other nondestructive test methods for determining properties other than strength: a few are listed as follows:

a) Magnetic methods—reinforcement cover and location;

b) Electrical methods—reinforcement corrosion, thickness of concrete pavements, moisture content, and moisture penetration;

c) Radioactive methods—density, voids, composition, and segregation; and

d) Ultrasonic pulse velocity and pulse echo techniques—to determine cracks and voids in mass concrete.

For additional test methods and their application and limitations, refer to ACI 228.1R and ACI SP-82 (Malhotra 1984).

**2.2.2.3** *Cause of distress*—In developing removal procedures, consider the cause of distress on the removal process as it may affect the structure's integrity.

**2.2.2.4** *Reuse of concrete rubble*—Refer to Chapter 5.

**2.2.2.5** *Transport and deposit of waste material*—Very little of the approximately 135 million tons (123 million tonnes) of removed concrete rubble in European communities, United States, and Japan is reused. Due to the declining availability of disposal sites, recycling alternatives should be evaluated as quality aggregate sources.

**2.2.3** *Report*

**2.2.3.1** *Summary of scope of work*—Define purpose and limitations of preliminary investigation and findings, concrete removal work plan, safety, schedule requirements, environmental aspects, or recycling plan.

**2.2.3.2** *Findings*—Describe the structure, its present condition, nature of loading and detrimental elements, original condition of the structure, materials used in construction, and practices used in constructing the structure. Photographs should be used to illustrate the conditions.

**2.2.3.3** *Recommendations*—Include complete or partial demolition, salvage, removal methods, safety and environmental considerations, and further investigation or testing as required.

**2.2.3.4** *Total estimated cost*—Provide cost estimates for various removal methods, partial or complete concrete removal, reuse, transportation and waste disposal, and additional inspection and testing. Other associated costs should be identified and estimated where practical, including protection of adjacent construction.

**2.2.3.5** *Photos and drawings*—Use of drawings illustrating as-built, current conditions and areas of concern (for example, concrete quality, distress, loading, and utilities) is required to demonstrate the need for concrete removal, the logic for the method, and amount of removal recommended. Photographs can illustrate distress manifestations and provide documentation of existing conditions. Where possible, include some means for identifying scale, such as including a ruler or other recognized object like a pencil or coin.

**2.2.3.6** *Supporting data in comprehensive form*—To support findings and recommendations, the data developed through visual examination, coring, nondestructive testing, petrography, photographs, drawings, and sketches should be arranged in a comprehensive format that can readily be followed. For example, plans could be labeled with symbols identifying where samples or photos were taken, with each sample or photo containing a brief but concise description. It is essential that the extent of damage be established, regardless of the cause. Whether concrete quality of the remaining structure is sufficient to support a sound repair should be determined.

**2.2.4** *Engineering survey*—Before starting any demolition operations, an engineering survey of the structure conducted by a competent individual is required. The purpose of the survey is to determine the condition of the structure so that precautionary measures can be taken, if necessary, to prevent premature collapse or failure of any portion of the structure.

**2.2.5** *Health and safety safeguards*—A number of steps should be taken to safeguard the health and safety of workers at the job site. These preparatory operations involve the overall planning of the demolition job, including the methods used to demolish the structure, the necessary equipment, and the measures to perform the work safely. Planning for demolition is as important as actually doing the work.

## 2.3—Types and degree of removal

**2.3.1** *Purpose of removal*

**2.3.1.1** *Material conditions*—Concrete removal from a structure may be required due to structure distress where the integrity of the concrete has deteriorated, or where upgrading or modification of a structure where sound concrete needs to be removed for an addition. In some instances where concrete removal is necessary due to distress, sound concrete may need to be removed for anchoring purposes.

**2.3.1.2** *Complete demolition (one-piece, multiple-piece, rubble, crushed)*—Several methods and various types of equipment can be used in concrete removal. Depending on the size, complexity, available equipment, and safety aspects, concrete elements can be removed as single or multiple pieces for disposal, or crushed and reduced to rubble for general disposal or recycling.

**2.3.1.3** *Partial removal*—In partial demolition of concrete structures, salvaging or utilizing the remaining, intact structure should be properly evaluated.

- Replace what is removed—a portion of a structure should be removed and replaced in kind with proper adjustments to the added element to prevent any previous distress.
- Do not replace what is removed—a section of a concrete element is removed and is not critical to the overall integrity of the remaining structure. An example would be removal of architectural or redundant elements that are not essential to the structural integrity.
- Create opening or void—partial demolition may be required to provide temporary or permanent access for equipment, fixtures, framing, or other purposes. The structure is thoroughly evaluated to determine whether partial demolition can be performed with or without temporary or permanent external supports.

With diminishing numbers of disposal sites, waste management has become widespread. In the development of a work plan for concrete removal, the recycling of the concrete waste—for example, reinforcing steel, aggregates, and concrete—will need to be evaluated for practicality and economics. Creative reuse of concrete can be challenging and rewarding. Refer to Chapter 5 of this report for reuse of hardened concrete in the production of ready-mix concrete.

**2.3.2** *Degrees of removal*

- Complete demolition
- Partial demolition may be performed to correct an alignment defect or other deficiency in new construction or remove deteriorated concrete in an existing structure.
  - i. Layer (overlay, cover, finish)—a partial demolition layer usually involves removal to a certain depth greater than 1/2 in. (13 mm)
    - (1) Physically defined limit (different mixtures, barrier, material integrity)
    - (2) Arbitrary limit (specific depth)
  - ii. Surface—a surface demolition usually is a surface removal of less than 1/2 in. (13 mm)
    - (1) Binder and fines only
    - (2) All constituents
- Piece of section
  - i. Entire element
  - ii. Portion of element
    - (1) Physically defined limit (joint, different mixtures, barrier, material integrity)
    - (2) Arbitrary limit (specified size)
    - (3) Reinforcement

## 2.4—Types of concrete and effects on removal and reuse

**2.4.1** *General*—Concrete structures can be classified generally into four groups: mass concrete structures; underground structures; reinforced concrete structures; and prestressed/post-tensioned structures. With the numerous demolition techniques available, such as crushing, chopping, splitting, blasting, cutting/drilling, laser, electric heating, and microwaving, selecting the appropriate method is important. When selecting a removal method the following considerations should be evaluated:

- Safety;
- Finance;
- Time limits;
- Quality of concrete and geometry of the demolished object;
- Quantities, location, and a breaking boundary;
- Aggregate hardness;
- Concrete compressive strength;
- Environment;
- Specific risks;
- Utility locations; and
- Adjoining construction.

**2.4.2** *Mass concrete structures*—Mass concrete structures include hydraulic structures, dams, large mat foundations, bridge piers, thick walls, and reactor foundations. Typical concrete removal methods used are explosive blasting, diamond wire sawing, presplitting using nonexplosive demolition agents and mechanical splitters, vehicle-mounted impact hammering and rotary head cutting, stitch cutting, and drilling. Methods less used but available include remote-controlled thermal lance cutting, abrasive water-jet blasting, electrical heating of steel reinforcement, and microwave heating of cover concrete.

**2.4.3** *Underground structures*—Removal of underground structures is more difficult, requiring the need for horizontal support and individuals experienced in both planning and supervising the removal. Underground structures may be removed using hydraulic breakers, large hammers, blasting, crushing augers, diamond wire saws, and chemical splitting.

**2.4.4** *Reinforced concrete structures*—Most of the methods discussed in Chapter 3 are applicable to reinforced concrete structures depending on the type, size, use, and degree of removal.

**2.4.5** *Prestressed/post-tensioned structures*—Prestressed/post-tensioned concrete structural elements may be removed using thermal lance, hydraulic breaker, drop ball, and jackhammer. Particular care should be taken in demolition as the stored energy in the tendons can, if released suddenly, cause structural collapse or whiplash of tensions on anchorage components (Occupational Safety and Health Administration 1991b). Never allow workers to be near anchorages during any form of removal other than controlled detensioning.

The *OSHA Technical Manual* (Occupational Safety and Health Administration 1991b) identifies four main categories of prestressed members. The category, or categories, should be identified before attempting any demolition, bearing in mind that any prestressed structure may contain elements of more than one category.

- Category 1—Members prestressed before the application of the superimposed loads and having all tendons fully bonded to the concrete or grouted within ducts.
- Category 2—As Category 1, but with the tendons left ungrouted. This type of construction can sometimes be recognized from the access points that may have been provided for inspection of the cables and anchors. Unbonded tendons have been used in the construction of beams, slabs, and other members. These tendons are protected by grease and may be surrounded by plastic sheathing instead of the usual metal duct.
- Category 3—Members that are prestressed progressively as the building construction proceeds and the dead load increases, using bonded tendons, as Category 1.
- Category 4—As Category 3, but using unbonded tendons as Category 2.

Examples of construction using members of Categories 3 and 4 may be found, for example, in the podium of a tall building or some types of bridges. They require that particular care be taken in demolition (Occupational Safety and Health Administration 1991b).

**2.4.5.1** *Pretensioned member*—Simple pretensioned beams and slabs of spans up to about 23 ft (7 m) have been demolished in a manner similar to ordinary reinforced concrete. Pretensioned beams and slabs may be lifted and lowered to the ground as complete units after the removal of any composite concrete covering from tops and ends of the units. If units are too large to be removed in one section, a plan that may involve temporary support should be developed by a professional engineer experienced in prestressed concrete removal.

**2.4.5.2** *Separately stressed precast units*—If possible, units of this type should be lowered to the ground before breaking up, if possible. Requirements dictated by an experienced engineer should be adhered to closely, especially where there are ungrouted tendons.

**2.4.5.3** *Monolithic structures*—A professional engineer experienced in prestressed concrete construction should be consulted before any attempt is made to expose the tendons or anchorages of structures where two or more members have been stressed together. Temporary supports are usually required so the tendons and the anchorage can be cautiously exposed. In these circumstances, it is essential that indiscriminate attempts to expose and destress the tendons and anchorages are not made.

**2.4.5.4** *Progressively prestressed structures*—The advice of a professional engineer is required for removal of progressively prestressed structures. The engineer's recommended removal methods should be strictly adhered to. The stored energy in this type of structure is large.

## 2.5—Monitoring and safety considerations

**2.5.1** *Methods to monitor the demolition*—Because each method of removal is different, a separate analysis should be prepared for each method. Outlined as follows is a general guideline to assist in developing a safety program. Each job will need to be evaluated individually and coordinated with affected governmental agencies. The following provisions are not all-inclusive.

**2.5.1.1** *Planning for construction*—Each operation and stage of a project should be planned in advance, beginning before the preparation of bids and then throughout the project. Superintendents and foremen should participate in this planning process. Thorough planning will provide a well-organized job, eliminating the potential for some accidents. The following items should be considered during planning.

- Location of utilities and services:
  a. Review locations of all utilities. Whenever operations are required to be within the minimum distances of power lines established in the OSHA regulation (Occupational Safety and Health Administration 1991a), arrangements should be made to have the line moved or de-energized, erect barriers, or set up special working procedures. Except on private easements, the appropriate regional notification center should be contacted to determine the location of subsurface utility installations in the area before excavation; and
  b. Locate equipment, tool sheds, and office in a safe and convenient place.
- Employee access problems should be resolved by the individual in charge at the project:
  a. Adequate work areas;
  b. Adequate walkways and runways;
  c. Adequate ladders, stairway, or elevators;
  d. Work areas and passageways clear of rubbish, debris, and nails;
  e. Protection of floor and roof openings; and
  f. Adequate illumination.
- Schedule work for safety:
  a. Have safety equipment (hard hats, goggles, ear plugs, trench jacks, safety belts, and respiratory protection) on site when needed;
  b. Plan work so that there are not too many trades in a small area at the same time; and
  c. Schedule work crews so the flow of equipment and manpower does not create a safety hazard.
- Work procedure:
  a. Material handling—
    1) Plan for methods of elevating, lowering, and handling materials (adequate space, proper auxiliary equipment, such as cranes, hoists, elevators, and trucks); and
    2) Plan for methods of loading and unloading (adequate space, proper auxiliary equipment, such as loaders, cranes, rigging, and forklifts).
  b. Plan for the use of tools and equipment—
    1) Repair, maintenance, and care;
    2) Inspection; and

3) Adequate supplies of the right tools for each part of the job.

**2.5.1.2** *General safety precautions*—The following are general safety precautions:

- Every reasonable effort should be taken to ensure the safety of workers in all situations, whether or not provided for in a company's rules and safety program;
- No worker should be required or knowingly permitted to work in an unsafe place, unless for the purpose of making it safe, and then only after proper precautions have been taken to protect the worker doing such work;
- Before the start of work, the supervisor or safety officer, or both, should survey site conditions for risks or hazards and determine safeguards necessary to accomplish the work in a safe manner;
- A training program should be designed and implemented during the project that will instruct workers in general safe work practices as well as methods to avoid the unique hazards of the workers' specific job assignments;
- Periodic inspections should be conducted during the project to identify unsafe conditions and work practices. Those unsafe conditions and work practices should be corrected immediately; and
- All required safety and health notices should be posted at the job site, as required, or be otherwise available at the site.

**2.5.1.3** *Safety program objectives*—The following are safety program objectives:

- To provide a safety and health program consistent with good construction demolition practices;
- To prevent accidents, injuries, and illnesses;
- To create an attitude of safety consciousness among general management, field supervision, and all crafts;
- To assign specific responsibilities for effective implementation and continuation of the safety program; and
- To provide continued development of safety and health education, training and testing.

**2.5.1.4** *Safety program implementation*—The following can help implement a safety program:

- Planning for safety in the concrete removal operation through job hazard analysis. Draw upon available or hired experience and expertise to anticipate and eliminate accident-prone conditions;
- Providing mechanical and physical safeguards to the maximum extent possible;
- Conducting a program of routine safety and health inspections to identify and correct unsafe working conditions or practices, control health hazards, and comply fully with the safety and health standards for every job;
- Training all individuals in proper safety and health practices;
- Providing necessary personal protective equipment and instructions for its proper use and care;
- Providing a means for employees to inform their supervisors of hazards at the work site;
- Investigating, promptly and thoroughly, every accident to determine the cause and correct the problem to prevent its recurrence; and
- Providing first-aid materials and trained first-aid personnel on job sites.

**2.5.1.5** *Safety program requirements*—The following are requirements for a safety program:

- Develop and implement a safety program with rules and assigned responsibilities;
- Make these rules and policies known to all employees and subcontractors;
- Appoint a safety coordinator;
- Establish a safety training program to ensure that employees are trained in basic hazards of the job site and specific hazards unique to each employee's job assignment;
- Provide superintendents with appropriate safety rules and regulations from government agencies;
- Discipline employees who willfully disregard this program; and
- Reward employees for good safety performance.

# CHAPTER 3—REMOVAL METHODS

## 3.1—Introduction

During the 1950s and 1960s, the contractor generally was limited to hand-held breakers and jackhammers operated by compressed air, core drills, walk-behind diamond saws, wrecking balls, small hydraulic hammers, and contractor-built drop hammers for breaking up concrete. A few specialty demolition contractors removed whole structures.

Today, this has all changed. Equipment and methods developed in one country are soon marketed worldwide and advertised in the various trade magazines. Trade associations provide a good source of firms performing a particular type of work, and contractors keep extensive lists of subcontractors that do work in particular cities. Equipment dealers, demolition contractors, concrete sawing and drilling contractors, and a wide range of construction magazines are helpful to stay abreast of equipment that is available for concrete removal. Due to the high cost, operator training, and skilled supervision required, many items of equipment and methods will be provided by specialty contractors (Peurifoy and Ledbetter 1985).

This chapter provides general description and summary information on concrete removal systems and methods. The advantages and limitations of various concrete removal methods can be found in ACI 546R.

## 3.2—Hand tools

A number of hand tools used in stone and masonry work for many years are good for removing concrete in small amounts. Pry bars, bush hammers, sledgehammers, drills, points and various chisels are just a few of these tools. Reshaping and hardening of the bits is needed.

## 3.3—Hand-operated power tools

**3.3.1** *Hand-held pneumatic tools*—Hand-held pneumatic tools are available in a wide range of sizes (pavement breakers and jackhammers being the most common.) These types of tools have been in use for almost 100 years and are of rug-

*Fig. 3.1—Drop blade (highway pavement demolition).*

ged construction. Compressed air is usually available on most construction sites. Lighter chipping hammers are also available. It is necessary to ensure an adequate supply of air pressure and volume as well as provisions for moisture collection and lubrication (Manning 1991).

**3.3.2** *Hand-held hydraulic tools*—Hydraulic power is provided by small, lightweight power packs that can also operate a number of other tools. The Hydraulic Tool Manufacturer's Association (HTMA) classifies hydraulic tools as Type I, II, or III with minimum flow rates of 5, 8, and 12 gpm (19, 30, and 45 lpm), respectively. A wide range of tools is available, including small impact hammers, drills, saws, and grinders for use in concrete removal.

**3.3.3** *Hand-held electrical tools*—Hand-held electrical tools are the smallest type of hand-held power tools available, have lower energy output, and are usually limited to use in confined areas.

**3.3.4** *Gasoline-powered tools*—Gasoline-powered tools are ideal for small drilling and breaking jobs in hard-to-reach locations. These tools are available in two models, one for drilling and percussion, the other with percussion only. Both tools weigh less than 60 lb (27 kg) with a number of drill steels and other tool bits available.

**3.3.5** *Drop hammers/blades*—Drop hammers/blades are used to demolish concrete highway pavements, parking lots, and other slabs on grade (Fig. 3.1). Weight and drop height are balanced to thickness and strength of concrete and degree of breakage required. Several firms manufacture small three-wheeled hydraulic powered, self-contained drop hammer concrete breakers that are operated by one person. They are available in several sizes. These units are faster than hand-operated pavement breakers and are available with several engine options and an assortment of tool bits. They are faster than a jackhammer or 90 lb (41 kg) pavement breaker. They produce very little dust. They only require one operator and the units are self-propelled and easily portable. The units are ideal for removing small areas of slab on grade up to 12 in. (300 mm) thick. Depending on the model, units are available with a breaking force up to 3800 ft-lb (5150 N-m).

*Fig. 3.2—Vehicle-mounted impact breaker (bridge deck demolition).*

## 3.4—Vehicle-mounted equipment

Demolition attachments of a wide range of sizes and types are available to mount on small backhoes, skid loaders, and equipment requiring carriers of over 200,000 lb (90,000 kg) in weight. A wrecking ball requires a crane boom. Other demolition attachments need to have a carrier equipped as a backhoe or excavator.

The vehicles can be rubber tired or crawler mounted. The unit should have sufficient hydraulic capacity to operate both the boom and the attachment. Small units have been raised with large cranes to upper levels of buildings. Where used on elevated slabs, care needs to be taken not to overload the slab or to remove structural supports holding up the slab supporting the equipment during demolition.

**3.4.1** *Hydraulic/pneumatic impact breakers/hammers*—Hydraulic/pneumatic impact breakers/hammers (Fig. 3.2) are common pieces of equipment available from many manufacturers. Several manufacturers market several different sizes with impact energy classes from 125 ft-lb (169 J) to over 20,000 ft-lb (27,000 J).

The hammer selected should be matched to the carrier it will be mounted on, and the frequency or impact rate, hydraulic pressure, working weight, and design details need to be considered when selecting a hammer. Some specifications limit the impact energy where only partial removal of an existing structure is required. Advantages of the impact hammers are the wide range of sizes and the ready availability. These units have essentially replaced the wrecking ball.

Pneumatic breakers are available in fewer sizes and by fewer manufacturers. The breakers, powered by compressed air, can be used where the carrier does not have sufficient hydraulic capability. Both pneumatic and hydraulic breakers can be used for underwater work.

**3.4.2** *Spring-action hammers*—Spring-action hammers (sometimes referred to as mechanical sledgehammers) are boom-mounted tools that are applicable for breaking concrete pavements, decks, walls, and other thin members. The arm of the hammer is hydraulically powered and the impact head is spring-powered. The spring is compressed by the downward movement of the arm of the backhoe or excavator, and its energy is released just prior to impact. There are truck units

Fig. 3.3—Spring-action breaker (bridge deck demolition).

Fig. 3.5—Single-drum rotary cutter head (planer).

Fig. 3.4—Twin-drum rotary cutter head.

available that make it easier to move between projects. The operation of the hammer and advancement of the truck during removal are controlled from a cab at the rear of truck. Spring-action hammers (Fig. 3.3) are available in several sizes with blow energies up to 300,000 ft.-lb. (400 kJ) (Manning 1991). This equipment is much faster than the impact hammers where the thickness of the concrete pavement permits its use. When the equipment is truck-mounted on rubber tires, it can be easily moved from job site to job site.

**3.4.3** *Wrecking ball and crane*—The wrecking ball is attached to a crane and is either dropped or swung into the concrete. The weight of the ball can vary depending on the crane capacity. This method requires a highly skilled operator for safe operation. The recommendations for wrecking ball versus crane capacity, safety factors, breaking strength of supporting live load, and other safety considerations can be found in the National Cooperative Highway Research Program Synthesis of Highway Practice 169 (Manning 1991).

**3.4.4** *Rotating cutter heads*—Rotating cutter head attachments provide continuous cutting by the rotation of the cutter drum(s) with sizes that fit various hydraulic excavators and skid loaders. Two styles of cutter heads are available for excavators: (1) transverse, twin drums (Fig. 3.4); and (2) in-line, single drum. The drum for the in-line cutter head rotates around the axis of the boom and works similar to a large drill. The drums are available with flat or rotating conical bits.

Skid loaders are used to remove concrete from top faces of decks, slabs, and lock walls, whereas excavators are typically used to remove concrete from vertical and overhead faces. Skid loaders use a single transverse drum attachment (Fig. 3.5).

**3.4.5** *Concrete crushers*—Concrete crushers, in a number of sizes and cutting jaw configurations, are ideal for removing curbs, parapets, slabs, and beam and wall sections, and for crushing large pieces of concrete removed by other methods. Models are available with one hydraulic cylinder, others with two cylinders, and a wide range of sizes, from small units with only a few tons, to large ones with 2500 tons (22,000 kN) of crushing power.

**3.4.6** *Ripper*—The ripper is a large blade attached to a backhoe used to break up slabs-on-grade and to separate the reinforcing steel from the concrete. Ripper blades have also been mounted on large crawler tractors to remove reinforcing steel after the concrete is broken up by other methods. The ripper is ideal for removing large areas of slab-on-grade and concrete pavement.

**3.4.7** *Resonant frequency breaker*—The resonant frequency breaker fractures or breaks concrete highway pavement using a self-propelled, four-wheel rubber-tired power unit that uses resonant beam technology to apply energy through a high-frequency resonant impact breaker to the concrete pavement (Fig. 3.6). The unit has been used successfully on interstate highway work with normal breaking rates averaging 10,000 $yd^2$/day (8400 $m^2$/day).

## 3.5—Explosive blasting

Explosive blasting has been successfully used for removal of large volumes of distressed and deteriorated concrete by the Corps of Engineers on a number of locks and dams (Fig. 3.7). Blasting has been used for complete building demolition and for underwater demolition (Kasai 1988).

Concrete is a difficult material to blast because of the variation in strength and amount of reinforcing steel present (Hemphill 1981). Safety regulations, environmental consid-

*Fig. 3.6—Resonant frequency breaker (highway pavement demolition).*

erations, and the need to monitor for ground vibrations limit applicable locations for this method. Controlled blasting techniques have been developed to minimize damage. The 1988 RILEM Symposium included 13 papers on blasting and related methods (Kasai 1988).

An explosive blasting technique referred to as mini-blasting (Lauritzen and Petersen 1991) has been used for partial demolition of concrete structural members. The technique requires a licensed worker and controlled blasting techniques to maintain safety and minimize damage to the concrete that remains and the surrounding environment. Blasting mats are used to minimize flyrock, and textile fiber mats are used to lower dust and noise levels.

## 3.6—Drills and saws

Drills and saws using hard cutting diamond tools provide smooth holes or surfaces. These tools have minimal vibration and, when water-cooled, minimize dust. Hard aggregates or high concentrations of reinforcing steel can greatly reduce the cutting speed and life of drill bit or saw.

**3.6.1** *Core drills*—Construction grade core drills generally are available in sizes from less than 1 in. (25 mm) up to 24 in. (600 mm) diameter. The drills can be powered by electricity, compressed air, or hydraulic power packs. Heavier units are usually powered with gasoline or diesel engines or compressed air and are truck- or skid-mounted. Compressed air or nitrogen have also been used to cool the bit where the use of water is a problem.

**3.6.2** *Diamond saws*—The most common type of saw blade for cutting concrete is the wet-cutting diamond blade. Dry-cutting diamond blades and abrasive blades are also available. There are a number of blade manufacturers with some producing several different quality levels. The composition of the bond, type, size, and concentration of diamonds varies. For cutting slabs and pavements, there are hand-held, walk-behind, and riding saws. Track-mounted saws are available for cuts in walls and the underside of slabs.

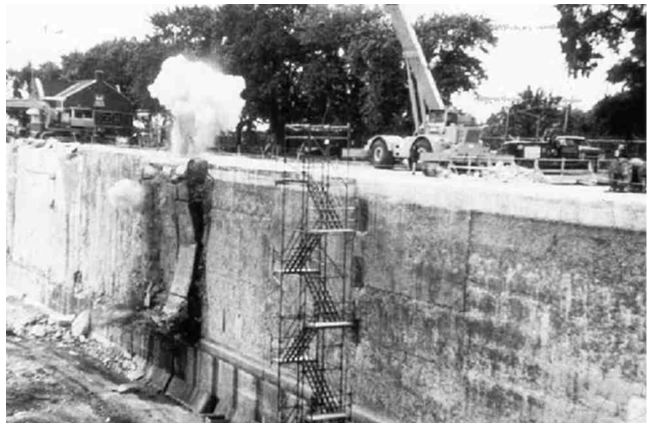

*Fig. 3.7—Explosive blasting (removal of lock chamber face).*

**3.6.2.1** *Hand-held diamond saws*—Hand-held diamond saws generally are available with 10, 12, or 14 in. (250, 300, or 350 mm) diameter blades and powered by electricity, gasoline engines, compressed air, or hydraulic power packs. These are lightweight units designed for intermittent sawing. Special hand-held saws are now available that use a chain saw cutting bar that can minimize overcutting at corners while providing cuts up to 15 in. (380 mm) deep. Another manufacturer has hand-held hydraulic saws that use ring-shaped blades that can make a 10 in. (250 mm) deep cut with a 14 in. (350 mm) diameter blade.

**3.6.2.2** *Walk-behind diamond saws*—Walk-behind diamond saws are the most commonly used power saws. There are two types: a light duty saw for small jobs, and heavier models with up to 65 hp (48 kW) engines. For use in confined areas, some models have blades that can be mounted on either the right or left side.

**3.6.2.3** *Rideable pavement saws*—Rideable pavement saws provide high productivity with blades up to 30 in. (760 mm) in diameter.

**3.6.2.4** *Wall saws*—Wall saws (Fig. 3.8) make accurate cuts in walls by riding on a track bolted to the concrete. Means are also provided to maintain pressure of the blade on the surface being cut. Blades sizes used are in the same range as floor saws. The saws are powered by a remote source using either compressed air, hydraulics, or an electrical system (Lazenby and Phillips 1978).

**3.6.2.5** *Diamond wire saws*—A diamond wire saw is a continuous loop of multistrand wire cable strung with steel beads bonded with diamond abrasive that is pulled through the concrete (McGovern 1992). The beads are separated with springs or spacers. Direction of the cable is changed with idler pulleys (Fig. 3.9). The power unit drives and provides tensioning of the cable. Use of this method has increased as more specialty contractors doing this work have become available. This method is ideal for mass concrete and other sections too thick for diamond-tipped circular saws and where noise or vibration may be a problem (as in hospitals).

Pilot holes are drilled through the concrete with the wire cable passed through and coupled to form the continuous loop. Drive units can be either hydraulically or electrically powered. When the limit of movement of the drive unit is

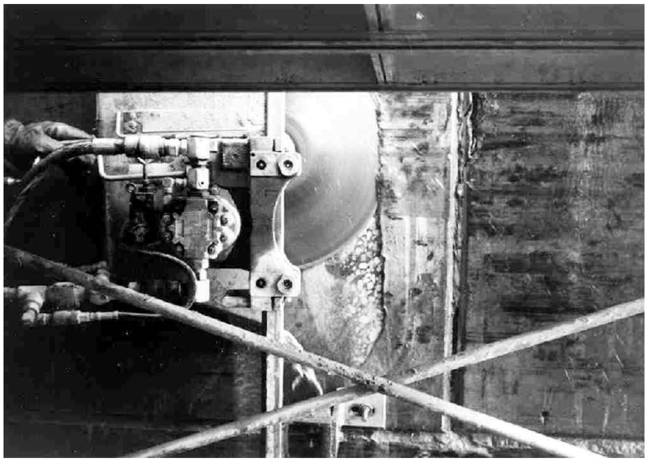

*Fig. 3.8—Wall saw (tapering of corner at monolith joint).*

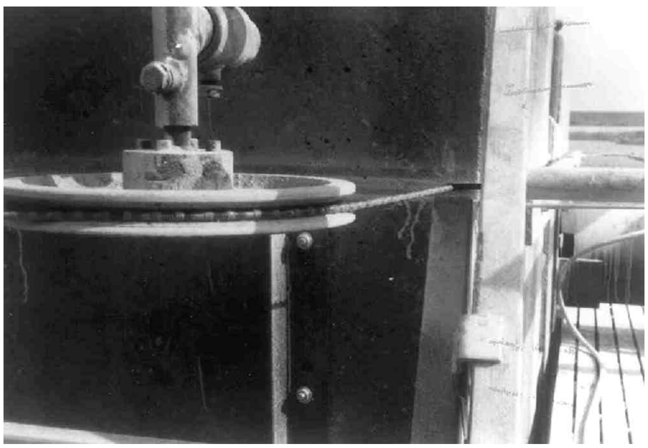

*Fig. 3.9—Diamond wire cutting (idle wheel redirecting wire).*

*Fig. 3.10—Stitch-drilled cut (dam overflow section).*

reached, the unit can be moved or the wire cable shortened. Water is used for the cooling and removal of cuttings. Several articles have been published on diamond wire saws (Franklin and Dusseault 1991; Hulick and Beckman 1989; and Manning 1991). The size of the concrete block removed is only limited by the clearances required and the capacity of available lifting equipment.

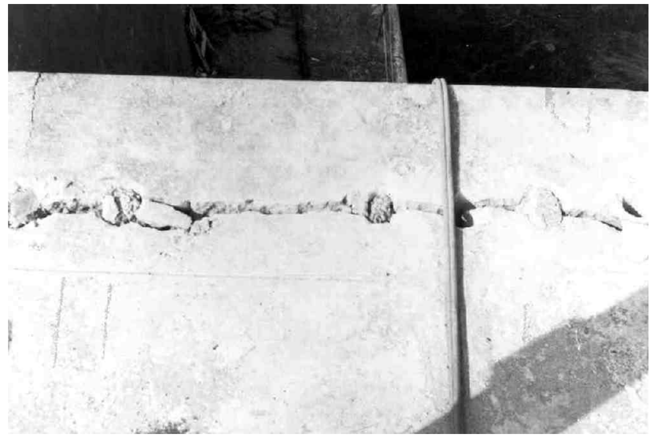

*Fig. 3.11—Results from use of nonexplosive agent (lock wall).*

**3.6.2.6** *Stitch drilling*—Stitch drilling is a technique used to produce cuts in concrete by overlapping drilled holes (Fig. 3.10). Stitch drilling may be used where depth of cut required is greater than can be cut with a diamond saw (Lazenby and Phillips 1978). The depth of cut is limited by the drilling equipment's accuracy in maintaining overlap between adjacent holes.

## 3.7—Nonexplosive demolition agents

Nonexplosive demolition agents (NEDA) were developed in Japan and first marketed about 1979. A proprietary mixture consisting primarily of calcium oxide and calcium silicate is mixed with water, poured into predrilled holes, and after a period of time, the mixture expands and exerts an expansion force sufficient to crack the concrete (Suprenant 1991). The results of the use of NEDA are shown in Fig. 3.11.

Careful planning of the demolition work, including hole size, spacing and pattern, amount of water used, temperature, mixing of materials, loading of holes, curing, and safety provisions need to be addressed. The drilled holes are usually 1-1/2 to 2 in. (38 to 50 mm) in diameter with a spacing of 16 to 24 in. (400 to 600 mm) for plain concrete, and 8 to 16 in. (200 to 400 mm) for reinforced concrete. While excellent results have been obtained, the agent must be used in sound concrete to achieve the desired crack propagation. Other equipment is required for complete removal of the concrete material. Safety considerations include caution during mixing and placing and danger from possible blowout of agent from the hole. Danger of blowout increases with larger-diameter holes.

Once placed in the holes, the mixture must be protected from running water. Plastic sleeves have been used where water is in the hole. The material must be allowed to cure similar to concrete otherwise the breaking force may not develop for 24 or more hours. The material continues to be improved and a number of types are now available for different temperature conditions and reaction times.

Eight papers discuss NEDA were presented at the 2nd RILEM Conference (Kasai 1988). Most of these dealt with splitting mechanism of the concrete under expansive pressure, others with chemical composition, properties, and applications.

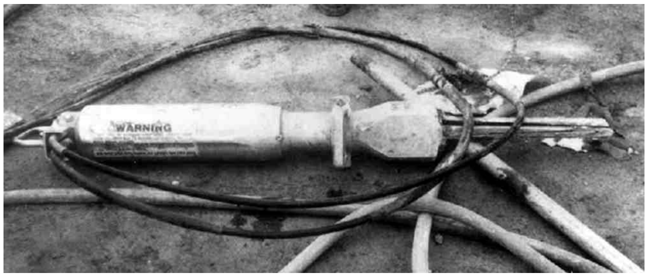


*Fig. 3.12—Plug and feather mechanical splitter.*

### 3.8—Mechanical splitters

Mechanical or hydraulic splitters are placed in predrilled holes, with the splitting action developed by a steel plug or wedge positioned between two hardened steel shims or feathers (Fig. 3.12). Placed in the retracted position, hydraulic pressure applied to the piston plug advances it, and the feathers are forced against the sides of the hole, producing the splitting action with a force of up to 700,000 lb (3100 kN), depending on the size of the unit. One manufacturer has several models with recommended predrilled hole diameters from 1-3/16 to 1-3/4 in. (31 to 45 mm) with spacing of holes from 12 to 36 in. (300 to 900 mm) (Manning 1991; Kasai 1988). One splitter manufactured in Germany that can be reinserted into holes (Fig. 3.13) was used to remove concrete from chamber faces at Dashields Lock (Meley 1989). This unit requires 3-1/2-in. diameter (90 mm) holes.

This method is adaptable to a wide range of job conditions. An open face or space is needed on at least one side to allow for movement of the broken concrete. Two free surfaces would be more efficient. When the splitter is used to cut an opening in a wall or slab, a starter hole provided by a core drill or other means is needed. The holes drilled for the splitters must be straight and of a specified diameter (Suprenant 1991).

### 3.9—Demolition of concrete structures by heat

Several papers on jet-flame cutter method, thermal cutting, and experimentation by applying electrical current through reinforcing steel, laser beam, and use of microwave energy were presented at RILEM 1988 Symposium (Kasai 1988).

**3.9.1** *Jet-flame cutter method*—The jet-flame cutter method consists of a cutting unit for generating a supersonic flame, a controller to control rate and pressure of oxygen, kerosene, and cooling waters to the cutter. A drive unit holds and moves the unit. This method has also been used underwater.

**3.9.2** *Thermal lance*—Thermal lances have been used for a number of years to cut mass concrete. The lance consists of a pipe filled with iron wire through which oxygen is passed. Once ignited, the pipe, wire, and oxygen are consumed, producing a high temperature. Various materials have been used in the pipe to produce a wide range of temperatures. Due to safety considerations, this method has had limited use in general concrete construction but has found use in heavy industrial facilities and nuclear facilities (Manning 1991; Lazenby and Phillips 1978; Kasai 1988).

**3.9.3** *Electrical heating of reinforcing steel*—The method of electrical heating of reinforcing steel is used to debond the concrete from around the reinforcement. Cracks develop in the concrete cover that facilitate its removal. The method uses alternating current.

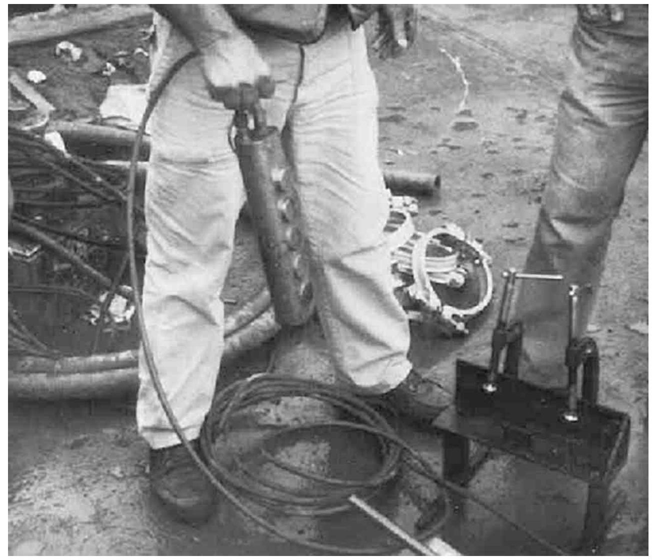

*Fig. 3.13—Piston-jack mechanical splitter.*

### 3.10—Hydrodemolition (water-jet blasting)

Hydrodemolition (also called water-jet blasting) is typically used where the preservation of the reinforcing steel is desired for reuse in the replacement concrete such as in the rehabilitation of bridge and parking garage decks (see also section 4.3.3) (Fig. 3.14). Hand-held water-jet guns have been used to cut concrete. This method is vibration free and avoids danger associated with fire with the flame cutting methods. Reinforcing bars are not cut or damaged (Manning 1991; Kasai 1988).

Water-jet systems have been used with abrasives to cut reinforcing steel in Japan. Three demolition projects are presented in Kasai's (1988) report where abrasive water-jet cutting was used.

## CHAPTER 4—SURFACE REMOVAL

### 4.1—Introduction

Surface removal of concrete is common for new and old construction. Typically, it is required to correct an alignment defect or prepare the surface for a subsequent treatment. Work may be on a small and crude scale with hand tools, or a large scale with motor driven equipment and automatic sensors.

The technology of removal has advanced substantially in recent decades. The advancements have been driven by a desire to reduce unit labor costs, to improve both worker comfort and safety, and to reduce environmental contamination.

This chapter presents a description of the available systems, their probable application, and advantages and disadvantages of various types of removal. Some of the systems are proprietary or developmental. Therefore, only limited data are available.

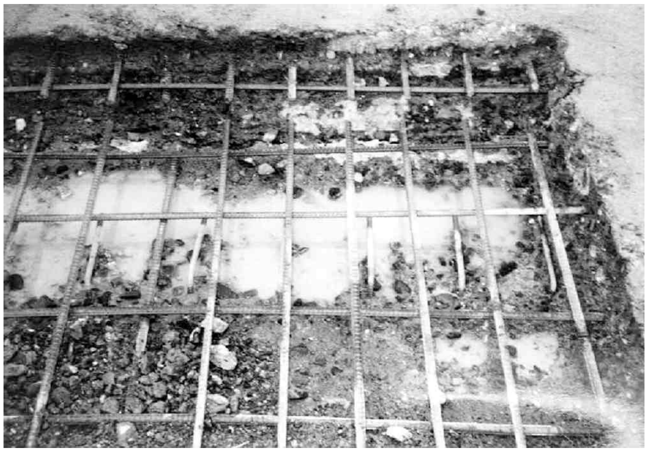

Fig. 3.14—Reinforcing steel exposed by hydrodemolition method.

Concrete surface removal can apply to horizontal, vertical, and overhead surfaces. Some systems, however, will only be suitable for one mode, typically horizontal.

Systems available for surface removal can be generally separated into:

- Mechanical removal (routing or grooving);
- Impact of hard particles (abrading); and
- Hydraulic removal (hydrodemolition).

In addition, there are chemical removal systems, commonly acid etching, that can be used for concrete removal. Their use, however, has been discouraged in recent years due to safety and environmental considerations.

Selection of a system will vary with accessibility, size of the work, locally available equipment and expertise and, most importantly, the end use of the surface. In many cases, more than one system can be considered.

The proprietary nature of systems combined with the range of final surface profiles that will result often necessitates consultation with removal contractors during system selection.

## 4.2—Purpose of surface removal

Common reasons for surface removal of concrete include:

- To correct unsound, stained, or damaged concrete such as weak and dusting surfaces;
- To correct alignments that may have been caused by construction errors such as bulges and high spots on slabs, or fins from formwork leakage; these are typically planeness corrections;
- To prepare the surface for subsequent layers such as overlays, toppings, tile, and coatings; and
- To improve skid resistance.

## 4.3—Systems available for surface removal

There are a wide range of systems available even within a particular generic type of removal equipment. Recently, there has been a movement to larger and self-propelled units as the construction industry becomes more involved in concrete rehabilitation. This section describes the general nature of the equipment with suggestions on advantages and disadvantages as well as possible uses. Additional information on removing concrete from bridges can be found in Manning (1991) and Vorster et al. (1992).

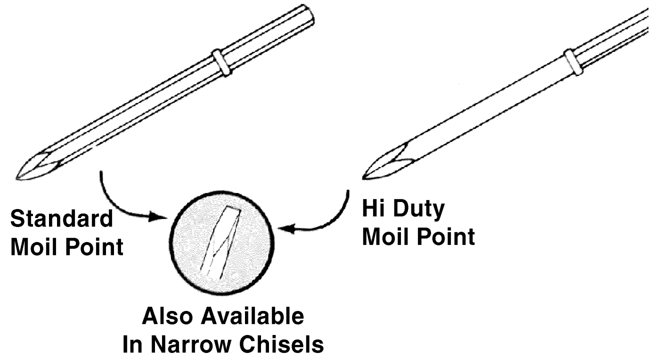


*Fig. 4.1—Chisels.*

**4.3.1** *Mechanical removal*

**4.3.1.1** *General*—Mechanical removal is a general term involving a wide range of removal equipment and techniques. Historically, most removal was done by mechanical means, and today the largest volume of removal is still using the mechanical removal system. Hand operations have been slowly replaced by mechanized systems.

One concern about mechanical systems is that, when used for surface preparation, tools can leave a "bruised" surface that in turn can reduce the bond strength to subsequent overlays (see Section 4.7). The "bruising" concern is particularly relevant with chipping tools.

**4.3.1.2** *Chipping*—Chipping tools, including hammer-driven and hand-held percussion breakers, are the most widely used removal tools. They are available in a wide range of sizes, tip types (hardened steels and carbine) and styles (chisel or moil point) (Fig. 4.1).

Hand-held pneumatic breakers are widely used and well-established tools for removing contaminated and deteriorated concrete. Their lightweight and excellent maneuverability make them ideally suited to remove damaged concrete from small, isolated areas and from vertical and overhead surfaces. They can be used on cracked, spalled, or delaminated concrete, and on chloride-contaminated concrete when the depth of removal is known from the evaluation of the structure.

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 or unsound concrete may not be removed;
- The surface of the remaining concrete 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; and
- 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, and the amount of concrete that should be removed.

**4.3.1.3** *Bush hammering*—Bush hammering is typically performed using a chipping hammer with a bushing tool (bit) having a serrated face with rows of pyramidal points or of parallel V-shaped grooves (Fig. 4.2).

Bush hammering can also be accomplished with hammer blows on a chisel-like tool or with a gang hammer that uses multiple independent bits. A gang hammer for horizontal surfaces is often known as a scabbler.

The depth of penetration and the roughness of the finished surface is controlled by the size and sharpness of the points on the bits.

Operations are noisy and dusty but good control of removal depth is normally achieved. Again "bruising" is a concern but excellent mechanical roughness for bond of subsequent layers can be achieved.

**4.3.1.4** *Needle scalers*—Needle scalers are tools primarily used for metal cleaning; however, they also find use in selective concrete surface removal. These tools are normally pneumatically driven and have upward of 20 steel needles approximately 1/8 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 $ft^3$/min (0.14 $m^3$/min) of compressive 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. In such cases, the lightweight of the tool is a distinct advantage and the low production rates are acceptable. The tools can also be fitted with a chisel point so that the concrete can be removed to almost the full depth using the chisel, with only the final concrete being removed by the needles.

One effective use of needle guns is in the touch-up of nonuniform exposed aggregate architectural concrete. In the hands of an experienced cement mason, color and texture variations can be reduced.

**4.3.1.5** *Scarifiers*—Scarifiers, sometimes called milling machines, remove concrete by applying a rotating cutting wheel to the surface. 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. In recent models, however, the cutting head rotates independently usually in a direction producing an upward cutting action on the concrete. Scarifiers range in size from walk-behind units with a 2 or 3 in. (50 or 75 mm) cutting path designed primarily for the removal of pavement markings and surface coatings to track-mounted units that weigh in excess of 100,000 lb (45,000 kg) with a cutting head up to 14 ft (4.3 m) wide.

Figure 3.4 shows a boom-mounted, twin-drum rotary head cutter that was adapted in the mid 1980s from a mining tool to a tool for removal from mass concrete structures. Figure 3.5 shows a single-drum cutter (planer) used for removal from horizontal surfaces. Both the units utilized tungsten-carbide bits.

Scarifiers are widely used in bridge rehabilitation, especially to prepare the concrete surface before the application

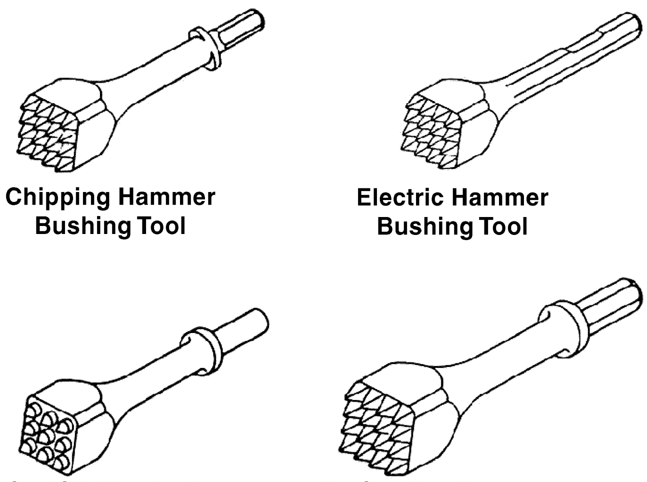


*Fig. 4.2—Bush hammers.*

of a concrete overlay. The single largest problem in using a scarifier on reinforced concrete is in areas of low concrete cover, where the scarifier may rip out the reinforcing bars, and the unit may be damaged. Scarifiers are not suitable for vertical or overhead surfaces, except for boom-mounted rotary head cutters that have been used to remove concrete from lock chambers and wall faces.

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, by a profile line. The surface roughness is determined by the spacing and shape of the teeth matched to its use, such as removing various surfacing, cleaning, and light or heavy milling. The teeth, which usually have tungsten carbide tips, wear out and should be replaced, sometimes after only a few hours of use.

Scarifiers are noisy, and some machines may create significant vibration. The larger machines are equipped with water tanks for cooling bits (preventing thermal damage) and conveyor systems for loading the scarified material directly into trucks. The use of water can result in a tightly adhering layer of surface dust that is difficult to remove.

Milling is a capital-intensive method of concrete removal using high-production machines to strip contaminated and deteriorated concrete from above the reinforcing steel. Milling machines are ideally suited to bridge deck rehabilitation projects requiring the removing of large volumes of concrete. Their inability to remove deteriorated concrete from below the reinforcing steel or from inaccessible areas such as at joint faces, drains, or around other obstacles means that methods such as pneumatic breakers are invariably required to support the operations and complete the detail work. Vorster et al. (1992) presents a detailed description of milling operations.

**4.3.2** *Particle impact removal*—A feature of systems involving particle impact is that removal is predominantly by abrading of the mortar phase of the concrete. Therefore, two aspects are:

Fig. 4.3—Shotblasting.

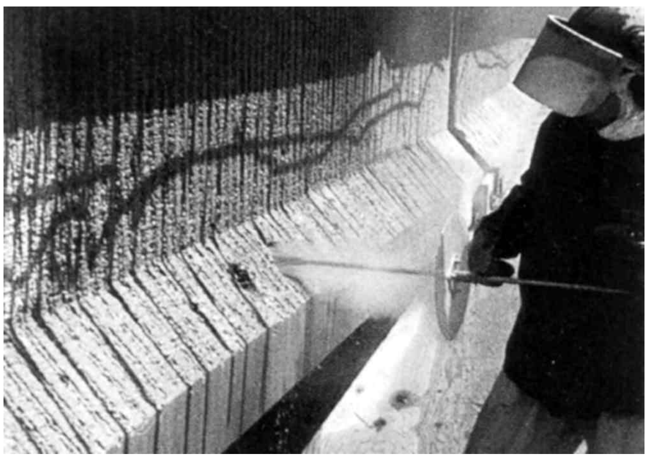

Fig. 4.4—High-pressure water lance.

- The resulting relief is much higher; and
- There is a tendency to be self-inspecting with regard to removal of softer areas because these naturally are removed deeper with the same effort.

**4.3.2.1** *Shotblasting*—A shotblasting machine (Fig. 4.3) may be manual or self-propelled. The abrasive used is steel shot. The shot is propelled by a rotating wheel that hits the concrete surface and rebounds into a recovery unit. A vacuum system collects dust and shot. Shot is separated by a magnet and removed. A magnetic broom can be used to pick up stray shot.

Cut depth is determined by size of the shot (for example, 0.05 in. [1.3 mm] diameter for concrete removal, and 0.02 in [0.5 mm] for removal of the surface skin only.) One manufacturer recommends selection of shot size as shown in Table 4.1.

The advantages of this method of removal are good dust control, little vibration and lack of major cleanup. Variable surface profiles can be obtained with the range of shot sizes.

**4.3.2.2** *Sandblasting*—Sandblasting is the traditional method of concrete surface preparation but its use has been reduced because of concern over environmental and health aspects. Wet sandblasting, in which water is injected into the abrasive stream, can be used to correct the dust problem but the efficiency of removal is reduced.

Fig. 4.5—Tractor-mounted hydromilling of bridge deck.

**Table 4.1—Steel shot selection**

| Diameter, in. (mm) | Profile | Application |
|---|---|---|
| 0.017 (0.43) | Very fine | New concrete |
| 0.023 (0.58) | Fine-medium | Concrete sealer; thin paint coats |
| 0.028 (0.71) | Fine-medium | Thin urethane coats |
| 0.033 (0.84) | Medium | Thick buildup; thick urethane removal |
| 0.039 (0.99) | Coarse | Heavy buildup; epoxy profile |
| 0.046 (1.17) | Extremely coarse | Removing 1/8 to 1/4 in. (3 to 6 mm) of surface |

Grit for sandblasting ranges from natural sand to slag, the latter now preferred because of superior hardness and particle shape.

Sandblasting is versatile. A range of relatively fine surface profiles can result depending on the grit used and the hardness of the mortar phase. Bruising is not a problem.

Good surface preparation can be achieved with sandblasting; however, its use is normally confined to small areas or cases where access for other systems is difficult. Sandblasting is an effective method of simultaneously cleaning corrosion product from reinforcing steel and preparing adjacent concrete surfaces in rehabilitation work.

**4.3.3** *Hydrodemolition*—Hydrodemolition (Fig. 4.4 and 4.5) is also called water-jet blasting, hydromilling, or power washing. It is generally used for surface preparation when the existing steel reinforcement is to be reused in the repair (Fig. 3.14) and where access and presence of washwater permit.

Equipment ranges from hand-held wands to large tractor-mounted units or others on remote operated rails.

The effectiveness of a particular system is dependent on:

- Nozzle type (Fig. 4.6);
- Nozzling pattern and distance to surface;
- Water pressure; and
- Contact time.

The water jet accomplishes its destructive action by means of three separate mechanisms: (1) direct impact, (2) pressurization of cracks, and (3) cavitation (Medeot 1989). These three processes reach their maximum efficiency when the water jet strikes the concrete paste. The nozzle is thus played rapidly and continually over the area to be removed and ex-

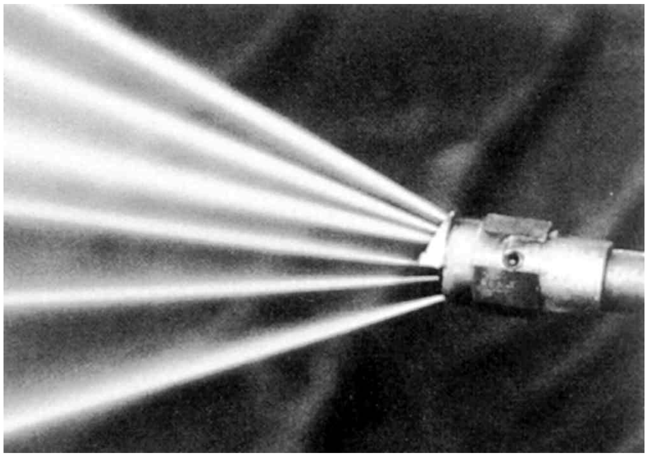

*Fig. 4.6—Hydromilling nozzle.*

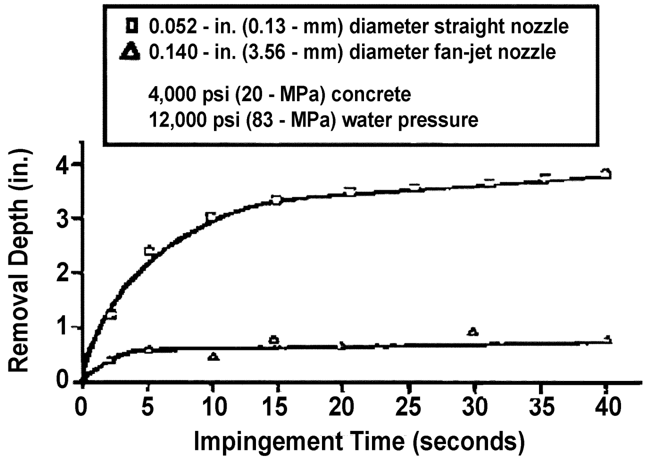


*Fig. 4.7—Effect impingement time on removal depth. (Note: to convert in. to mm, multiply by 25.4.)*

cess water allowed to drain away. Jet efficiency is maximum when the jet itself is stable, and stability is determined by shape and configuration of feeding pipe and nozzle, exit speed of water, and distance from point of impact.

Simply stating an operating pressure of a certain amount, as is commonly done, is not sufficient. For major or deep removal, operating pressures vary among manufacturers. One system may operate at a pressure of 17,000 psi (120 MPa) and a flow rate of 40 gpm (150 L/min), and another at a pressure of 35,000 psi (240 MPa) and a flow rate of 20 gpm (76 L/min). Units having pressures up to 50,000 psi (340 MPa) are reported. If the pressure is less than 10,000 psi (70 MPa), surface cleaning rather than removal is generally achieved.

Hydrodemolition can readily remove up to 3/4 in. (20 mm) of good quality concrete. It is possible to calibrate gang-mounted water jets for a particular depth of removal by adjustment of the four factors noted previously. Variations will be experienced, however, if there is a variation in concrete strength. Figure 4.7 illustrates the affect of impingement time on removal depth.

As with particle impact systems (see Section 4.3.2), hydrodemolition is, to a degree, self-inspecting with regard to removal of softer or unsound concrete. Residual protruding aggregate may require separate removal.

**4.3.4** *Microwave heating*—The microwave heating method results in removal of shallow spalls and this method has potential use for removing contaminated concrete surfaces (Kasai 1988).

**4.3.5** *Comparison of systems and combined systems*—The research work by (Vorster et al. 1992), although focused on bridge rehabilitation, is relevant to this report. Concrete removal techniques studied were pneumatic breakers, milling machines, and hydrodemolition. It was found that each of these methods are, in fact, not competitors in any given task, and each has both strengths and weaknesses. Pneumatic breakers are extremely flexible in terms of size and depth of removal tasks to which they are suited; they are also the most expensive of the three techniques. Although milling is the cheapest on a unit cost basis, it is the most inflexible, as it can only be used to remove concrete above the reinforcing steel on large horizontal surfaces. Hydrodemolition is relatively inexpensive; it is flexible with regard to depth of removal, but is limited to large horizontal surfaces and resulting environmental impact of wastewater.

## 4.4—Definition of final surface

**4.4.1** *General*—The required features of the completed surface removal will include one or a combination of:

- Profile or planeness;
- Elevation or face dimension;
- Degree of aggregate exposure or depth of relief; and
- Degree of microcracking in surface.

Some of these can be defined with a reasonable degree of definition and tolerance, but most are subjective and difficult to define and therefore become the subject of contract disputes.

**4.4.2** *Specification systems*—There are two basic approaches to specifications: performance specifications, and prescriptive specifications. In the former, the contractor is told what is required as the final surface, how it is to be measured, and what will be the criteria for acceptance. In the latter, the contractor is told how to do the work, such as type of equipment to use, procedures to follow, or both, and is given a general definition of final surface requirements. Items such as measurement or acceptance may be included in the recipe method, but are often not. The performance approach is recommended where practical.

**4.4.3** *Use of job-site mock-up*—Regardless of the approach to specifications, it is strongly recommended that an on-site qualification mock-up be constructed. Once approved, this forms the reference for acceptability of the features in Section 4.4.1. Such mock-ups can be conducted as separate assemblies or integrated into the initial work. To be meaningful, the mock-up should be prepared with the same workmen and equipment as is to be used for the actual construction. Therefore, the test area should be of sufficient size to make this workable.

**4.4.4** *Some approaches to specification*—The following are approaches that have been used by specifying authorities. Most are intended to apply to formed or finished concrete surfaces, so their use in specifying surface conditions after removal may require modification.

**4.4.4.1** *Planeness horizontal*—The methods of specifying planeness of horizontal surfaces (flatness and levelness) are probably better developed than the other surface features. Methods include the use of incremental measurements (F-Number System) and the straight-edge (ACI 117). Flooding and observing water ponding can also be effective for some flat work. Procedures for measuring planeness using incremental measurements (F-Number System) can be found in ASTM E 1155.

The straight-edge can provide reasonable control of planeness if:

- Extremely fine tolerances are not required; and
- The method of use is defined. This includes length of straight-edge, frequency and orientation of application, and method of support (end blocks or resting on high spots). ACI 301 provides guidance.

**4.4.4.2** *Planeness, vertical*—String lines or straight-edges are satisfactory if method of use is defined.

**4.4.4.3** *Surface texture*—The surface texture is one feature that suffers from subjectiveness. If light removal by hand tools, power tools, or sandblasting is specified, the Steel Structural Painting Council (SSPC) Standards, SP2, SP3, or SP6, respectively, may be used. While the depth of removal is often specified, it is difficult to measure to any degree of accuracy.

Surface texture has been specified by these crude removal facets:

- Surface skin removal;
- To a depth of mortar (that is, no exposed aggregate); and
- To a degree of exposure of coarse aggregate particles.

In all cases, agreement on the designer's needs and contractors performance can only be reached by the mock-up approach described in Section 4.4.3.

One unique method of quantifying horizontal surface texture (ASTM E 965) is to pour a given volume of dry sand (usually one-size silica sand) onto the surface and determine, when spread with a squeegee, what area it covers.

**4.4.4.4** *Cleanliness*—It is common in specifications to require surfaces to be "clean." Gaul (1984) and ASTM D 4258 provide information on cleanliness before coating application.

A simple, practical test for cleanliness is to wipe a dark cloth across the concrete surface; there should be no evidence of white powder on the cloth. Oily surfaces may be detected by sprinkling water and observing if droplets are formed.

**4.4.4.5** *Soundness of surface*—A common specification clause in remedial work is to remove "...all unsound concrete...," which is far from definitive but understood to generally mean all voided or cracked concrete obvious by visual examination or sounding. Unfortunately, this will not address any concrete that contains microcracks bruised as a result of the removal process. In a practical sense, a sound surface is one that will resist stress that may be exerted by the repair material, be it from shrinkage during curing, differential thermal strains, or structural loading.

## 4.5—Requirements for surface preparation

ASTM has a number of standards and test methods relevant to surface preparation. Their scope is summarized as follows:

- ASTM D 4258—This practice includes surface cleaning of concrete to remove grease, dirt, and loose material before the application of coatings. Procedures include broom cleaning, vacuum cleaning, air-blast cleaning, water cleaning, detergent water cleaning, and steam cleaning. This practice is not intended to alter the surface profile of the concrete but to clean the surface.
- ASTM D 4259—This practice includes surface preparation of concrete before application of coatings and it recognizes the three generic types of surface removal—mechanical, water-jet blasting, and abrasive blasting. The acceptance is based on visual examination and an optional pull-off test for coatings (D 4541). Interestingly, D 4259 suggests that water-jet blasting is for cleaning while other methods are for abrading. In fact, current practice in the industry is to use water-jet blasting (hydromilling) extensively for removal, probably more so than the other two methods.
- ASTM D 4260—This practice includes surface preparation of concrete to prepare the surface before application of coatings, and it is intended to alter the surface profile of the concrete and to remove foreign materials and weak surface laitance.
- ASTM D 4541—This test method covers a procedure and apparatus for evaluating the pull-off strength (commonly referred to as adhesion) of a coating by determining either the greatest perpendicular force (in tension) that a surface area can bear before a plug of material is detached, or whether the surface remains intact at a prescribed force (pass/fail). Failure will occur along the weakest plane within the system comprising the test fixture, adhesive coating system, and substrate that will be exposed by the fracture surface. This test method directly measures tensile stress as compared to the shear stress tested by other methods, such as scratch or knife adhesion, and results may not be comparable. The apparatus is shown in Fig. 4.8.

## 4.6—Concrete pavement surface removal

The purpose of concrete pavement surface removal may be:

- To correct skid resistance of rutted or polished surfaces; or
- To remove unsound concrete surface layers.

Systems used generally involve mechanical removal (see also Section 4.3.1). One system uses wet cutting with diamond blades (Fig. 4.9).

Concrete road surfaces can be provided with narrow groove patterns (0.16 in. [4 mm] wide, 0.16 in. [4 mm] deep, and spaced 3/4 to 1 in. [20 to 25 mm] apart) by wet cutting with diamond blades. Grooving by dry milling is not recommended, as this tends to cause structural disintegration of the ridges between the grooves.

It is also possible to extend pavement service life by removal of a deteriorated surface. Highway grinding may be considered where no more than 10% of the slabs need full-depth replacement and where the surface damage does not exceed about 0.67 in. (17 mm) in depth. Where these conditions apply, restoration is generally more economical than an overlay of asphalt or concrete, or full replacement of the road surface. Most concrete roads can be ground at least once as the majority of highway grinding operations removes only 0.08 to 0.12 in. (2 to 3 mm) of concrete. In general, surface improvement is the most cost-effective alternative for pavements that are structurally adequate and do not have concrete durability problems.

## 4.7—Influence of surface conditions on bond properties

**4.7.1** *Related research*—Felt (1956) concluded that surface texture does not have a predictable or consistent influence on bonding. For example, he obtained poor results on sandblasted surfaces where the effect of the sandblasting was to polish the surface. Felt concluded that factors influencing bond of new and old concrete were not easily isolated and controlled. The most important factor was the condition of the old surface—its cleanliness, roughness, and strength or soundness. If the surface was clean, slightly rough, and free of weak outer skin, good bond was generally obtained; otherwise, relatively poor bond was obtained.

Talbot (1993) assessed the bond of shotcrete to concrete surfaces prepared with various procedures—sandblasting, chipping with jackhammers, grinding, or hydrodemolition. It was concluded that the type of surface preparation has a strong influence on the strength and durability of the bonding, and that hydrodemolition is probably the best type of surface preparation. The shotcrete mixture composition, however, was found to have relatively little influence on bonding. Talbot assessed both wet-mix and dry-mix shotcretes and found little difference in the bond strengths. The assessment was based on pull-off tests described in CAN/CSA A23.2-6B (Section 4.7.2). Talbot's data also showed that there can be some reduction in bond strength with time (tests between 2 and 6 months).

Hindo (1990) reported a pull-off test apparatus similar to the CSA test procedure described in Section 4.7.2 was used to compare the bond strength developed between jack-hammering and hydrodemolition. He found significantly higher bond strengths were obtained by hydrodemolition and attributed it to the following:

- Lack of a bruised layer;
- Irregular, wavy surface profile;
- Increased number of micropores; and
- Greater surface area.

The paper by Hindo contains some micrographs that show the bruised layer phenomenon, and concludes that "The use of pneumatic hammers for concrete removal and surface preparation should be discouraged and replaced where applicable with a hydrodemolition method."

Hindo's data show bond strengths approximately 125 psi (0.86 MPa) by the jackhammering method, and 200 psi (1.38 MPa) by the hydrodemolition method. With both procedures, failures frequently occurred below the bond interface. In effect, it was largely the base concrete tensile strength that was being assessed, and therefore the significant effect of the subsurface microcracking on bond strength.

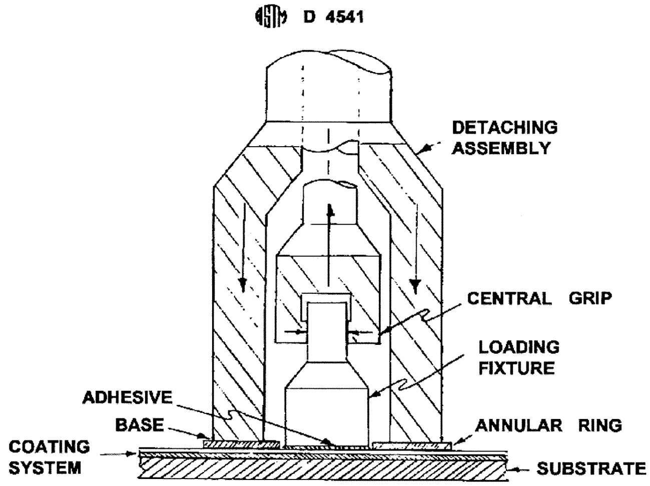


*Fig. 4.8—Schematic pull-off adhesion tester (ASTM D 4541).*

*Fig. 4.9—Pavement grooving.*

**4.7.2** *Test procedures*—A number of pull-off test procedures have been suggested. Most are based on the "over core" approach. A specified standard test procedure is presented in CAN/CSA A23.2-6B. Figure 4.10 shows cores from pull-off testing.

ASTM D 4541 for determining the bond strength of coatings applied to concrete is described in Section 4.5.

**4.7.3** *Specifications*—ACI 503 recommends a pull-off strength of 100 psi (0.7 MPa) for epoxy-based mortars. CAN/CSA A23.2 recommends 145 psi (1.0 MPa) for bonded toppings when tested to the procedures described in CAN/CSA A23.2-6B.

Results reported in the literature range from 40 to 600 psi (0.4 to 4.1 MPa). Higher values often are associated with failure in the base concrete, whereas lower values are asso-

*Fig. 4.10—Pull-off test core failures.*

ciated with failure at the bond line. A high degree of variability in pull-out bond test results is to be expected.

## CHAPTER 5—PRODUCTION OF CONCRETE FROM RECYCLED CONCRETE

### 5.1—Introduction

The problem facing most urbanized nations is the decline of available disposal sites. These sites are declining for a variety of reasons, especially environmental. In many urban areas in the United States, existing disposal sites are being exhausted. Also, sources of good quality aggregates are rapidly becoming depleted. Reuse of concrete as aggregates is a process whose time has arrived.

This chapter discusses some of the considerations for evaluating and processing waste concrete for production of aggregates suitable for reuse in concrete construction.

### 5.2—Aggregate production process

**5.2.1** *Site*—Production of recycled concrete begins at the demolition site. In general, concrete pavements are first broken into about 24 in. (600 mm) pieces with a large hydraulic hammer. Then the pavements are broken up with a large hooked instrument (called a rhino-horn, due to its shape) mounted on a rubber-tired loader or excavator in lieu of the standard bucket. As the hook is pulled through the pavement the slabs are broken up and most of the reinforcement is removed. Demolition of elements from buildings or other structures are generally first broken with vehicle-mounted impact hammers. Once a rubble pile is produced on the ground, hydraulic breakers can be used to reduce the rubble to a suitable size for further handling.

Hydraulic shears and torches are used to remove 90 to 95% of the reinforcement. The remaining steel is removed from the concrete at the final processing plant. Jaw-type crushers have proven successful for processing materials with steel in them. The steel itself is also recyclable.

Demolished concrete is then loaded into trucks and transported to a plant for further processing. This plant may either be directly associated with the specific demolition and removal construction, or may be a separate entity set up to dispose of the concrete, similar to facilities for recycling aluminum cans.

**5.2.2** *Plant operation*—Upon arrival at the plant, the concrete will either directly enter the crushing and reprocessing operation, or it may be broken down further with hydraulic breakers mounted on tracked or wheeled excavators. There are standard attachments available for most varieties of excavators. The preferred method of reducing the primary waste feed is to process it through a jaw crusher.

The unprocessed material that is generally in the range of 12 to 16 in. (300 to 400 mm) is reduced to 2-1/2 to 3 in. (64 to 76 mm). After discharge from the first crushing operation in the plant, the remaining reinforcing steel can easily be removed with a self-cleaning magnet run over the product. The product is then further reduced with a smaller jaw crusher, cone crusher, or impact crusher to produce a finished product of 3/4 to 1 in. (19 to 25 mm) top-size. The final aggregate produced normally has less than 2% passing the No. 200 (0.75-mm) sieve (Hansen 1986).

After the reinforcement is removed, pavement concrete is relatively clean. But this is not the case with all demolished concrete. Once the steel is removed from the concrete, there is still no guarantee that the material produced will be of suitable quality for use as concrete aggregates. Other contaminants may still be present in the material and should be removed. These contaminants could include plaster, wood, plastic, oil droppings, and other nonmetallic building materials. Salt-contaminated pavement concrete should not be used as recycled aggregates for reinforced concrete to be exposed in a moist environment. Larger particles can be removed by hand or mechanical implements, but additional dry or wet processing will be necessary to remove all of the potential contaminants. A pilot study carried out in Denmark showed that, when properly organized, demolition rubble can be sorted on site and sold as economically as disposal of all the debris (Hansen 1986).

**5.2.3** *Plant design*—Plants for processing recycled concrete are very similar to those plants where virgin materials are processed. The effects of processing, handling, and beneficiation are discussed in ACI 221R. Almost the same equipment is used with only minor variations for the removal of contaminants that are not usually found in regular aggregate deposits. The aggregate processing plant may be either an open or closed system. The closed system is preferred because it allows greater control over the maximum particle size produced. It produces a higher uniformity to the finished product (Hansen 1986). Typical schemes for aggregate processing are shown in Fig. 5.1 and 5.2. These diagrams represent what are referred to as "first-generation plants." Second-generation plants are capable of handling debris and removal of unsuitable materials. The flow diagram for a typical second-generation plant is shown in Fig. 5.3.

**5.2.4** *Crushers*—Jaw crushers provide the particle-size distribution of recycled aggregate required for quality concrete production. Cone crushers can be effectively used on concrete up to 8 in. (200 mm) maximum feed size. Swing hammer mills are seldom used. Impact crushers supply better particle-size distribution for road construction purposes and they are less sensitive to material that cannot be crushed such as reinforcing bars (Commissie voor Uitvoering van

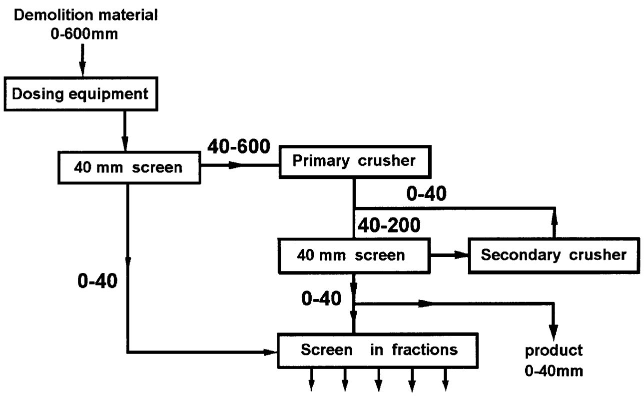


*Fig. 5.1—Flow chart of typical plant for closed system production of recycled aggregate from concrete debris that is free from foreign matter. (Note: to convert mm to in., divide by 25.4.)*

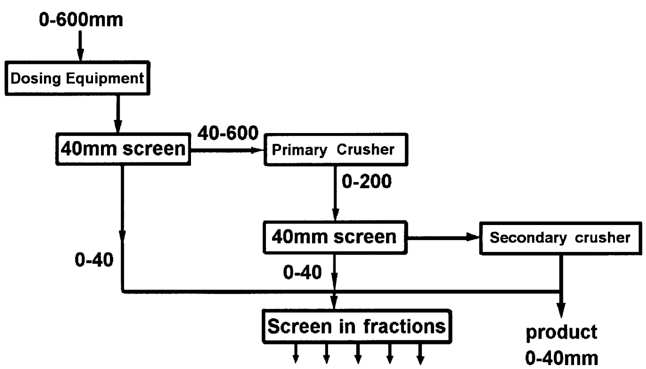


*Fig. 5.2—Flow chart of typical plant for open system production of recycled aggregate from concrete debris that is free from foreign matter. (Note: to convert mm to in., divide by 25.4.)*

## Table 5.1—Overall grading of crusher products

| Sieve openings, in. (mm) | Amount finer than each laboratory sieve, mass percent |
|---|---|
| > 1.5 (37.5) | 97 |
| 1.5 (37.5) | 68 |
| 1.0 (25.0) | 53 |
| 0.75 (19.0) | 34 |
| 0.50 (12.5) | 26 |
| 0.38 (9.5) | 13 |
| 0.19 (4.75) | 0 |

Research [CUR] 1983). Impact crushers not only break up the concrete but will also break the aggregate particles (Building Contractors Society of Japan 1978).

If demolition waste is to be recycled, methods of demolition should be used to reduce the maximum particle size to approximately 48 in. (1200 mm) for fixed plants and 16 to 28 in. (400 to 700 mm) for mobile plants.

**5.2.5** *Processing and beneficiation*—Most fine impurities, such as dirt, gypsum, and plaster, can be eliminated by screening. Nix (1984) reported that most lightweight materials were removed from crushed debris and brought to acceptance by wet screening process. Heimsoth (1984) claimed that the same was achieved by dry screening process when

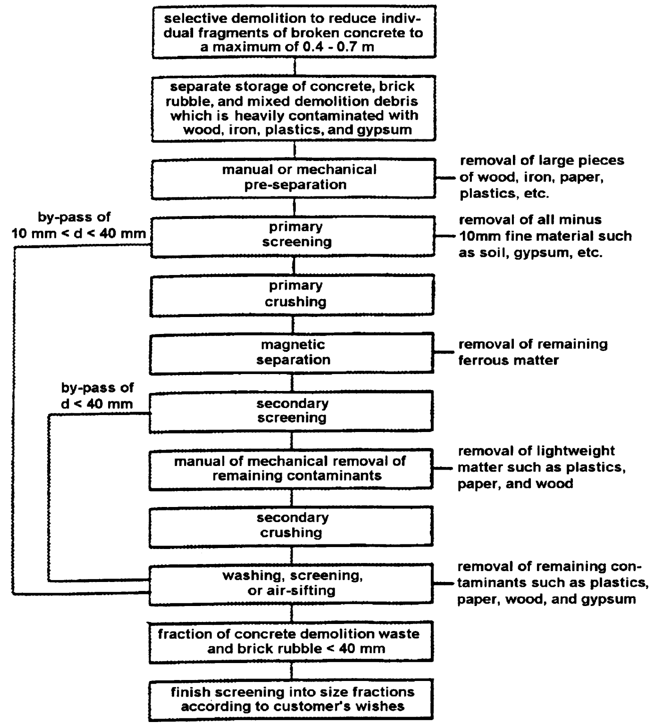


*Fig. 5.3—Processing procedure for building and demolition waste. (Note: to convert mm to in., divide by 25.4.)*

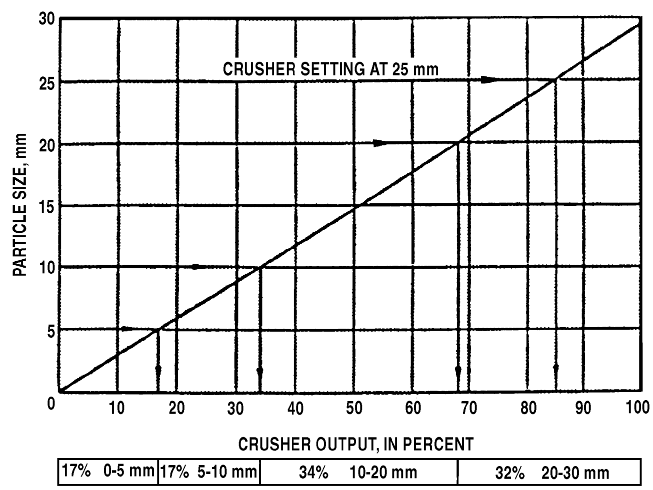


*Fig. 5.4—Correlation between crusher setting and particle size distribution of crusher products. (Note: to convert mm to in., divide by 25.4.)*

impurities are heavier than water. Other beneficiation separation devises for removing lightweight contaminants can be found in ACI 221R.

**5.2.6** *Grading of crusher products*—The material sizes produced in crushers are assumed to have a linear particle-size distribution as shown in Fig. 5.4. This is never actually the case. Concrete reduced by a jaw crusher set to an opening of 1 in. (25 mm) normally supplies a product as shown in Table 5.1.

## 5.3—Aggregate quality

**5.3.1** *Aggregate size*—Once the materials have been processed, they should be sized for proper use. Hansen (1986)

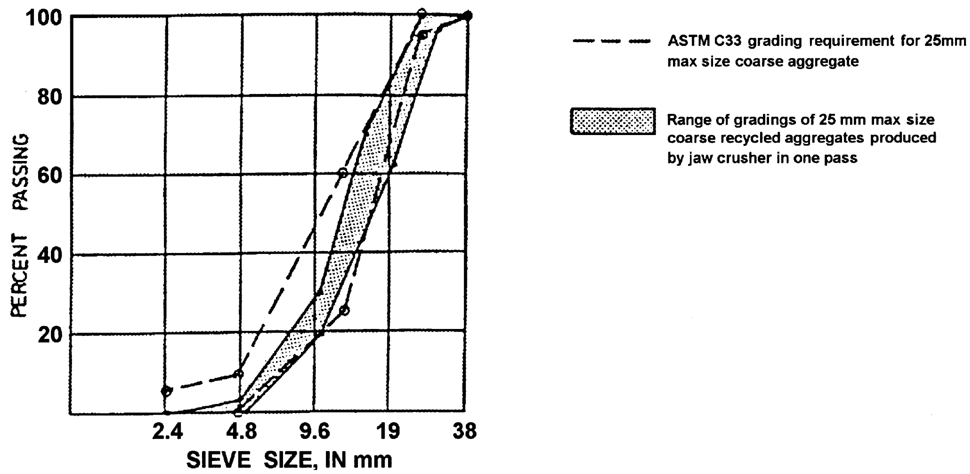


*Fig. 5.5— Range of gradings of 1 in. (25 mm) coarse, recycled aggregates produced by jaw crusher in one pass. (Note: to convert mm to in., divide by 25.4.)*

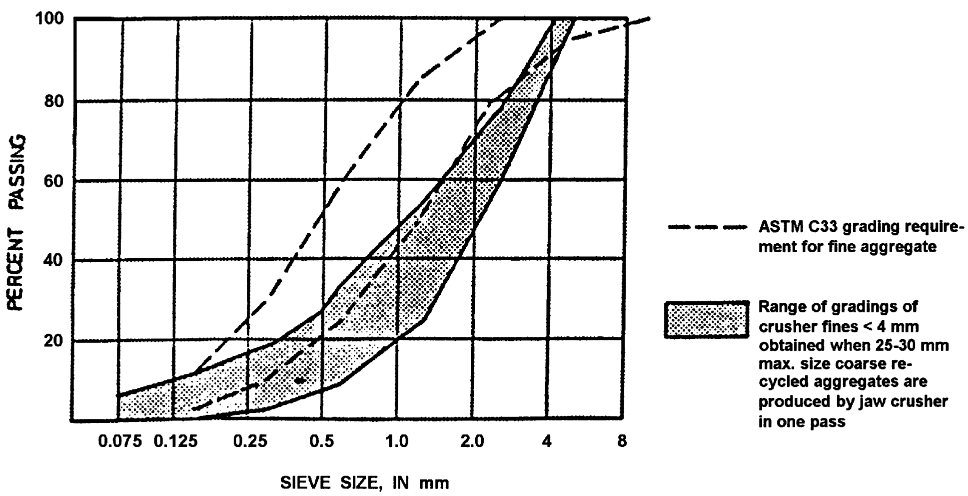


*Fig. 5.6— Range of gradings of crusher fines < 0.157 in. (4 mm) obtained when 1 to 1.2 in. (25 to 30 mm) maximum size coarse, recycled aggregates are produced by jaw crusher in one pass. (Note: to convert mm to in., divide by 25.4.)*

reported analysis of data from two studies where coarse aggregates were produced. After screening on a No. 4 (4.75 mm) screen, the products produced are shown in Fig. 5.5. Hansen (1986) concluded that both aggregates meet the specification range by adjusting the setting of the crusher opening, and that it is reasonably easy to produce acceptable coarse aggregates from recycled concrete.

An investigation was made into fine aggregate production where data from three different investigations produced materials falling within the area shown on Fig. 5.6. These materials are coarser than those specified for ASTM C 33. In fact, they are coarser than generally all standard sands used in production of concrete. Hansen (1986) concluded that recycled fine aggregates, as they come from the crusher, are somewhat coarser and more angular than that needed to produce good quality concrete. Also, the results of these studies indicated that this coarseness and increased angularity are the reasons that concrete made with these materials tend to be somewhat harsh and unworkable. Adding a portion of a finer natural blending sand to the recycled sand can produce materials with suitable concrete making properties (Hansen 1986).

Additional areas of concern are the percentage of fine particles remaining in the aggregates. A number of studies have been performed to determine the amount of fine materials retained on coarse aggregate fractions. Hansen (1986) concluded that most recycled aggregates could be used without washing.

**5.3.2** *Density*—Recycled aggregates generally had densities slightly less than the original materials used. This is a result of the low density of the cement mortar that remained attached to the aggregates (Building Contractors Society of Japan 1978; Hansen 1986). Variations in water-cement ratios of the concrete do not appear to have a significant impact on the densities (Hansen 1986).

**5.3.3** *Water absorption*—One of the most marked physical differences between recycled aggregates and virgin aggregates is higher water absorption. The Building Contractors Society of Japan (1978) and Hansen (1986) concluded that the higher water absorption of the coarse aggregates is a re-

**Table 5.2—Volume percentages of impurities***

| Impurities | Lime plaster | Soil | Wood (Japanese cypress) | Hydrated gypsum | Asphalt | Paint made of vinyl acetate |
|---|---|---|---|---|---|---|
| Percent of aggregate by volume | 7 | 5 | 4 | 3 | 2 | 0.2 |

*Resulting in 15% or greater reductions of compressive strength as compared to control concrete.

**Table 5.3—Maximum allowable amounts of deleterious impurities in recycled aggregates**

| Type of aggregate | Plasters, clay lumps, and other impurities of densities < 3300 lb/yd$^3$ (1950 kg/m$^3$), lb/yd$^3$ (kg/m$^3$) | Asphalt, plastics, paints, cloth, paper, wood, and similar material particles retained on a 0.047 in. (1.2 mm) sieve (also other impurities of densities < 2000 lb/yd$^3$ [1200 kg/m$^3$], lb/yd$^3$ (kg/m$^3$) |
|---|---|---|
| Recycled coarse | 17 (10) | 3 (2) |
| Recycled fine | 17 (10) | 3 (2) |

sult of the absorption of the old cement mortar attached to the aggregate particles.

**5.3.4** *Los Angeles abrasion loss*—ASTM C 33 indicates that aggregates for use in concrete construction should have abrasion loss of less than 50% for general construction and for crushed stone used under pavements should have losses less than 40%. Based on data available, Hansen (1986) concluded that recycled concrete aggregates produced from all but the poorest quality recycled concrete can be expected to pass ASTM requirements for concrete aggregates.

**5.3.5** *Sulfate soundness*—Sulfate soundness tests (ASTM C 88) are required by ASTM C 33 and recycled concrete fine and coarse aggregates may be tested by ASTM C 88 to ensure that appropriate resistance to freezing and thawing of the recycled aggregates.

**5.3.6** *Contaminants*—The variety of contaminants that could be found in recycled aggregates as a result of demolition of existing structures can severely degrade the strengths of the concrete made with them. Some of these materials are plaster, soil, wood, gypsum, asphalt, plastic, or rubber. Table 5.2 summarizes strength losses based on inclusion of contaminants in the recycled aggregates. Table 5.3 provides the allowable amounts of deleterious impurities in recycled aggregates (Hansen 1986).

## 5.4—Effects of recycled aggregates on concrete properties

**5.4.1** *Coarse recycled and natural sand*—A number of studies have investigated the strengths of concrete made with recycled aggregates. Most found reductions in strengths from approximately 5 to 24% using recycled aggregates (Hansen 1986). Data are summarized in Fig. 5.7.

Hansen and Narud (1983) found that recycled aggregate concrete obtained approximately the same strengths as the original concrete from they were made. Bernier, Malier, and Mazars (1978) found similar results, except that in the case of high-strength concrete produced from low-strength recycled coarse aggregates, they found that the compressive strength was 39% lower than the high-strength concrete produced from high-strength recycled aggregates. Data are summarized in Table 5.4.

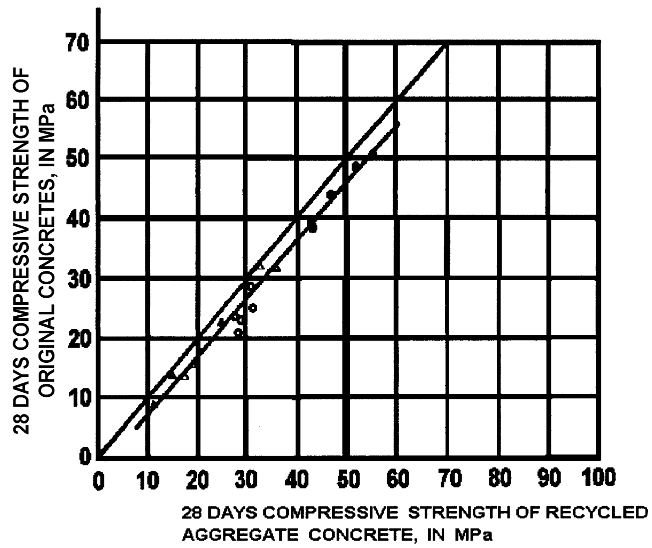


*Fig. 5.7—Compressive strengths of recycled aggregate concretes as a function of the strengths of original concretes. (Note: to convert MPa to psi, multiply by 145.)*

Hansen and Narud (1983) concluded that the compressive strength of recycled concrete depends on the strength of the original concrete and it is largely controlled by a combination of the water-cement ratio (*w/c*) of the original concrete and the *w/c* of the recycled concrete. Reports by Hansen and Narud (1983) and Buck (1976) concluded that higher-strength concrete could be made from recycled aggregates from lower-strength concrete.

**5.4.2** *Coarse and fine recycled aggregates*—Concrete manufactured from both coarse and fine recycled aggregates has been investigated. The majority of researchers found that the compressives strengths for concrete manufactured from recycled coarse and fine aggregates were lower by 15 to 40% of strengths of concrete made with all naturally occurring materials. Blends of 50% natural and 50% recycled sands produced strengths 10 to 20% less than recycled concrete made with all-natural sands. Data from the Building Contractors Society of Japan (1978) are summarized in Table 5.5.

Further examination reveals that certain portions of the fine recycled aggregates appear to inhibit recycled concrete performance. Studies indicate that the majority of strength loss is brought about by that portion of the recycled aggregate smaller than 2 mm. Therefore, the use of any recycled fines in concrete production may be prohibited (Hansen 1986).

**5.4.3** *Strength variations*—Concrete manufactured from recycled aggregates from different sources and different concretes will have greater variations than concrete manufactured from aggregates produced from only one source. De Pauw (1981) found variations in 28-day compressive strengths of 4600 to 7100 psi (31.7 to 49.1 MPa) when concrete of identical mixture proportions were produced from recycled concrete of different sources.

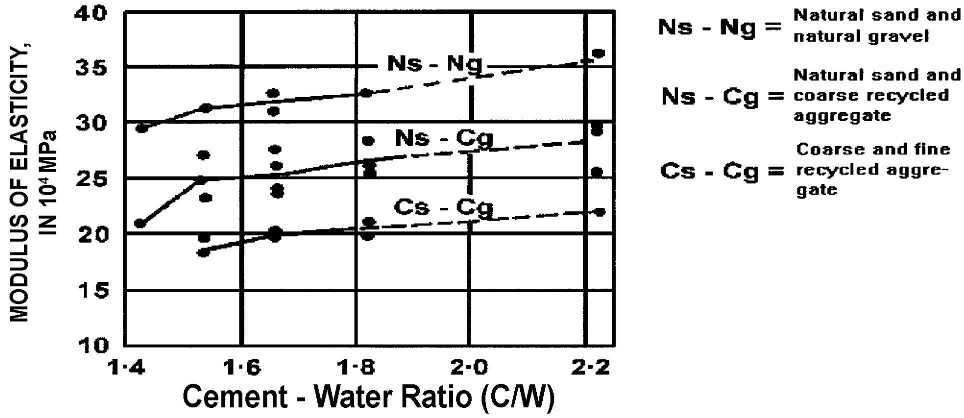


*Fig. 5.8—Modulus of elasticity as a function of water-cement ratio of original and recycled aggregate concrete.*

### Table 5.4—Compressive strength of original and recycled aggregate concrete* (Bernier et al. 1978)

| | Compressive strength of original and recycled aggregate concretes, psi (MPa) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Series | H | H/M | H/M | H/L | M | M/H | M/M | M/L | L | L/H | L/M | L/L |
| 1 | 8178 (56.4) | 8870 (61.2) | 7150 (49.3) | 5020 (34.6) | 4990 (34.4) | 5090 (35.1) | 4780 (33.0) | 3900 (26.9) | 2000 (13.8) | 2150 (14.8) | 2100 (14.5) | 1940 (13.4) |
| 2 | 8870 (61.2) | 8800 (60.7) | — | — | 5220 (36.0) | — | 5250 (36.2) | — | 2100 (14.5) | — | — | 1970 (13.6) |
| 3 | 8480 (58.5) | 8790 (60.6) | — | — | 4810 (33.2) | — | 5220 (36.0) | — | 2180 (15.0) | — | — | 1860 (12.8) |

*After 38 days of accelerated curing.
Symbols H, M, and L indicated original high-strength, medium-strength, and low-strength concrete made with natural gravel. Symbol H/M indicates a high-strength, recycled concrete made with coarse, recycled aggregate produced from medium-strength concrete.

### Table 5.5—Compressive strength of original concrete and recycled aggregate concrete*

| | Compressive strength of concrete, psi (MPa) | | | |
|---|---|---|---|---|
| *w/c* | Natural coarse and fine aggregate (original concrete) | Recycled concrete aggregate and 100% natural sand | Recycled coarse aggregate, 50% recycled fine aggregate, and 50% natural sand | Recycled coarse aggregate and 100% recycled fine aggregate |
| 0.45 | 5440 (37.5) | 5360 (37.0) | 4930 (34.0) | 4350 (30.0) |
| 0.55 | 4190 (28.9) | 4130 (28.5) | 3620 (25.0) | 3120 (21.5) |
| 0.68 | 3190 (22.0) | 3040 (21.0) | 2540 (17.5) | 1880 (13.0) |

*Made from the same original concrete using recycled coarse aggregate and various proportions of recycled fine aggregate and natural sand.

Table 5.6 shows the compressive strengths of recycled aggregate concrete produced from old concrete of various qualities. The standard deviation was 725 psi (5 MPa) and the coefficient of variation was 12% (Hansen 1986). The majority of test data accumulated are based on laboratory tests, and undoubtedly, these variations will increase as more actual field application data are received.

Recycling plants that allow unrestricted input materials will produce concrete aggregates that will have higher variations in quality. The major problem with this is that in order to produce concrete of acceptable quality, greater standard deviations are to be used in preparing concrete mixture proportions. There will also be a corresponding cost increase in the concrete (Hansen 1986).

**5.4.4** *Modulus of elasticity*—Building Contractors Society of Japan (1978) investigated the change in modulus of elasticity of concrete made using recycled concrete aggregates. They reported that the reductions in modulus of elasticity made with recycled coarse and fine aggregates varied from 25 to 40%. They also reported that the reductions in modulus of concrete made with recycled coarse aggregates varied only from 10 to 33%. Typical results from Building Contractors Society of Japan (1978) are shown in Fig. 5.8.

**5.4.5** *Creep*—Various researchers (Hansen 1986) have found creep for concrete manufactured from recycled aggregates to be 30 to 60% greater than for concrete manufactured from virgin materials. These results are not surprising because concrete containing recycled aggregates has up to 50% more paste volume, and creep of concrete is proportional to the content of paste or mortar in concrete.

**5.4.6** *Drying shrinkage*—Concrete made with recycled coarse aggregates and natural sands produced shrinkages of 20 to 50% greater than concrete made with all natural aggregates (Building Contractors Society of Japan 1978). Concrete made with recycled coarse and fine aggregates produced shrinkages that are 70 to 100% greater than that of corresponding natural aggregates (Building Contractors Society of Japan 1978). Hansen (1986) found that shrinkages

**Table 5.6—Compressive strengths of recycled aggregate concrete***

| *w/c* of original concrete | Compressive strength of 15-year-old concrete, psi (MPa) | *w/c* of recycled aggregate concrete | Compressive strength of recycled aggregate concrete at 28 days, psi (MPa) |
|---|---|---|---|
| 0.53 | 10,900 (75.1) | 0.57 | 7120 (49.1) |
| 0.67 | 7470 (51.5) | 0.57 | 5840 (40.3) |
| 0.65 | 8600 (59.3) | 0.57 | 6250 (43.1) |
| 0.80 | 5640 (38.9) | 0.57 | 5510 (38.0) |
| 0.50 | 10,600 (73.1) | 0.57 | 6870 (47.4) |
| 0.59 | 9050 (62.4) | 0.57 | 6280 (43.3) |
| 0.65 | 9850 (67.9) | 0.57 | 6040 (41.8) |
| 0.81 | 6100 (42.1) | 0.57 | 4640 (32.0) |
| 0.50 | 8980 (61.9) | 0.57 | 5770 (39.8) |
| 0.50 | 12,300 (84.8) | 0.57 | 5340 (36.8) |
| 0.53 | 10,600 (73.4) | 0.57 | 4380 (29.7) |
| 0.50 | 9290 (64.1) | 0.57 | 5100 (35.2) |

*Produced from old concrete of various qualities.

were greater for higher-strength concrete than for lower-strength concrete.

**5.4.7** *Tensile and flexural strength*—Various researchers have investigated the effect of recycled aggregates on flexural and tensile strengths. The majority of findings indicates that concrete made from recycled coarse aggregates and natural fine aggregates has generally the same or, at most, a 10% reduction in tensile strength. Generally, concrete made from recycled coarse and fine aggregates has reductions in tensile strengths of less than 10% and a maximum of 20% reduction for the worst case (Hansen 1986). These results contradict information available from Malhotra (1976).

**5.4.8** *Permeability*—Concrete made from recycled aggregates *w/c*s of 0.5 to 0.7, has permeability two to five times that of concrete made with natural aggregates (Hansen 1986). Rasheeduzzafar (1984) found that the low strength and corresponding high water absorption for recycled concrete could be offset by lowering the *w/c* of the recycled concrete by 0.05 to 0.10.

**5.4.9** *Freezing-and-thawing resistance*—Many studies of freezing-and-thawing resistance indicate that there is almost no difference between that of concrete made with virgin aggregates and with recycled aggregates (Hansen 1986). A report by the Building Contractors Society of Japan (1978), however, indicated that concrete made from recycled coarse and fine aggregates had significantly reduced resistance to freezing-and-thawing damage. They also found that if the fine aggregates were replaced with virgin materials, the freezing-and-thawing resistance was comparable to the original concrete. Another Japanese study indicated that air-entrained concrete made with recycled aggregates has less freezing-and-thawing resistance than the concrete made with virgin materials (Hasaba et al. 1981). One of the differences between most of the Japanese and American studies is the quality of the concrete from which the recycled aggregates were made. The American work has been based primarily on recycled pavements while the Japanese work was from fairly low-quality concrete.

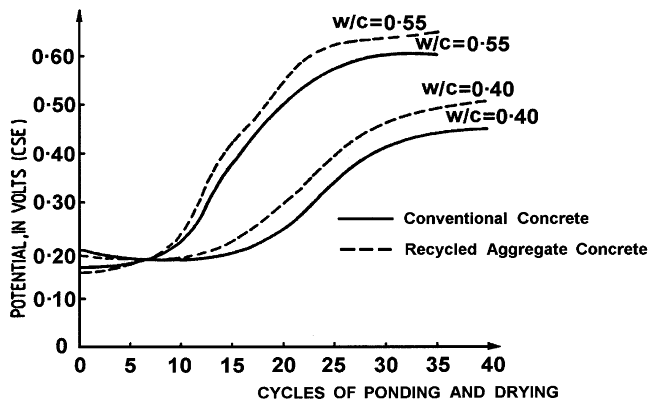


*Fig. 5.9—Half-cell potentials of steel bars embedded in specimens made from recycled and conventional aggregate concretes.*

**5.4.10** *Carbonation, chloride penetration, and reinforcement corrosion*—The Building Contractors Society of Japan (1978) concluded that the rate of carbonation of a recycled aggregate concrete made with concrete that had already suffered carbonation was 65% higher than the control concrete made with conventional aggregates. The Building Contractors Society of Japan also concluded that reinforcement in recycled concrete may corrode faster than in conventional concrete. This accelerated corrosion, however, could be offset by reducing the *w/c* of the recycled concrete. Additional studies by Rasheeduzzafar (1984) confirmed these conclusions. It can be seen in the Fig. 5.9 that a reduction in *w/c* reduces corrosion potential of recycled concrete (Hansen 1986).

## 5.5—Mixture proportions

**5.5.1** *Water-cement ratio*—Selection of the *w/c* is the most critical part of controlling the concrete strength. There is excellent correlation between *w/c* and compressive and flexural strength. Hansen concluded the *w/c* is valid for recycled aggregate concrete as it is for concrete made with virgin materials, but only the level of strength development would be reduced (Fig. 5.10) (Hansen 1986).

To produce a similar workability, Mukai et al. (1979) found that 5% more water was required for a recycled coarse aggregate concrete. Buck (1976) has found that approximately 15% more water was needed to produce the same workability for both fine and coarse recycled aggregate concrete.

Mukai et al. (1979) and Hansen and Narud (1983) found that bleeding from recycled aggregate concrete to be slightly less than that of those using virgin aggregates.

**5.5.2** *Unit weight and air content*—Mukai et al. (1979) and Hansen and Narud (1983) concluded that unit weights of concrete made using recycled concrete as aggregate were within 85 to 95% and 95%, respectively, of the original concrete mixture. Mukai et al. (1979) found that air contents of freshly recycled concrete were higher and varied more than air contents of fresh control mixtures. Hansen and Narud (1983) found that air contents of recycled aggregate concrete were up to 0.6% higher. Hansen (1986) concluded that the air con-

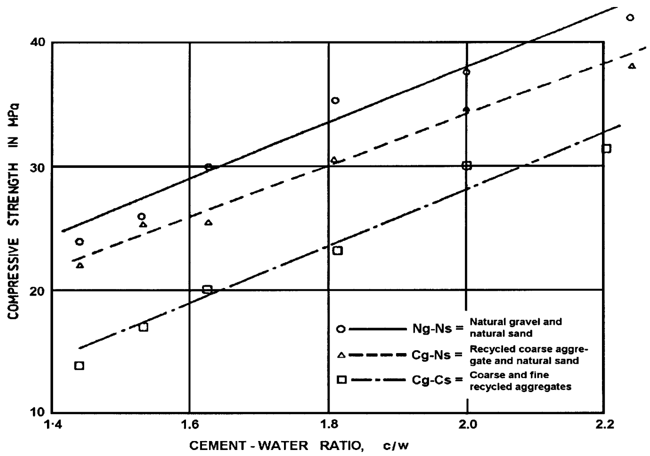


*Fig. 5.10—Relationship between water-cement ratio and compressive strength of concretes made with natural and recycled aggregates.*

tents of recycled aggregate concrete were slightly higher and that densities can be 5 to 15% lower.

**5.5.3** *Fine-to-coarse aggregate ratio*—From the point of view of both economy and cohesion of fresh concrete, Building Contractors Society of Japan (1978) found that the optimum ratio of fine-to-coarse aggregate is the same for recycled aggregate concrete as it is for concrete made from virgin materials (Hansen 1986).

Mixer studies by Kasai (1985) indicate that the fineness of recycled concrete aggregates decreases with time of mixing. This is most likely a result of mechanical removal of cement paste from the recycled coarse aggregates.

**5.5.4** *Mixture proportioning*—The following are guidelines for developing for mixture proportions using recycled concrete aggregates:

- To determine a target mean strength on the basis of a required strength, a higher standard deviation (700 psi [4.83 MPa]) should be used when designing a concrete with recycled concrete aggregates of variable quality than when recycled aggregate of uniform quality or virgin aggregates are used;
- At the design stage, it may be assumed that the *w/c* for a required compressive strength will be the same for recycled aggregate concrete as for a conventional concrete when coarse recycled aggregate is used with conventional sand. If trial mixtures show that the compressive strength is lower than assumed, an adjustment to a lower *w/c* should be made;
- For the same slump, the free water requirement of recycled coarse aggregate concrete is 5% more than for conventional concrete;
- Specific gravity, unit weight, and absorption of aggregates should be determined before mixture proportion studies;
- The mixture proportion should be based on the measured density of the recycled aggregates intended in the job concrete;
- The sand-to-aggregate ratio for recycled aggregate concrete is the same as when using virgin materials; and
- Trial mixtures are absolutely mandatory. If the placing will include confined spaces and irregular form shapes, trial placements should also be included.

## 5.6—Concrete production

Although concrete production (batching, mixing, transporting, and placing) of recycled aggregate concrete is similar to the conventional concrete, additional care should be taken when manufacturing recycled aggregate concrete. The following items are recommended for production of recycled aggregate concrete:

1) An important requirement of all recycled aggregate concrete is presoaking the aggregates to offset the high water absorption of the recycled aggregates (Hansen 1986); and

2) Materials smaller than No. 8 sieve (approximately 2 mm) be eliminated from aggregates prior to production.

# CHAPTER 6—REFERENCES

## 6.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

*American Concrete Institute*

117 Standard Specifications for Tolerances for Concrete Construction and Materials
201.1R Guide for Making a Condition Survey of Concrete
201.3R Guide for Making a Condition Survey of Concrete Pavements
221R Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete
228.R1 In-Place Methods for Determination of Strength of Concrete
301 Specifications for Structural Concrete for Buildings
503R Use of Epoxy Compounds with Concrete
546R Concrete Repair Guide

*American National Standards Institute*

A10.6 Construction and Demolition Operations—Safety Requirements
A10.21 Demolition—Safe Guarding Building Construction and Demolition Operations

*American Society for Testing and Materials*

C 33 Standard Specifications for Concrete Aggregates
C 88 Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
C 457 Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
C 856 Standard Practice for Petrographic Examination of Hardened Concrete

| | |
|---|---|
| D 4258 | Standard Practice for Surface Cleaning Concrete for Coating |
| D 4259 | Standard Practice for Abrading Concrete |
| D 4260 | Standard Practice for Acid Etching Concrete |
| D 4541 | Standard Test Method for Pull-Off Strength of Coatings using Portable Adhesion Testers |
| E 965 | Standard Test Method for Measuring Surface Macrotexture Depth using a Volumetric Technique |
| E 1155 | Standard Test Method for Determining Floor Flatness and Levelness using the F-Number System |

*Canadian Standards Association*

| | |
|---|---|
| A23.2-6B | Method of Test to Determine Adhesion by Tensile Load |

Steel Structures Painting Council

| | |
|---|---|
| SP2-63 | Surface Preparation Specification No. 2, Hand Tool Cleaning |
| SP3-63 | Surface Preparation Specification No. 3, Power Tool Cleaning |
| SP6-63 | Surface Preparation Specification No. 6, Commercial Blast Cleaning |

These publications may be obtained from these organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

American National Standards Institute
1430 Broadway
New York, NY 10018

American Society for Testing Materials
100 Barr Harbor Dr.
West Conshohocken, PA 19428

Canadian Standards Association
178 Rexdale Blvd.
Rexdale, Ontario M9W 1R3, Canada

Steel Structures Painting Council
400 Fifth Ave.
Pittsburgh, PA 15213

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