Guide to Removal and Reuse of Hardened Concrete

Reported by ACI Committee 555

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Synopsis

This guide presents information on removal and reuse of hardened concrete. The applicability, advantages, limitations, and safety considerations of various types of concrete removal methods including hand tools, hand-operated power tools, vehicle-mounted equipment, drills and saws, mechanical splitters, and hydrodemolition are provided. The available surface removal systems, their probable applications, and advantages and disadvantages of various types of surface removal are discussed. Considerations for evaluation and processing of waste concrete for production of aggregates is presented. Use of demolished waste concrete as aggregates in unbound applications and as aggregate in concrete are discussed. Potential impacts of the use of demolished concrete as aggregates in new concrete on mechanical properties and durability are discussed. Several case studies of demolished concrete being used as aggregate in new concrete in pavements, bridges, and building applications are presented.
Keywords: aggregates; concrete removal; demolition waste; recycled aggregate concrete; recycled concrete aggregate; recycled materials; returned concrete aggregate; unbound aggregates.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

With increasing urbanization, population growth, and impacts from natural and human-driven deterioration and damage, the long-term sustainability of concrete infrastructure around the world should be considered across all of its lifecycle stages, including construction, maintenance, repair, and removal. A primary focus of this report is the concrete removal, rebuilding, and decommissioning stages. While traditional concrete removal methodologies and techniques are continuing to be used, new technologies for both the full and partial removal of concrete are being developed and implemented. In addition, driven by economics, resource scarcity, and an overall impetus towards more sustainable construction practices, the recycling and reuse of crushed concrete from a single project (where quality is known) or from collected concrete rubble from mixed sources (where quality is more variable) is becoming more commonplace in the United States, Canada, Europe, and in other countries around the world. Typically, concrete is removed in large chunks or slabs and then crushed, sized, and processed into several sizes. During the process, any reinforcing steel is removed for recycling using magnetic, mechanical, and manual methods.

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1.2—Objective

The objective of this document is to provide a detailed reference for practitioners involved with the design, specification, and facilitation of concrete demolition and removal operations. In addition, this report provides a detailed summary of the state-of-the-art of the production, properties, and use of recycled concrete aggregates (RCA) as an unbound fill or base material and as a full or partial replacement for natural aggregate in new concrete. Another objective of this document is to demonstrate the practical use of these materials by presenting a number of case studies involving the use of RCA in pavement base construction, concrete pavements, architectural concrete, and in other types of reinforced concrete structures.

1.3—Scope

This report comprises two parts: Part 1: Concrete Removal, and Part 2: Concrete Reuse. Part 1 (which includes Chapters 3 and 4) provides information on preremoval structural assessments for specific concrete types/structures, a comprehensive overview of partial and full-depth surface removal methods, and a detailed guidance on undertaking the demolition of concrete structures and pavements. Additional emphasis is placed on how the type of concrete element removed (that is, plain-unreinforced, reinforced, prestressed, and post-tensioned) and its location within a structure directly affect the removal methods and strategy. Selection of proper tools and equipment are critical for ensuring a cost-effective and safe concrete removal project. Part 2 (which includes Chapters 5 through 7) discusses the production and applications of recycled concrete aggregates (RCAs). An extensive overview of durability, mechanical, and environmental-related properties of concrete incorporating RCA as aggregate (RCA concrete) is also presented. The final chapter

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of this report (Chapter 8) presents several case studies where RCAs have been used in pavements
and other structural applications.

CHAPTER 2—DEFINITIONS

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of
definitions. Definitions provided herein complement that resource.

adhered mortar—attached mortar remaining on the original aggregates after crushing of the
original (or recycled) concrete.

natural aggregate concrete—concrete produced using natural (virgin) coarse aggregates.

original aggregates—natural aggregates used to produce the original (or source) concrete from
which recycled concrete aggregate source was derived.

recycled concrete aggregate concrete—concrete produced using recycled concrete aggregate as
a full or partial replacement for natural aggregate.

recycled concrete aggregate—aggregate(s) derived from the crushing and processing of
demolished concrete structures (buildings, pavements, bridges); resulting agglomerate of the
original aggregate and the adhered mortar is the recycled concrete aggregate or recycled concrete
aggregate.

recycled concrete—hardened concrete that has been processed for reuse, usually as aggregate.

residual mortar—attached mortar remaining on the original aggregates after crushing of the
original (or recycled) concrete.

CHAPTER 3—ASSESSMENT OF METHODS FOR REMOVAL OF IN-PLACE
3.1—Introduction
This chapter addresses complete and partial removal of concrete from different types of concrete structures and the related assessment of structures considering safety, stability, cost, constructability, and environmental impact. The partial or complete removal of prestressed, reinforced, and unreinforced concrete structures should be assessed, in all its phases, by a competent and experienced entity. Crushed excess or rejected concrete that is returned to batch plants is not included in this chapter. Such concrete is discussed in Chapter 5.

When partial removal is undertaken, sound concrete should be identified and examined, and consideration should be given to the effect that the removal may have on the remaining concrete and reinforcement. Most importantly, concrete removal or demolition should be performed under appropriate supervision, regardless of the project size.

3.2—Structural Assessment

3.2.1 General considerations—Guidance on performing a condition survey of concrete structures is covered in ACI 201.1R. Listed in the following are other general items to consider prior to either partial or complete concrete removal. It should be noted that, if the decision to undertake concrete removal is based on economics or for reasons other than addressing concrete deterioration
concerns, a detailed condition survey may not be required.

3.2.1.1 Safety—A predemolition structural survey should be performed to determine if the planned work has the potential to cause instability or collapse of the structure. Prior to starting demolition and removal work, a survey of the job site should be completed to determine the safeguards necessary to mitigate hazards and to ensure that work can be performed safely. Continuous checking for hazards that could emerge due to weakening of the structure is required. Appropriate safety regulations and precautions should be followed at all times. Providing overhead protection for falling debris is often necessary.

3.2.1.2 Environmental impact—A work plan requiring the removal of a structure, either partially or completely, should address the impact of the associated removal activities on the surrounding environment. This should consider neighboring tenants and surrounding structures and include noise pollution, dust pollution, water runoff due to work or storms or both, and other factors that may cause environmental concerns, such as the removal of asbestos, mercury, lead paint, and other hazardous substances. An inventory of potential environmental impacts should be developed and used as a checklist during concrete removal operations. Appropriate environmental regulations should be followed at all times.

3.2.1.3 Plans for assessment documentation—During the condition survey of the concrete structure, drawings and sketches need to be prepared that reflect existing conditions. These drawings and sketches become part of the condition survey report to document preremoval conditions.
3.2.1.4 Complete set of structural, architectural, and civil engineering 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. Civil engineering drawings, which identify locations of underground services (that is, gas, water, and electrical), should also be used as needed. 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 safety hazards, environmental impacts, and costly errors. If original drawings are not available or if modifications appear to have been made, spot destructive exploration may be required to ascertain reinforcement location, size, and condition.

3.2.1.5 Budgetary and logistic constraints—Budgetary and logistic constraints should be identified and incorporated into the work plan performance.

3.2.2 Evaluation of concrete—Before a concrete structure is to be demolished, a thorough evaluation is generally needed. ACI 364.1R presents general procedures for the evaluation of concrete structures, including preliminary and detailed investigation, documentation, field observation, condition survey, sampling and material testing, evaluation, and final reporting.

3.2.2.1 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 using visual inspections.

3.2.2.2 Detailed examination

a) Petrography: The usefulness of petrographic examination for the objectives of the investigation proposed or underway can be determined in consultation with a specialist petrographer. ASTM C457/C457M can be used to assess whether the recycled product can...
be resistant to freezing and thawing and explain, if any, why freezing-and-thawing-related damage has occurred. ASTM C856 provides a list of objectives for petrographic examination of concrete as follows:

i. Detailed determination of the condition of concrete in a structure

ii. Determination of inferior quality, distress, or deterioration of concrete in a structure

iii. Determination of whether alkali-silica or alkali-carbonate reaction, or cement-aggregate reaction, or reactions between contaminants and the matrix have taken place, and their potential effects upon reuse of the concrete

iv. Determination of whether the concrete has been subjected to and affected by sulfate attack, other chemical attacks, early freezing, or other harmful effects of freezing and thawing

v. Determination of whether concrete that has been subjected to fire is essentially undamaged, moderately damaged, or seriously damaged

b) Nondestructive testing (NDT): There are numerous NDT methods for estimating the strength of concrete (ACI 228.2R; Malhotra and Carino 2003), some of which are listed below:

i. Surface hardness methods (rebound hammer)

ii. Penetration resistance techniques

iii. Pullout tests

iv. Ultrasonic pulse velocity method

There are also other NDT methods for determining concrete properties other than strength, including:

a) Sounding (hammer or chain dragging) - spalling, delamination, and voids

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b) Magnetic methods (coverters) - reinforcement cover and location

c) Electrical methods (half-cell potential) - reinforcement corrosion, thickness of concrete pavements, moisture content, and moisture penetration

d) Radioactive methods - density, voids, composition, and segregation

e) Ultrasonic pulse velocity and pulse echo techniques – to determine cracks and voids in concrete

f) Nuclear methods – composition, density, and structural integrity

g) Ground penetrating radar methods – reinforcing bar location, concrete thickness, and delamination

h) Infrared thermography methods – delamination and uniformities

i) Impact echo and acoustic emission – delamination, cracks, and uniformities

The aforementioned methods are often used in conjunction to obtain more comprehensive information about structural integrity and extent of any damage. Methods that are used specifically for fresh and early-age concrete properties, such as pull-off tests and maturity tests, are not included herein.

For additional test methods and their application and limitations, refer to ACI 228.2R and Malhotra (1984).

3.2.3 Cause(s) of distress—In developing removal procedures, the cause(s) of distress, if any, should be considered as it may affect the integrity of the structure.

3.2.4 Transport and deposit of concrete rubble—Nearly 400 million tons of concrete construction and demolition waste and debris are generated in the United States each year (Environmental Protection Agency 2016). Due to the declining availability of suitable disposal
sites, recycling such construction and demolition waste as aggregate should be evaluated as an alternative to crushed stone and other virgin aggregate sources.

3.2.2.3 Reporting

3.2.2.3.1 Scope of work—The purpose and limitations of preliminary investigation and findings, concrete removal work plan, safety considerations, schedule requirements, environmental aspects, and recycling plan should be defined.

3.2.2.3.2 Findings—The structure; its present condition; nature of loading; detrimental elements such as asbestos, lead, mercury, polychlorinated biphenyls (PCB), chlorofluorocarbons, and radioactive sources; the original condition of the structure; materials used in construction; and practices used in constructing the structure should be clearly described. Photographs should be used to illustrate the conditions.

3.2.2.3.3 Recommendations—Recommendations should be made for complete or partial demolition, salvage potential, removal methods, safety and environmental considerations, and further investigation or testing as required.

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

3.2.2.3.5 Photographs and drawings—Use of structural, architectural, and civil engineering drawings illustrating the as-built current conditions and areas of concern (for example, concrete quality, distress, loading, and utilities) is needed to demonstrate the need for concrete removal and to justify the recommended method and amount of removal. Photographs can be used to illustrate manifestations of distress and provide documentation of existing conditions. Where possible, some
means for identifying scales, such as including a ruler or other recognized object like a pencil or coin, should be used.

3.2.2.3.6 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 be readily followed. For example, plans could be labeled with symbols identifying where samples or photos were taken, with each sample or photo containing sufficient and concise description. It is essential that the extent of damage, if present, be established. Whether the concrete quality of the remaining structure is adequate to support a sound repair should be determined.

3.2.3 Engineering survey—Prior to starting any demolition operations, an engineering survey of the structure conducted by a competent entity (for example, professional engineer) 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.

3.2.4 Health and safety safeguards—Several measures should be taken to safeguard the health and safety of workers at the job site. These preparatory operations consider the overall planning of the demolition work, 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.
3.3—Types and degree of removal of in-place concrete

3.3.1 Purpose of removal

3.3.1.1 Material conditions—Concrete removal from a structure may be required due to structural distress or materials-related distress, where the integrity of the concrete has deteriorated, or due to the need for upgrading or modification of a structure where sound concrete may need to be removed. In some instances where concrete removal is necessary due to distress, sound concrete may need to be removed for anchoring purposes.

3.3.1.2 Complete demolition—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 a single piece or in multiple pieces for disposal or crushed and reduced to rubble for recycling.

3.3.1.3 Partial removal—When undertaking partial demolition of concrete structures, salvaging or using the remaining intact structure should be properly evaluated. As an example, several replacement scenarios may be considered:

   a) Replace what is removed. A portion of a structure is removed and replaced, considering proper adjustments to the added element to prevent further distress.

   b) 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 the removal of architectural or redundant elements that are not essential to the structural integrity.

   c) Create an 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 depleting suitable disposal sites, renewed interest in sustainability and green concrete waste management has become widespread. In the development of a work plan for concrete removal, recycling of the removed concrete and reinforcing steel need to be evaluated for practicality and economics. Creative reuse of concrete can be both challenging and rewarding. Refer to Chapter 7 of this report for reuse of hardened concrete in the production of concrete.

3.3.2 Degree of removal—Based on the degree of removal, demolition can be categorized as complete demolition or partial demolition. Partial demolition may be performed to correct an alignment defect or other deficiency in new construction or to remove deteriorated concrete in an existing structure. Partial demolition can be further categorized as:

a) Layer (overlay, cover, finish)—A partial demolition layer usually involves removal to a certain depth greater than 1/2 in. (13 mm)

i. Physically defined limit (different mixtures, barrier, material integrity)

ii. Arbitrary limit (specific depth)

i. Surface—A surface demolition usually is a surface removal of less than 1/2 in. (13 mm): Binder and fines only

ii. All constituents

Piece of section can be categorized into:

a) Entire element

b) Portion of element:

i. Physically defined limit (joint, different mixtures, barrier, material integrity)
ii. Arbitrary limit (specified size)

iii. Reinforcement

3.3.3 Types of concrete and effects on removal and reuse

3.3.3.1 General—Concrete structures can generally be classified into four groups: mass concrete structures, underground structures, reinforced concrete structures, and prestressed/post-tensioned structures. With the numerous demolition techniques available (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:

a) Safety,

b) Cost

c) Time limits

d) Quality of concrete and geometry of the demolished concrete

e) Quantities, location, and breaking boundary

f) Aggregate hardness

g) Concrete compressive strength

h) Environmental factors

i) Specific risks

j) Utility locations

k) Adjoining construction

3.3.3.2 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 include explosive blasting, diamond wire sawing, presplitting using nonexplosive

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demolition tools and mechanical splitters, vehicle-mounted impact hammering and rotary head cutting, stitch cutting, and drilling. Other available methods that are less commonly used include remote controlled thermal lance cutting, abrasive water jet blasting, electrical heating of steel reinforcement, and microwave heating of cover concrete.

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

3.3.4 Reinforced concrete structures—Most of the methods discussed in Chapter 4 are applicable to the removal of reinforced concrete structures depending on the type, size, use, and degree of removal.

3.3.5 Prestressed/post-tensioned concrete structures—Prestressed/post-tensioned concrete structural elements may be removed using a thermal lance, hydraulic breaker, drop ball, and jack hammer. 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 (29 CFR 1926:1998). Never allow workers to be near anchorages during any form of removal other than controlled detensioning.

29 CFR 1926 identifies four main categories of prestressed concrete members. The category, or categories, should be identified prior to attempting any demolition while considering that any prestressed structure may contain elements of more than one category. Four separate categories are outlined in the following:

a) Category 1: Members are prestressed before the application of the superimposed loads, and all cables or tendons are fully bonded in the concrete or grouted within ducts.
b) Category 2: Similar to Category 1, but the tendons are left ungrouted. This type of construction could be recognized from the access points that may have been provided for inspection of the cables and anchors. More recently, unbonded tendons have been used in the construction of beams, slabs, and other members; these tendons are protected by grease and surrounded by plastic sheathing, instead of the usual metal duct.

c) Category 3: Members are prestressed progressively as construction proceeds and the dead load increases, using bonded tendons as in Category 1.

d) Category 4. Similar to Category 3 but using unbonded tendons as in Category 2.

Examples of construction using members of Categories 3 or 4 are relatively rare. However, they may be found, for example in the podium of a tall building or some types of bridges. They require special care during their demolition (29 CFR 1926).

3.3.3.6 Pretensioned members—Simple pretensioned beams and slabs of spans up to approximately 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.

3.3.3.7 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. Under these circumstances, it is essential that indiscriminate attempts to expose and destress the tendons and anchorages are not made.
3.3.3.8 Progressively prestressed structures—The methods for removal of progressively prestressed structures should be defined by the professional engineer and shall be strictly adhered to.

3.4—Safety

3.4.1 Methods for monitoring demolition—Because methods of removal are different, a separate analysis should be prepared for each method. Outlined in the following 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 for guidance and are not all-inclusive.

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

   a) Location of utilities and services:
      i. Review locations of all utilities: Whenever operations are required to be within the minimum distances of power lines established in 29 CFR 1926, arrangements should be made to have the line moved or deenergized, to 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 vicinity of any excavation works prior to starting excavation.
      ii. Locate equipment, tool sheds, and offices in a safe and convenient place.
b) Employee access problems are to be resolved by the individual in charge of the project:

i. Adequate work areas

ii. Adequate walkways and runways

iii. Adequate ladders, stairways, or elevators

iv. Work areas and passageways clear of rubbish, debris, and nails

v. Protection of floor and roof openings

vi. Adequate illumination

c) Schedule work for safety:

i. Have safety equipment (hard hats, goggles, ear plugs, trench jacks, safety belts, respiratory protection) on site as needed.

ii. Plan work and coordinate subcontractor activities to avoid site congestion.

iii. Schedule work crews so the flow of equipment and manpower does not create a safety hazard.

iv. Ensure environmentally hazardous materials such as asbestos, lead-based paint, and mercury components are properly removed.

d) Work Procedure:

i. Materials handling:

1) Plan for methods of elevating, lowering, and handling materials (adequate space and proper auxiliary equipment such as cranes, hoists, elevators, and trucks)

2) Plan for methods of loading and unloading (adequate space and proper auxiliary equipment such as loaders, cranes, rigging, and forklifts).

ii. Plan for the use of tools and equipment:

1) Repair, maintenance and care

2) Inspection

3) Adequate supplies of the right tools for each part of the job
3.4.1.2 General safety precautions

a) Every reasonable effort should be taken to ensure the safety of workers in all situations, whether provided for in a company's rules and safety programs or not.

b) 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.

c) Prior to the start of work, the supervisor, safety officer, or both, should survey site conditions for risks or hazards and determine safeguards necessary to accomplish the work in a safe manner.

d) 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.

e) 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.

f) All required safety and health notices should be posted at the job site, as required, or be otherwise available at the site.

3.4.1.3 Safety program objectives

a) To provide a safety and health program consistent with proper construction demolition practices

b) To prevent accidents, injuries, and illness

c) To create an attitude of safety consciousness among general management, field supervision, and all crafts
d) To assign specific responsibilities for effective implementation and continuation of
   the safety program

e) To provide continued development of safety and health education, training, and
   testing

3.4.1.4 Safety program implementation

a) Planning for safety in concrete removal operations through job hazard analysis,
   drawing upon available or hired experience and expertise to anticipate and eliminate
   accident-prone conditions.

b) Providing mechanical and physical safeguards to the maximum extent possible.

c) 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.

d) Training all individuals in proper safety and health practices.

e) Providing necessary personal protective equipment and instructions for its proper use
   and care.

f) Providing a means for employees to inform their supervisors of hazards at the work
   site.

g) Investigating, promptly and thoroughly, every accident to determine the cause(s) and
   correct the problem(s) to prevent its recurrence.

h) Providing first-aid materials and trained first-aid personnel on job sites.

3.4.1.5 Safety program requirements

i. Develop and implement a safety program with rules and assigned responsibilities.

ii. Make these rules and policies known to all employees and subcontractors.
iii. Appoint a safety coordinator.

iv. 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.

v. Provide superintendents with appropriate safety rules and regulations from governmental agencies.

vi. Discipline employees who willfully disregard this program.

vii. Reward employees for adhering to and promoting good safety practices.

3.5—Summary

This chapter covered assessment methods of in-place concrete demolition and removal considering safety, stability, cost, constructability, and environmental impact. The chapter also discussed general aspects of removal of in-place concrete in different types of structures, including the degree of removal and different complete or partial removal methods, and safety operation during removal. The chapter provides background information for Chapter 4.

CHAPTER 4—REMOVAL METHODS

4.1—Introduction

Methods selected for concrete removal should provide efficient and economical demolition rates, but in cases of partial demolition or surface-only removal, should also result in the desired substrate concrete condition. Ultimately, the method used should ensure that the integrity of the remaining structure is not compromised to an unacceptable extent. In all types of removal activities, the
comfort and safety of the operator should also be considered, as many of these methods are tedious and have associated safety and health issues (Abudayyeh 1997).

In the past, contractors were generally 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, more automated and efficient concrete removal equipment and methods have been developed in many countries and are marketed worldwide and advertised in the various trade magazines. Trade associations provide a good source for identifying firms performing a particular type of work, and contractors keep extensive lists of subcontractors that do work in particular areas. Due to the high cost, operator training, and skilled supervision requirements, many pieces of equipment and methods are provided by specialty contractors (Peurifoy et al. 2010). Ultimately, if recycling and reuse of the removed concrete is the desired goal of stakeholders, the condition removed concrete (such as particle size, presence of water, or other contaminants and removal of reinforcing steel) should be a consideration in selection of the type(s) of equipment used for removal. Knowledge of the design strength, age, and exposure conditions of the concrete is also useful in both selection of removal method as well as determining the suitability of the removed material for other uses such as recycled concrete aggregate (RCA). Loading, transport, and processing of the material into RCA will be affected by choice of removal method.

This chapter provides a general description and summary information on concrete removal systems and methods. Not all removal methods will necessarily yield concrete derivatives suitable for reuse as aggregate (that is, RCA), but considerations that will promote production of reusable material are identified where appropriate. Section 4.2 provides guidance for removing the surface of
existing concrete, typically performed prior to repairs or application of coatings. Section 4.3 provides guidance on demolition of concrete structures for disposal or reuse as recycled concrete aggregate. A discussion of combined systems for concrete removal is presented in 4.4. Throughout this chapter, advantages and limitations of various concrete removal methods are presented and discussed, and additional information can be found in ACI 546R.

4.2—Surface removal

Surface removal of concrete is common for new construction as well as repair and rehabilitation of existing construction. Typically, removal of surface concrete is required to correct an alignment defect or to prepare the surface for a subsequent treatment, although concrete removal may be required for a variety of other reasons such as those listed in 4.2.1. Work may be carried out on a small and crude scale with hand tools, or on a large scale with motor driven equipment and automatic sensors. Jobsite constraints such as doorway openings, the availability of power and water, and tolerance for noise and dust can also influence or limit the techniques available for use. 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 worker comfort and safety, to provide ease of equipment access and use in more constraining jobsite conditions, and to reduce environmental impacts. Systems available for surface removal can be generally separated into:

a) Mechanical removal

b) Impact of hard particles (abrasive blasting)

c) Hydraulic removal (hydrodemolition)

d) Chemical removal

e) Thermal removal

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Selection of a concrete removal system will vary with accessibility, size of the work, locally available equipment and expertise, and most importantly, the end use of the surface. Proper concrete removal techniques and surface preparation are critical to the successful application of repair materials, coatings, and protective systems. The proprietary nature and availability of systems combined with the range of final surface profiles that will result often necessitates consultation with removal contractors during system selection.

In this section, a description of available systems is presented, along with their typical applications, advantages, and disadvantages. Some of the systems are exclusive or evolving. Depending on project conditions and the desired results, more than one removal method may be required.

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

### 4.2.1 Purpose of surface removal

Common reasons for surface removal of concrete include:

a) To resurface unsound, stained, or damaged concrete, such as weak and dusting surfaces

b) 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

c) To prepare the surface for subsequent layers, such as overlays, toppings, tile, and coatings

d) To improve skid resistance of concrete pavements

e) To mitigate damage imparted to the substrate concrete remaining from more aggressive concrete removal techniques

### 4.2.2 Definition of final surface
4.2.1 General—The required features of the completed surface removal will include one or a combination of:

a) Profile or planeness

b) Elevation or face dimension

c) Degree of aggregate exposure or depth of relief

d) Degree of micro-cracking in surface

Some of these can be defined with a reasonable degree of tolerance, but others are subjective and difficult to define, and therefore can become the subject of contract disputes. In the following sections, guidance on specification provisions and verification methods is provided.

4.2.2 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 the criteria for acceptance will be. In the latter, the contractor is told how to do the work, such as type of equipment, procedures, or both, and a general definition of final surface requirements. Items such as measurement or acceptance may be included in the prescriptive specifications but are often omitted. The performance approach is recommended where practical. ICRI 110.1 provides recommended specification text, guidelines for optional requirements, and commentary to assist with development of project specifications for concrete removal and surface preparation.

4.2.3 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 of the final work product. 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 representative.

4.2.2.4 Some approaches to specification—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.

4.2.2.4.1 Planeness

a) Horizontal: The methods of specifying planeness of horizontal surfaces (flatness and levelness) are better developed than the other surface features. Methods include the use of incremental measurements (F-number system) and the straight-edge (ACI 117.1R). 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 E1155. The straight-edge can provide reasonable control of planeness if:

i. Extremely fine tolerances are not required
ii. 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 for this method.

b) Vertical: String lines or straight-edges are satisfactory if method of use is defined.

4.2.2.4.2 Surface texture—Until recent years, the surface texture of concrete is one feature that historically has suffered from subjectiveness. Several crude methods have been used in the past to specify removal extent and exposed surface texture. These included:

a) Surface skin removal
b) Surface mortar removal (no exposed aggregate)
c) To a degree of exposure of coarse aggregate particles

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Due to the emergence of more reliable, quantitative systems to define and specify the desired surface texture, the aforementioned techniques are not recommended. ICRI 310.1R is a commonly used resource in the repair industry. ICRI 310.1R identifies 10 different concrete surface profiles (CSPs) that are often used in specifications and product requirements to describe the degree of roughness suitable for application of repair or coating materials. CSP designations range from 1 (minimal roughness) to 10 (very rough, approximately 1/4 in. [6.35 mm] or greater amplitude of surface profile). A set of molded replica chips is available from ICRI to provide visual standards to assist with quality assurance/control and acceptance. Guidance on the ability of surface removal options to achieve the desired CSP is provided in ICRI 310.2R.

If light removal by hand tools, power tools, or by sandblasting is specified, the Steel Structural Painting Council (SSPC) Standards, SP2, SP3, or SP6, respectively, may be used. Other methods for determining the quality and consistency of finished surfaces include measuring surface profile using replica putty (ASTM D7682), replica tape (ASTM D4417), laser profileometry, and the sand method as per ASTM E965. In the ASTM E965 sand method, the horizontal surface texture is quantified by pouring a given volume of dry sand (usually one-size silica sand) onto the surface and determining, when spread with a squeegee, the area it covers. Additional details on each of these methods, along with some guidance on selection of their use, is presented in ICRI 310.2R. However, in some cases, agreement on the designer's needs and contractor’s performance can only be reached by the mock-up approach described in 4.2.2.3.

4.2.2.4.3 Cleanliness—It is common in specifications to require surfaces to be clean, which typically means free of soil, debris, loose particles, chemical contaminants, laitance, and other substances. Gaul (1984) and ASTM D4258 provide information on cleanliness prior to coating application. The U.S. Army Corps of Engineers (2012) suggests procedures suitable for removing

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contaminants and otherwise cleaning concrete. A simple practical test for clean is to wipe a dark cloth across the concrete surface and 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.

4.2.2.4 Soundness of surface—A common specification clause in repair work is to remove all unsound concrete, which is far from definitive, but generally understood to mean removal of 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. Bruising is a phenomenon in which the substrate concrete surface experiences microcracking damage through the construction operations and is subsequently weakened (ACI 346.1R). In a practical sense, a sound surface is one that will resist stress that may be exerted by the repair material, such as stress due to shrinkage during curing, differential thermal strains, or structural loading.

4.2.3 Surface conditions and surface preparation requirements—Successful performance of repair materials or surface coatings is highly dependent on the texture and consistency of the substrate surface remaining after removal of the desired amount of concrete. The following sections discuss the influence of surface conditions on the achieved bond of applied materials, test methods to assess the quality of the substrate surface after removal methods are used, and specification considerations.

4.2.3.1 Influence of surface conditions on bond properties—Adhesion (or bond) relies on mechanical interaction and chemical bonds, along with other thermodynamic mechanisms. Adhesion is often characterized in one of two approaches (Bissonnette et al. 2012):

1) The conditions and kinetics of two adjoining materials, taking into account different bond mechanisms

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2) The quantitative measure of the magnitude of adhesion, usually expressed in terms of stress or energy required to separate the two materials.

Early research into the influence of surface conditions on bond properties was performed by Felt (1956), who concluded that factors influencing bond of new and old concrete were not easily isolated and controlled. Felt’s findings, echoed by many current researchers and practitioners, indicated that the most important factor affecting bond 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. Pigeon and Saucier (1992) and Emmons and Vaysburd (1993) considered the interface between existing concrete substrate and new concrete to act in a manner similar to the bond between aggregate and paste, with a transition zone between the two layers.

Ultimately, the mechanical anchorage of a repair is linked to the roughness and porosity of the substrate concrete (interface texture), which is influenced by concrete removal methods and surface preparation (Bissonnette et al. 2012). In addition to surface texture, other factors including substrate moisture condition, repair material properties, concrete carbonation, and substrate temperature have all been found to influence bond strength (Bissonnette et al. 2012; Delatte et al. 2000; Pigeon and Saucier 1992; Gulyas et al. 1995; Zhu 1992).

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 (1993) assessed both wet- and dry-mix shotcretes and found little difference in the bond

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strengths. The assessment was based on pull-off tests described in CSA A23.1/CSA A23.2. Talbot’s (1993) data also showed that there can be some reduction in bond strength with time (tests between two and six months).

Hindo (1990) reported a pull-off test apparatus, similar to the CSA A23.1/CSA A23.2 test procedure previously described, 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:

a) Lack of a bruised (containing microcracks) layer

b) Irregular wavy surface profile

c) Increased number of micro-pores

d) Greater surface area

Hindo (1990) contains some micrographs that show the bruised layer phenomenon and concludes that the damage caused by use of pneumatic hammers for concrete removal and surface preparation often warrants that these removal methods should be discouraged. Instead, Hindo (1990) recommends a hydrodemolition method be used where applicable. Hindo’s (1990) data show bond strengths generally on the order of 125 psi (0.86 MPa) by the jack-hammering method and 200 psi (1.38 MPa) by hydrodemolition. With both procedures, failures frequently occurred below the bond interface. Results showed that the base concrete tensile strength was largely being assessed by these tests, and therefore the significant effect of the subsurface microcracking on bond strength.

Bissonnette et al. (2012) described the findings of a study that featured tensile (pull-off) and shear bond testing of substrates prepared using a variety of methods. The authors provide typical tensile and shear bond test results for surfaces prepared by waterblasting (276 psi [1.9 MPa] pull-off; 232

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psi [1.6 MPa shear]), sandblasting (232 psi [91.6 MPa] for both pull-off and shear), and chipping with mechanical hammer (189 psi [1.3 MPa] pull-off; 290 psi [2.0 MPa] shear). The influence of carbonation and moisture on bond strength was documented for different types of prepared substrates, and both were found to significantly influence bond. Shortcomings of the tensile pull-off test (ASTM C1583/C1583M) were identified, and include possible misalignment of the test apparatus, potential failure outside of the interfacial zone (cohesive failure within the repair material or substrate), and damage to the interface from the coring operation. These researchers also concluded that among the techniques available for assessment of surface texture, the ICRI CSP chip technique (discussed in 4.2.2.3) is best suited for use in specifications and quality control (Bissonnette et al. 2012).

4.2.3.2 Test methods—Without adequate surface preparation, the long-term performance of concrete repairs and bonded overlays is negatively impacted by bonding issues and cracking. For repairs to be successful, a durable bond surface should exist to ensure the substrate concrete and bonding material act monolithically, with a long-lasting bond surface (Bissonnette et al. 2012). Guidance for surface preparation is provided in the ACI Concrete Repair Manual (American Concrete Institute 2013), ACI 546.2R, and other documents previously referenced within this section. Additionally, ASTM has a number of standards and test methods relevant to surface preparation. Their scope is summarized as follows:

a) ASTM D4258: This practice includes surface cleaning of concrete to remove grease, dirt, and loose material prior to 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.

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b) ASTM D4259: This practice includes surface preparation of concrete prior to 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 (ASTM D4541). Interestingly, ASTM D4259 suggests that water-jet blasting is for cleaning, whereas 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.

c) ASTM D4260: This practice includes surface preparation of concrete using acid etching to prepare the surface prior to application of coatings. Methods are intended to alter the surface profile of the concrete and to remove foreign materials and weak surface laitance.

d) A number of pull-off test procedures have been suggested. Most are based on the over-core approach. ACI 546.1R discusses three direct tension bonding test methods (ASTM C1404/C1404M; Gillespie et al. 1998) for measuring bond strengths for repair applications. Figure 4.2.3.2a shows cores resulting from pull-off testing using the over-core method. It is noted that ASTM C1404/C1404M has been withdrawn, and no standard has replaced it to date.

e) Adhesion tests for coatings include ASTM D7234. 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 tests (ASTM D6677) and results may not be comparable. The apparatus is shown schematically in Figure 4.2.3.2b.

Fig. 4.2.3.2a: Pull-off test core specimens.

Fig. 4.2.3.2b—Schematic pull-off adhesion tester (from ASTM D4541).
4.2.3.3 Specifications—ACI 562 provides extensive guidance for design of structural repairs, including testing and analysis procedures for assessing the interface bond between the repair materials and existing substrate. ICRI 201.3R-13 gives guidance in determining the number of tests and acceptance criteria for the direct pull-off testing. Other standards provide additional guidance. ACI 503 recommends a pull-off strength of 100 psi (0.7 MPa) for epoxy-based mortars. CSA A23.1/CSA A23.2 recommends 145 psi (1.0 MPa) for bonded toppings when tested to the procedures described. A high degree of variability in pull-out bond test results is to be expected. Bissonnette et al. (2012) discusses bond testing as part of research on best practices for preparing concrete surfaces prior to concrete repairs and overlays.

4.2.4 Systems available for surface removal—A wide range of systems are available even within a particular generic type of removal equipment. Recently, there has been a movement to more efficient and self-propelled units as the construction industry becomes more involved in concrete rehabilitation. This section provides a general overview of equipment types along with suggestions on advantages and disadvantages and possible uses. For additional information on some of these concrete removal techniques, with specific considerations, advantages, and limitations associated with subsequent repair of the remaining substrate concrete, refer to ACI 546.1R.

4.2.4.1 Mechanical removal—Mechanical removal is a general term involving a wide range of removal equipment and techniques. Over time, hand operations have been slowly replaced by more powerful mechanized systems with greater production rates. One concern about mechanical systems is that, when used for surface preparation, tools can leave a bruised surface (that is, containing microcracks) that in turn can reduce the bond strength to subsequent overlays. The bruising concern is particularly relevant with chipping tools, where the briefly applied blows can exceed concrete strength, resulting in cracking and other damage such as fractured or loosened
aggregates. Low impact or nonimpact repair methods reduce the potential for bruising and the subsequent lowering of bond strengths of repair materials and coatings. The relative potential of bruising for each method is outlined in ICRI 310.2R. Surfaces that are removed using mechanical methods typically have high-amplitude profiles, and often require treatment using other less-abrasive methods (sand or water blasting) prior to application of coatings.

With all mechanical methods, concrete particles and dust should be removed. Methods include vacuuming during or after removal work, sweeping, rinsing or flushing with water, air cleansing systems, and other methods. Disposal of dry particles often uses traditional methods such as collection and disposal in appropriate landfills or beneficial reuses such as burial on site as fill (if allowed). Wastewater produced during these processes should be collected and contained prior to disposal. Slurries and wastewater may require treatment, including sedimentation, neutralization with acid, or both, prior to disposal (ACI RAP Bulletin 12; ICRI 310.3R; IGGA 2011; Yonge and Shanmugam 2005).

4.2.4.1.1 Chipping—Chipping tools, including hammer-driven and hand-held percussion breakers, are widely used removal tools. They are available in a wide range of sizes, tip types (hardened steels and carbides), and styles (chisel, tile, bull point, moil point, and others). A variety of attachment types are shown in Figure 4.2.4.1.1a.

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 chipping procedure is tedious and the quality of the work is highly dependent on the care of the operator. The process has a number of disadvantages:

a) All of the deteriorated or unsound concrete may not be removed

b) The surface of the remaining concrete (both paste and aggregates) may be extensively micro-cracked (bruised) by the blows from the breakers

c) Striking the reinforcement with the breakers may nick the bar and, of greater concern, may destroy the bond adjacent to the removal area.

d) The procedure is slow, noisy, and dusty.

e) Contaminants may become airborne.

Production rates vary and are influenced by the quality of the concrete, the ease of access, and the amount of concrete that is to be removed. The smallest chipping hammers, powered electrically, pneumatically, or hydraulically, usually weigh anywhere from under 20 lb to 100 pounds (under 9 kg to 45 kg) (Vorster et al. 1992). Weight is generally a reasonable indicator of a tool’s power, that is, the heavier the tool, the more powerful. The chipping action of this type of equipment (Fig. 4.2.4.1.1b) is rapid, ranging from 900 to 2400 blows per minute (Abudayyeh et al. 1998).
Fig. 4.2.4.1.1a—Chisel attachments for rotary hammer drill (image courtesy of familyhandyman.com).

Figure 4.2.4.1.1b—Chipping hammer.

4.2.4.1.2 Bush hammering—A bush hammer is a masonry tool used to texturize stone and concrete and is typically a chipping hammer modified with a bushing tool (bit) having a serrated face with rows of pyramidal points or parallel V-shaped grooves (Figure 4.2.4.1.2). Bush hammers exist in many forms, from simple hand-held hammers to large electric machines, but the basic functional property of the tool is always the same: a grid of conical or pyramidal points at the end of a large metal slug. The repeated impact of these points into stone or concrete creates a rough, pockmarked texture that resembles naturally weathered rock. Bush hammers can help to increase bonding effectiveness when applying new concrete to an existing concrete surface by increasing the surface area of the bonding zone. The head resembles modern day framing hammers with their distinctive waffle head pattern for extra grip.

Bush hammering can also be accomplished with hammer blows on a chisel-like tool, or with a gang hammer that employs multiple independent bits. A gang hammer for horizontal surfaces is
often known as a scabbler. Multi-head scabbler units are also available as walk-behind equipment, with these units typically containing 2 to 11 bits (piston-mounted) that operate using compressed air (Suprenant and Malisch 1986). The depth of penetration and the roughness of the finished surface are controlled by the size and sharpness of the points on the bits, with some bits able to remove up to ¼ in. (6 mm) of concrete in a single pass (Manning 1991; Vorster et al. 1992). Operations are noisy and dusty, but vacuum operations can follow the scabbler to mitigate the dust.

![Fig. 4.2.4.1.2—Bush hammers.](image)

**4.2.4.1.3 Needle scalers**—Needle scalers are tools primarily used to remove rust, mill scale, and old paint from metal surfaces. However, they also find use in selective concrete surface removal. These tools are typically 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/minute to a model weighing 11 lb (5 kg) and delivering 2900 blows/minute. The tools require approximately 5 ft³/minute (0.14

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m³/minute) of compressive air at 90 psi (620 kPa). They are also available as hydraulic tools delivering about 5000 blows/minute (Manning 1991).

Needle scalers (shown in Fig. 4.2.4.1.3) 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 property of the tool is a distinct advantage. However, low production rates can be expected. 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 (Manning 1991).

![Fig. 4.2.4.1.3—Needle scaler.](image)

4.2.4.1.4 Scarifiers—Scarifiers, sometimes called milling machines or rotomillers, 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. However, in recent models, 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 (Manning 1991). Scarifiers generate a lot of dust, which is often controlled by either prewetting the concrete surface or by using vacuum equipment (Suprenant and Malisch 1986).

Figure 4.2.4.1.4a shows a self-propelled scarifier that could be ideal for concrete or asphalt jobs such as parking deck repairs, factory floor preparation, or road repairs. Larger scarifying equipment (shown in Figure 4.2.4.1.4b) (typically called milling machines) are widely used in bridge and pavement rehabilitation, especially to prepare the concrete surface before the application of a concrete overlay. These larger machines are equipped with water tanks for cooling bits (preventing thermal damage) and conveyor systems for loading the scarified material directly into trucks. Scarifying or milling has been identified as a relatively cheap option on a per unit area cost basis, but can also be seen as an approach limited to cover concrete (above reinforcing steel) and horizontal surfaces as the scarifier may rip out or damage the reinforcing bars, resulting in damage to the scarifier unit as well as to the substrate concrete (Manning 1991).

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 (Manning 1991). 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 will need to be replaced, sometimes after only a few hours of use. Scarifiers are not suitable for vertical or overhead surfaces, except for boom-mounted rotary head cutters that have been used to remove concrete
from wall faces such as in lock chambers. Self-propelled equipment may have limitations on access close to corners, edges, and other structural features. Scarifiers are noisy, and some machines may create significant vibration. The use of water can result in a tightly adhering layer of surface dust that is difficult to remove (Manning 1991).

Fig. 4.2.4.1.4a—Self-propelled scarifier (photo courtesy of Edco).

Fig. 4.2.4.1.4b—Track-mounted scarifying (milling) machine (photo courtesy of Schibeci).

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4.2.4.2 Particle impact removal—Particle impact removal systems, also known as abrasive blasting systems, remove concrete by propelling small abrasive particles into the surface of concrete to be removed. Removal is achieved predominantly by abrading of the mortar phase of the concrete. Therefore, some key aspects of these methods are:

a) The resulting surface profile is much higher

b) 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

c) The characteristics of some of the available handheld systems (hose/nozzle) facilitate access to edges, corners, and other surfaces that can be problematic to access with other removal equipment

4.2.4.2.1 Shotblasting—In shotblasting, a metallic abrasive material is propelled by a rotating wheel, impacting and scouring the concrete surface. The shot is rebounded into a recovery unit, and a vacuum system collects both dust and shot. A shotblasting machine (Fig. 4.2.4.2.1) may be manual or self-propelled. A magnetic broom can be used to pick up stray shot. Variable surface profiles can be obtained using a range of shot sizes by varying the amount of abrasive material used and varying the speed of the machine (Suprenant and Malisch 1986). 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). The largest available shot (0.046 in. [1.2 mm]) is typically used for concrete removal (Manning 1991). The advantages of this method of removal are good dust control, little vibration, and an effective cleanup procedure.
4.2.4.2 Sandblasting—Sandblasting is the traditional method of concrete surface preparation, but its use has been reduced because of concern over environmental health and safety risks (Manning 1991). Wet sandblasting, in which water is injected into the abrasive stream, can be used to mitigate the dust problem, but the efficiency of concrete removal is reduced by introduction of water to the blast stream. Grit for sandblasting ranges from natural sand to slag; the latter is now preferred because of superior hardness and particle shape (Manning 1991). Sandblasting is relatively versatile compared to other mechanical removal methods, as a range of relatively fine surface profiles can result depending on the grit used and the hardness of the mortar phase. In Fig. 4.2.4.2.2, a concrete surface is shown before and after it is sandblasted. Adequate 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. An advantage of sandblasting is that it can be used on vertical and steeply sloped surfaces (Manning 1991).
Sandblasting is an effective method of simultaneously cleaning corrosion products from reinforcing steel and preparing adjacent concrete surfaces in rehabilitation work (ICRI 310.1R). For all abrasive blasting methods, dust control and cleanup of the removed material is a consideration to be addressed. Workers are required to wear continuous-flow air-line respirators to minimize exposure (OSHA 2016). Systems such as recuperative or wet systems are often used to mitigate the dust issue as well as facilitate easier cleanup. Some limitations associated with access to edges, corners, or other structural features can be an issue with walk-behind abrasive blasting equipment (Manning 1991).

![Sandblasted concrete](image)

**Fig. 4.2.4.2.2—Sandblasted concrete.**

**4.2.4.3 Chemical removal**—Chemicals, typically acids, can be used for removal of surface concrete. One of the most commonly used of these techniques is acid etching, which has been shown to effectively remove surface paste, laitance, and dirt, as well as open the pore structure of concrete. Limitations associated with use of acid etching include applications where concrete is...
very young or weak; the surface is contaminated with oils, grease, or other materials; and when metal components are in the vicinity (Manning 1991). Environmental concerns associated with use and disposal of corrosive chemicals also provide limitations to their use in some applications. During early ages after concrete placement, surface retarders can also be used to remove cement paste. These surface retarders, which restrict the hydration of cement paste, result in exposed aggregates and a more open surface pore structure (Kosmatka and Wilson 2016).

4.2.4.4 Microwave heating—In the microwave heating method, microwave energy is directed to the concrete surface, heating the concrete and free water present in the matrix. Stresses induced in the concrete from steam pressure result in fracture and spalling of the surface (White et al. 1992). This method results in removal of shallow spalls, and this method also has potential use for removing contaminated concrete surfaces (Kasai 1988; Zdeněk and Goangseup 2003). Although this method was investigated several decades ago for several different types of applications, including removal of residual radioactive contamination of concrete structures (White et al. 1992, 1995, this approach has not moved to typical practice. However, recent efforts to improve the sustainability aspects of concrete production and in-service performance of concrete infrastructure has led to a new interest in research and development of microwave technologies for use in concrete construction and demolition, including those for removal methods. Design of microwave applications, as well as guidance for use in demolition and drilling are presented in Ong and Akbarnezhad (2017).

4.2.4.5 Hydrodemolition—Hydrodemolition 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 and where access and presence of wash water is permitted. Equipment
ranges from hand-held wands (Fig. 4.2.4.5a) to large tractor-mounted units (Fig. 4.2.4.5b) or others remotely operated on rails. The effectiveness of a particular system is dependent on:

a) Nozzle type
b) Nozzling pattern and distance to the surface
c) Water pressure
d) 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 sprayed rapidly and continually over the area of concrete to be removed and excess water is allowed to drain away. A typical nozzle is shown in Fig. 4.2.4.5c. Removal depth is controlled by adjusting the water pressure, nozzle speed, and the speed at which the machine is propelled along the concrete (Suprenant and Malisch 1986). Hydrodemolition is unique because, properly used, it will only demolish unsound concrete while also creating an appropriately roughened bonding surface for new concrete (Nittinger 2001). This method is often used for removal of concrete on bridge decks in preparation for an overlay.

It is possible to calibrate gang-mounted water jets for a particular depth of removal by adjustment to the four factors noted previously, and steel elements are protected from damage (VanOcker et al. 2010). However, variations in the concrete surface profile will be experienced if there is a variation in concrete strength. As with particle impact systems, hydrodemolition is to a degree self-inspecting with regard to removal of softer or unsound concrete. Residual protruding aggregate may require separate removal. Hand-held hydrodemolition units have a limited production rate, and can result in operator fatigue and other safety risks (Phares et al. 2014).

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Simply stating an operating pressure of a certain amount, as is commonly done, is not sufficient. For major or deep removal, operating pressures and flow rates vary among manufacturers. Bissonnette et al. (2012) provide guidance for hydrodemolition water pressures to be used for various extents of concrete removal and surface preparation. Units having pressures up to 50,000 psi (340 MPa) are reported. Water blasting at lower pressures (typically between 5000 and 15,000 psi (35 and 105 MPa) rather than removal of concrete material is generally achieved.

Fig. 4.2.4.5a—High pressure water lance (photo courtesy of Jet Edge Water Systems).

Fig. 4.2.4.5b—Tractor-mounted hydromilling machine (from www.forconstructionpros.com).

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4.2.4.6 Diamond grinding and grooving—In general, surface improvement is the most cost-effective alternative for concrete structures (such as pavements, slabs, and bridge decks) that are structurally adequate and do not have concrete durability problems. The purpose of concrete pavement surface removal may be:

a) To correct skid resistance of rutted or polished surfaces
b) To remove unsound concrete surface layers

Systems used generally involve mechanical removal. However, some chemical and water-blasting methods have been used on airfield pavements to remove rubber from aircraft tires (Airport Cooperative Research Program 2008; Ashtiani et al. 2016).

One commonly used mechanical system uses wet cutting with diamond blades (Fig. 4.2.4.6a), typically called diamond grinding. Diamond grinding is often performed to rehabilitate a concrete pavement surface by removing deteriorated concrete, effectively extending the service life of the pavement. It is possible to reduce road noise, as well as increase skid resistance by grinding specific surface textures, and the removal of surface irregularities immediately improves pavement
smoothness. Most concrete roads can be ground at least once as the majority of highway grinding operations removes only 3/16 to ¼ in. (4 to 6 mm) of concrete (Correa and Wong 2001). Diamond grinding requires a constant stream of water, and the equipment typically includes a vacuum apparatus surrounding the saw blades. Diamond grinding equipment is shown in Fig. 4.2.3.2b. Additional information on best practices and guide specifications for diamond grinding are presented by Rasmussen et al. (2012) and CPSCP GS 1-11.

Concrete road surfaces can also be provided with narrow groove patterns to increase tire traction and to decrease the chance of vehicle accidents in inclement weather. Grooves are typically specified to be 1/8 to 3/16 in. (3.2 to 4.8 mm) deep, 1/8 in. (3.2 mm) wide, and spaced ¾ in. (19 mm) center-to-center. Grooving of pavements is similar to the process used for grinding. However, grooving equipment typically consists of a smaller vehicle-mounted water-cooled saw, a separate source water tank, and a separate vacuum system (Fig. 4.2.4.6c). Grooving by dry milling is not recommended, as this tends to cause structural disintegration of the ridges between the grooves.
Fig. 4.2.4.6a—Typical diamond grinding blade and grinded surface (Tymvios et al. [2016]).

Fig. 4.2.4.6b—Typical diamond grinding machine (photo courtesy of Tymvios et al. [2016]).
4.2.4.7 Removal method selection—When concrete removal is required, project personnel should determine the most suitable method of concrete removal based on the desired finished surface, as well as other economic, environmental, access, and safety considerations. The characteristics of a specific project, as well as the economic impact of use of more capital-intensive technologies, should be carefully considered prior to selection of a removal system or a combined system (Weyers et al. 1993). For example, Vorster et al. (1992) compared and combined systems for concrete removal in bridge applications and provided an economic analysis of selected removal methods, assessment of technical and risk considerations, and guidance on selection of approach and tools. Concrete removal techniques studied were pneumatic breakers, milling machines, and hydrodemolition. It was found that each of these methods has specific strengths and weaknesses when considered for use in any given task. For example, pneumatic breakers are flexible in terms of size and depth of removal for which they are suited; they are also the most expensive of the three techniques. Although milling is the most economical on a unit cost basis, it is the most inflexible method, as it can only be used to remove concrete above the reinforcing steel on large horizontal surfaces. Hydrodemolition is relatively inexpensive and is flexible with regard to depth.
of removal. However, hydrodemolition is limited to large horizontal surfaces and its resulting environmental impact of wastewater (Vorster et al. 1992).

A comprehensive table summarizing features and considerations/limitations for concrete removal methods is presented in ACI 546. ICRI 310.2R is a resource useful to aid in selection and specification of equipment and techniques for removal of surface concrete to prepare the resulting concrete surface for repair and coating purposes. Guidance specific to removal of concrete for bridge repair and rehabilitation is provided in Manning (1991), Vorster et al. (1992), and Weyers et al. (1993). Reports on research and best practices for removing concrete from pavements is provided in Hiller et al. (2011) and National Highway Institute (1998). Concrete residuals from surface removal should be managed in accordance with environmental regulations, and will eventually be disposed of or reused beneficially. Disposal of these residuals is still common, with solids often taken to landfills and wastewater disposed of in treatment facilities (Tymvios et al. 2016). However, several beneficial reuse applications for these residuals, particularly the finer portion of the concrete material, exist and are becoming increasingly used. These applications include use as soil amendments, fill material, or in new concrete (Line 2016; Rowden 2016; Townsend et al. 2016).

4.3—Demolition of concrete structures

4.3.1 Hand tools and hand-operated power 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, sledge hammers, drills, points, and various chisels are just a few of these tools. Reshaping and hardening of the bits is often needed. Production rates tend to vary by the type of equipment used, the skill of the operator, and the quality of concrete being removed. In addition
to potential issues with consistency of performance, worker safety and long-term health impacts (associated with respiratory issues and hand-arm vibration syndrome) are issues to be dealt with when using hand tools) (Manning 1991).

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 more than 100 years and are of rugged 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).

Hydraulic power is provided by small, lightweight power packs that can also operate a number of other tools. A wide range of tools is available including small impact hammers, drills, saws, and grinders for use in concrete removal. Hydraulic hammers, which are often lighter than pneumatic hammers, have a higher energy to weight ratio (Manning 1991).

Hand-held electrical tools are the smallest type of hand-held power tools available and have lower energy output. Electric tools are typically limited to use in confined areas (Manning 1991). Gasoline-powered tools are ideal for small drilling and breaking jobs in hard-to-reach locations. These tools are available in two types of configurations, 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 (Manning 1991).

Drop hammers (also called drop blades) are used to demolish concrete highway pavements, parking lots, and other slabs-on-ground (Fig. 4.3.1). 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

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operated by one person. 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, and produce relatively little dust. The units are ideal for removing small areas of slab on-ground up to 12 in. (300 mm) thick.

![Fig. 4.3.1—Drop blade (photo courtesy of NHI).](image)

### 4.3.2 Vehicle-mounted equipment—Demolition attachments with a wide range of sizes and types are available to mount on small backhoes, skid loaders, and equipment requiring carriers. The vehicles can be rubber tired or crawler mounted (Fig. 4.3.1). The unit should have sufficient hydraulic capacity to operate both the boom and the attachment. In addition to sizing the unit for the required production capabilities, a demolition plan needs to consider the loads of the equipment imparted to the structure (Medina and Vargas 2004). 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.
4.3.2.1 Hydraulic/pneumatic impact breakers/hammers—Hydraulic/pneumatic impact breakers/hammers are common pieces of equipment available from many manufacturers. Advantages of the impact hammers are the wide range of sizes and the ready availability. A photo of a hammer mounted to an excavator is shown in Fig. 4.3.2.1a. 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) (Manning 1991). 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 may limit the impact energy where only partial removal of an existing structure is required, or where disturbance to underlying layers or utilities may be an issue (Hiller et al. 2011).

Hydraulic or pneumatic breakers are available in several sizes and by several manufacturers. Typical breakers of this type are shown in Fig. 4.3.2.1b and c. Both pneumatic and hydraulic breakers can be used for underwater work. Impact breakers can achieve production rates of 9700 to 12,000 ft²/hour (900 to 1100 m²/hour) (Dykins and Epps 1987; National Highway Institute 1998). Advantages of vehicle-mounted hammers include high productivity, excellent mobility, the ability to be used underwater, remote control operation, and reduced safety and health risks for the operator. Disadvantages include noise and dust production (Abudayyeh et al. 1998). Another potential disadvantage for recycling applications is that the demolished fragments of concrete produced by this equipment can be quite small and may be problematic to efficiently load into trucks for transport to crushing operations for recycled concrete aggregate (RCA) production.

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**Fig. 4.3.2.1a**—Vehicle mounted impact breaker (photo courtesy of Bell et al. [2014]).

**Fig. 4.3.2.1b**—Hydraulic or pneumatic hammer (photo courtesy of NHI).
4.3.2.1c—Trailer-mounted diesel hammer (photo courtesy of NHI).

4.3.2.2 Spring-action hammers—Spring-action hammers (sometimes referred to as mechanical sledgehammers or whiplash hammers) 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 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 the truck. Spring-action hammers 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 jobsite to jobsite. One disadvantage to whiplash hammers is the high energy input required to facilitate the high production rate (Abudayyeh et al. 1998).

4.3.2.3 Wrecking ball and crane—The wrecking ball is attached to a crane and either dropped or swung into the concrete. The weight of the ball (or other irregularly shaped object) can vary depending on the crane capacity. Wrecking balls typically weigh from 1000 to 4000 lb (455 to 1818 kg), with some balls weighing up to 13,500 lb (6136 kg) (Hudgens 1987; Manning 1991). Advantages of this method include simplicity, widespread availability, and the separation distance between the operator and the concrete to be demolished. Disadvantages include the required operator skill for safe operation; generation of dust, noise, and vibration; and potential damage to concrete desired to remain in place (Phares et al. 2014).
4.3.2.4 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 (shown in Fig. 4.3.2.4a); and 2) in-line single drum. The drum for the in-line cutter head rotates around the axis of the boom and works like 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. 4.3.2.4b).

Fig. 4.3.2.4a—Cutting wheels on self-propelled scarifying unit (from Honway)
4.3.2.5 Concrete crushers—Concrete crushers, which are available in a variety 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. Not to be confused with mobile or stationary crushers used to produce RCA, these crushers are portable and primarily consist of two cutting jaws that grab and crush sections of concrete from the in-place structure or pavement. Models are available with one or two hydraulic cylinders, and a wide range of sizes from small units (suitable for handheld operation) with only a few tons of crushing power to large ones with 350 tons (3100 kN) of crushing power (Koski 1993). Advantages to using crushers include minimal dust production and vibration, high mobility, usability in inclement weather, reduced noise, and the ability to separate embedded steel from concrete (Abudayyeh et al. 1998).

4.3.2.6 Ripper—A ripper, also known as a rhino horn, is a large blade attached to a backhoe used to break up slabs on grade and to separate the reinforcing steel from the concrete (National Highway Institute 1998) (Fig. 4.3.2.6). 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

Fig. 4.3.2.4b—Cold planer attachment (from www.forconstructionpros.com).
ideal for removing large areas of slab-on-ground and concrete pavement. Large-sized pieces of concrete (up to 24 in. [600 mm] in length) can be removed using the ripper, which is often used after an impact or other type of breaker (Hiller et al. 2011).

Fig. 4.3.2.6—Ripper or rhino horn (photo courtesy of CP Tech Center).

4.3.2.7 **Resonant frequency breaker**—The resonant frequency breaker fractures or breaks concrete highway pavement using a self-propelled, four-wheeled, rubber-tired power unit that uses resonant beam technology to apply energy through a high-frequency resonant impact breaker to the concrete pavement (Fig. 4.3.2.7). The unit has been used successfully on interstate highway work with
normal breaking rates averaging less than 7200 ft²/hour (670 m²/hour), which is less than the production rate of traditional hydraulic or pneumatic impact breakers described in 4.3.2.1 (Hiller et al. 2011; National Highway Institute 1998).

4.3.3 Explosive blasting—Explosive blasting has been used to effectively remove full and partial sections of concrete structures in a number of applications worldwide (Abudayyeh et al. 1998). In the United States, blasting has been successfully used for removal of large volumes of distressed and deteriorated concrete by the U.S. Corps of Engineers on a number of locks and dams. Concrete is a difficult material to blast because of the variation in strength and amount of reinforcing steel present (Hemphill 1981). Safety regulations, environmental considerations, and the need to monitor for ground vibrations limit applicable locations for this method, although controlled blasting techniques have been developed to minimize damage. An explosive blasting technique referred to as mini-blasting has been used for partial demolition of concrete structural members (Lauritzen and Petersen 1991). The technique requires a licensed worker and controlled blasting

Fig. 4.3.2.7—Resonant frequency breaker (pavement demolition) (photo courtesy of FAA 2004).
techniques to maintain safety and minimize damage to the remaining concrete and the surrounding environment. Blasting mats are used to minimize flyrock and textile fiber mats are used to reduce dust and noise levels. Information on blasting techniques is presented in Kasai (1988), Abudayeh et al. (1998), and Phares et al. (2014).

4.3.4 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, minimal dust. Hard aggregates or high concentrations of reinforcing steel can greatly reduce the cutting speed and life of a drill bit or saw, and production rates vary by type of cutting equipment. Research provide insights into the production rates and capabilities of a number of these types of tools currently available, particularly in pavement applications (Bell et al. 2014; Edwards et al. 2015).

4.3.4.1 Core drills—Construction-grade core drills generally are available in sizes from less than 1 in. (25 mm) up to 24 in. (600 mm) in 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 in applications that are water-sensitive.

4.3.4.2 Diamond saws—The most common type of saw blade for cutting concrete is the wet-cutting diamond blade (Manning 1991). 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 saws, walk-behind, and riding saws. Track-mounted saws are available for cuts in walls and the underside of slabs. Using a saw has the advantage of efficiently dismantling part of a structure and leaving behind clean, straight edges.
Disadvantages include noise and limitations on the depth of cut (Abudayyeh et al. 1998).

4.3.4.2.1 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. Hand-held hydraulic saws are also available that use ring-shaped blades that can make a 10 in. (250 mm) deep cut with a 14 in. (350 mm) diameter blade. Concrete chain saws (utility chain saws) are also available (Fig. 4.3.4.2.1). These units are typically less than 25 lb (11 kg), with blade lengths and operational characteristics similar to conventional chain saws (Bell et al. 2014; Edwards et al. 2015).

Fig. 4.3.4.2.1—Utility chain saw with diamond blade (Bell et al. 2014).
4.3.4.2 Walk-behind diamond saws—Walk-behind diamond saws are the most commonly used power saws, and a typical unit is shown in Fig. 4.3.4.2.2. 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.

Fig. 4.3.4.2.2—Walk-behind diamond blade saw (Bell et al. 2014).

4.3.4.2.3 Rideable pavement saws—Rideable pavement saws provide high productivity with blades up to 30 in. (760 mm) in diameter. However, other methods of pavement breaking and removal are more common for recycling (National Highway Institute 1998).

4.3.4.2.4 Diamond blade saw attachments—Diamond blade saw units that can be attached to heavy equipment (such as tractors and loaders) are available with a variety of blade configurations and production rates. Blades are available in a variety of sizes (typically up to 24 in. [600 mm] in cutting depths). Production rates vary upon the saw manufacturer and mounting equipment, and a research provides insight into the production rates and capabilities of a number of these types of tools (Bell et al. 2014; Edwards et al. 2015).

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4.3.4.2.5 Wheel saws—Wheel saws (sometimes called rockwheels) use silicon carbide teeth to cut through concrete. Wheel saws are available as attachments that can be mounted to heavy equipment (such as tractors and compact track loaders) and can therefore be used in several configurations based on the manner of mounting. Wheel saw attachments can be similarly mounted to other equipment, as shown in Fig. 4.3.4.2.5, and produce wider cut widths (up to several inches [millimeters] wide) than traditional sawblades (Bell et al. 2014; Edwards et al. 2015).

Fig. 4.3.4.2.5—Rockwheel attachment on tracked equipment (Edwards et al. 2015).

4.3.4.2.6 Concrete cutters—Wheeled concrete cutter machines are available where the cutting wheel is mounted near the center of the equipment rather than on an attached arm, as shown in Fig. 4.3.4.2.6. These machines have a cab to protect the operator and are equipped with water tanks. The cutting wheel makes a wider cut than a typical sawblade, with one model making a 5.5 in. (140 mm) wide cut (Bell et al. 2014).
4.3.4.2.6 Concrete cutter machine (Edwards et al. 2015).

4.3.4.2.7 Wall saws—Wall saws make accurate cuts in walls by riding on a track bolted to the concrete, as shown in Fig. 4.3.4.2.7. Means are also provided to maintain pressure of the blade on the surface being cut. Blade 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).

Fig. 4.3.4.2.7—Wall saw (photo courtesy of ABC Cutting Contractors of Alabama).

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4.3.4.2.8 *Diamond wire saws*—A diamond wire saw is a continuous loop of multi-strand 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. Pilot holes are drilled through the concrete with the wire cable passed through and coupled to form the continuous loop. A power unit drives and provides tensioning of the cable, while the direction of the cable is changed with idler pulleys. Water is used for the cooling and removal of cuttings. A typical setup of this system is shown in Fig. 4.3.4.2.8a.

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 (Hulick and Beckman 1989). Drive units can be either hydraulically or electrically powered. When the limit of movement of the drive unit is reached, the unit can be moved or the wire cable shortened (Manning 1991). Disadvantages include limits to the depth of cut and issues with cutting reinforcement in certain geometries (Hulick and Beckman 1989). Wire cutting demolition methods can also require use of other heavy equipment such as cranes (as shown in Fig. 4.3.4.2.8b) to support loads during and after cutting, as well as to remove the sawcut segments of the structure (Medina and Vargas 2004).
4.3.4.2.9 *Stitch drilling*—Stitch drilling is a technique used to produce cuts in concrete by overlapping drilled holes. An example of this technique is shown in Fig. 4.3.4.2.9. 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 (ACI 546R. In situations of partial concrete removal, particularly in the case of bridge decks or other elevated structural elements, blowout of the bottom of the hole is a risk (Phares et al. 2014).
4.3.5 Nonexplosive demolition agents—Nonexplosive demolition agents, sometimes called expansive grouts or soundless chemical demolition agents, were developed in Japan and first marketed in the late 1970s. These agents have been suggested for use in areas where demolition must occur in a controlled manner, or where dust, noise, or vibration is an issue (as in the case of a historic structure) (Gambatese 2003). A proprietary mixture consisting primarily of calcium oxide and calcium silicate is mixed with water and is poured into predrilled holes. After a period of time, the mixture expands and exerts an expansion force sufficient to crack the concrete (Suprenant and Malisch 1986). The use of nonexplosive demolition agents is shown in Fig. 4.3.5. Careful planning of the demolition work, including hole size, spacing, pattern, amount of water used, temperature, mixing of materials, loading of holes, curing, and safety provisions need to be addressed (Phares et al. 2014). The drilled holes are usually 1 to 2 in. (25 to 50 mm) in diameter to a depth of 0.5 to 10 ft (0.15 to 3.0 m) with a spacing of 6 to 24 in. (150 to 600 mm) (Phares et al. 2014). Shorter hole spacings are required in larger demolition applications, and expansive pressure is dependent on the thermal and moisture conditions of the surrounding concrete (Harada...
et al. 1993; Hinze and Brown 1994). Obtaining the desired crack propagation patterns to control the extent of the demolition has been the object of both manufacturer and research studies (Phares et al. 2014).

Practical considerations can limit use of these agents. Once placed in the holes, the mixture should be protected from running water. The material should be allowed to cure, otherwise the breaking force may not develop in the specified number of hours. Other equipment is required for complete removal of the concrete material. Safety considerations include wearing appropriate personal protective equipment during mixing and placing, as well as following manufacturer’s instructions due to danger from possible blowout of agent from the hole. The danger of blowout increases when working with larger diameter holes (Manning 1991). The material continues to be improved and a number of types of nonexplosive demolition agents are now available for different temperature conditions and reaction times.

![Fig. 4.3.5—Placement of nonexplosive demolition agent into holes (photo courtesy of Dynacem).](image.png)
4.3.6 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. 4.3.6). 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 820,000 lb (3650 kN), depending on the size of the unit (Manning 1991). Models are available 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). A splitter was used to remove concrete from chamber faces at Dashields Lock (Meley 1989) using 3-1/2 in. (90 mm) diameter holes.

This method is adaptable to a wide range of job conditions. An open face or space is typically needed on at least one side to allow for movement of the broken concrete, although it is also possible to remove large pieces of concrete (such as a pier cap) without working from a free surface (Manning 1991). 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 should be straight and of a specified diameter (Suprenant 1991). Advantages include the relatively low cost of this equipment, lack of dust and noise production, and ability to use underwater. Disadvantages include the amount of time required to perform the process, as well as the need for additional tools to cut reinforcing steel (Abudayyeh et al. 1998).
4.3.7 Demolition of concrete structures by heat—Thermal removal of concrete is often used in specialized applications using several techniques (Kasai 1988):

a) Boring and cutting by exposure to a high temperature source such as flame or plasma

b) Removal of the concrete cover by heating of reinforcing steel (typically by electrical methods)

c) Removal of concrete from the surface using direct application of heat

Advantages of these methods, particularly boring and cutting methods, include cutting speed, low noise, and effectiveness in areas with heavy steel reinforcement or in areas where other steel framing members are adjacent to the concrete (Abudayyeh et al. 1998). Worker safety is a consideration for use of all thermal methods due to both the potential exposure to heat as well as fumes. Additionally, thermal removal methods can impact the integrity of concrete allowed to remain in place and could be of concern (Vorster et al. 1992).

4.3.7.1 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 water to the cutter. A drive unit holds and moves the unit. This method has also been used in underwater applications.

4.3.7.2 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, but more commonly used lances provide heat up to 12,000°F (6700°C) (Vorster et al. 1992). 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 (Kasai 1988; Lazenby and Phillips 1978; Manning 1991).

4.3.7.3 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 facilitates its removal. Power requirements for these methods are high because the reinforcing bars may need to be heated to an excess of 750°F (400°C) to induce cracking (Mashimo et al. 1988).

4.3.8 Hydrodemolition—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 (4.2.3.5). Hand-held water-jet guns have been used to cut concrete (Abudayyeh et al. 1998). This method is vibration free and avoids danger associated with fire with the flame-cutting methods. Reinforcing bars are typically not cut or damaged, as shown in Fig. 4.3.8 (Kasai 1988; Manning 1991), although water-jet systems have been used with abrasives to cut reinforcing steel and for full demolition projects (Abudayyeh et al. 1998; Kasai 1988).
4.4—**Combined systems**

Often demolition of concrete structures (and of other components) uses multiple tools and techniques outlined previously. For example, bridge demolition often begins with removal of the concrete deck using hammer or shear methods, then subsequent removal of the girders using a crane or excavator (Bartosottelli and Avci 2013; Singh et al. 2008). Ultimately considerations include the loads that can be supported by elevated elements (Bartosottelli and Avci 2013), economics of production rate and capital cost of equipment (Vorster et al. 1992), safety, clearances, and other factors (Abudayyeh et al. 1998). Additional guidance on combined methods for removal for concrete pavements is presented in resources published by the Federal Highway Administration (2007) and the American Concrete Pavement Association (2009).

4.5—**Summary**

In this chapter, tools, systems, and methods available for removal of concrete are presented. Options available for removal of surface concrete and for more extensive removal or complete...
demolition of concrete structures are discussed, along with associated advantages and limitations.

For surface removal of concrete, guidance on achieving the desired final surface is presented, along with specification approaches. The condition of the final surface, which will be highly influenced by the method of concrete removal selected, is critical for bonding of new materials to the substrate concrete. A number of test procedures and specifications for achieving adequate bond are currently available, along with ACI 562.

Removal of concrete often uses multiple techniques and tools, as described in this chapter. Economic and safety considerations, along with project- and equipment-specific limitations will drive selection of the removal methods and tools for specific applications. If recycling or reuse of concrete removed from a structure is planned, the characteristics of the removed concrete need to be considered during selection of the removal equipment and technique(s). As described in this chapter, the various removal methods and pieces of equipment accomplish removal using a variety of methods, resulting in different particle sizes, removal efficiencies, and contaminant levels. The impact of the characteristics of the removed/demolished concrete on the collection, transport, and processing of the removed concrete for recycling should be considered. The effects of the demolition method on the characteristics of the aggregates produced are not well documented. If demolished concrete is to be used as recycled aggregate, appropriate specification provisions and QA/QC measures should be implemented to ensure the desired characteristics of the recycled aggregate are obtained.

CHAPTER 5—PRODUCTION AND PROPERTIES OF RECYCLED CONCRETE

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AGGREGATES

5.1—Introduction

A major problem most urbanized nations face is the decline of available waste disposal sites. The number of waste disposal sites are declining for a variety of reasons including a lack of space and environmental requirements. In particular, urban populations are becoming increasingly conscious of the environmental impact of instating new waste disposal sites and, as a result, local authorities are being met with increasing pressure to move the development of these sites to more remote locations. In combination, existing disposal sites within many urban areas are reaching their capacity. In conjunction, sources of high-quality aggregates that are suitable for use as aggregate in concrete are rapidly becoming depleted (Winfield and Taylor 2005). As such, alternative sources of aggregates that include reusing crushed concrete as aggregates has the potential to be a supplement to current virgin aggregate reserves. Recycled concrete aggregates (RCA) is viable for many concrete and construction applications. This chapter discusses the manufacturing processes required to produce quality RCA as well as their associated physical and mechanical properties.

5.2—Preparatory work

Production of recycled concrete aggregates (RCA) begins at a location where an existing concrete structure (building, bridge, road pavements, curb, or sidewalk) is being demolished. In the case of concrete pavements, they are first broken down into manageable sections (approximately 24 in. [600 mm]) using a large hydraulic drop/blade hammer or impact breaker. The pavements are then broken up with a large hooked instrument called a rhino-horn (due to its shape) mounted on a rubber-tired loader or excavator in place of the standard bucket. As the hook is pulled through the pavement, the sections are broken up and most of the reinforcement is removed. Demolition of

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concrete 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. Further information on demolition of concrete can be found in Chapter 4.

Hydraulic shears and torches can be used to remove 90 to 95 percent of the reinforcement. The remaining steel is then removed from the concrete at the final processing plant. Jaw-type crushers in particular have proven successful for processing materials with steel in them. At this stage, the separated reinforcing steel can also be sorted and recycled.

Once the concrete has been reduced to a suitable size for handling, it is then loaded onto 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.

5.3—Crushing and screening

It has been found that the equipment required to successfully crush concrete is not significantly different than that normally used in the crushing of natural aggregate with the exception of having to remove the reinforcing steel in demolished concrete structures (Hansen 1986). Notwithstanding this, only minor adjustments to the process are required to obtain the desired coarse fraction.

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 processing the initial large sections of concrete is by using a jaw crusher. The unprocessed material that is generally in the range of 12 to 16 in. (300 to 400 mm) is reduced to

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2-1/2 to 3 in. (64 to 76 mm) using this method. After discharge from the first crushing operation in the plant, the remaining reinforcing steel can readily be removed with a self-cleaning magnet run over the material. 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) maximum aggregate size. The aggregate produced using this method has typically been found to contain less than two percent of material passing the No. 200 (0.75 mm) sieve (Hansen 1986).

Once the steel is removed from demolished 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, if possible. Potential contaminants could include asbestos, plaster, wood, plastic, oil droppings, asphalt, and other nonmetallic building materials. Chloride-contaminated concrete is not recommended for use as RCA for reinforced concrete. Larger deleterious particles can be removed by hand or mechanical implements, but additional dry or wet processing may be required to remove all of the potential contaminants.

5.3.1 Plant design—Plants for processing crushed concrete into RCA are very similar to those plants where natural materials are processed. The effects of processing, handling, and beneficiation are discussed in ACI 221R. 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 and produces a higher uniformity within the finished aggregate (Hansen 1986). Typical schemes for aggregate processing through an open and closed system are shown in Fig. 5.3.1a and 5.3.1b, respectively. These diagrams represent what are referred to as first-generation plants. First-generation plants take demolished concrete that is free of deleterious materials and process them through a system of crushers and screenings. Initial sizes of the material can be up to 24 in. (600 mm) in size and, after successive crushing and screening processes, will produce graded aggregates.
for use in construction applications. The difference between the system in Fig. 5.3.1a and 5.3.1b is that the system described in Fig. 5.3.1b does not reintroduce the material that is produced from the secondary crusher into the screening process to be crushed a third (or more times) if the size of the material coming out of the secondary crusher is too large. Instead the system described in Fig. 5.3.1b will use that material as is. A second-generation plant uses similar equipment with minor variations but is capable of handling debris and removing of deleterious materials directly within the production process. The flow diagram for a typical second-generation plant is shown in Fig. 5.3.1c.

Fig. 5.3.1a—Flow chart of typical plant for closed system production of RCA from concrete debris free from deleterious materials.
Fig. 5.3.1b—Flow chart of typical plant for open system production of RCA from concrete debris free from deleterious materials.
Selective demolition to reduce individual fragments of broken concrete to a maximum of 400 – 700 mm (16 – 28 in)

Separate storage of concrete, brick, rubble, and mixed demolition debris which is heavily contaminated with wood, iron, plastics, and gypsum

Manual or mechanical pre-separation

By-pass of 10 – 40 mm (0.4 – 1.5 in) material

Primary screening

Primary crushing

By-pass of < 40 mm (1.5 in) material

Magnetic separation

Secondary screening

Secondary crushing

Manual or mechanical removal of remaining contaminants

Washing, screening, or air sifting

Fraction of concrete demolition waste and brick rubble < 40 mm (1.5 in)

Finish screening into size fractions according to needs

Removal of large pieces of wood, iron, paper, plastics, etc.

Removal of all minus 10 mm (0.4 in) fin material such as soil and gypsum

Removal of remaining ferrous matter

Removal of remaining contaminants such as plastics, paper, wood, and gypsum

Fig. 5.3.1c—Flow chart of typical production process of a second-generation plant from concrete containing deleterious materials.

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5.3.2 Crushers—Jaw crushers produce RCA of the particle size distribution required for quality concrete production. Cone crushers can be effectively used on concrete up to 8 in. (200 mm) maximum feed size and 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 Research 1983). Impact crushers not only break up the concrete but will also break up the aggregate particles (Building Contractors Society of Japan 1978). As discussed in 5.2, 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.

The high stresses applied often result in extensive destruction not only of the concrete, but also of the original natural aggregates (Nagataki et al. 2004). It is not possible to obtain clean RCA free of cement paste by using traditional crushers. Newer methods of crushing allow for the removal of an increasing amount of adhered mortar while avoiding overstressing of aggregates. After the traditional crushing, a second process using abrasion, such as the friction drum, rotation mill (Yanagibashi 2002), or other methods follows. Mueller and Linss (2004) describe a method using high-performance sonic impulses, which are generated by an electrical discharge under water. The resulting stress acts directly at the interfacial transition zone between the concrete and the natural aggregate. The experiments demonstrated that a high percentage of RCA can be produced that contain very little adhered mortar. However, Müller and Winkler (1998) found that, due to its high energy consumption of approximately 12 kWh per ton of concrete, this method was not competitive compared with common mechanical crushing methods such as using an impact crusher, which uses only 1.5 kWh per ton of concrete.
5.3.3 Processing and beneficiation—Most fine impurities such as dirt, gypsum, and plaster can be eliminated from the crushed concrete by screening. Nix (1984) reported that most lightweight materials were removed from crushed debris and brought to acceptance by wet screening. Heimsoth (1984) claimed that the same was achieved by dry screening process when impurities are heavier than water. Other beneficiation separation devices for removing lightweight contaminants are described in ACI 221R.

5.3.4 Crushed returned concrete as aggregate for new concrete—Every year, it is estimated that 2 to 10 percent (5 percent on average) of the estimated 455 million cubic yards of ready-mixed concrete produced in the U.S. is returned to the concrete plant (Obla et al. 2007). A common approach is to discharge the returned concrete at a location in the concrete plant for processing (Fig. 5.3.4a). The hardened discharged concrete can be subsequently crushed by a crusher (Fig. 5.3.4b) and the RCA (Fig. 5.3.4c) can be used as a portion of the coarse and fine aggregate components in new concrete. Therefore, this source of RCA and its methods of production is slightly different than those described in the preceding sections.

Figure 5.3.4a—Ready mixed concrete truck discharging returned concrete at the plant.
Figure 5.3.4b—Crusher used to produce returned concrete RCA at the plant.
Figure 5.3.4c—Returned concrete RCA stockpiled at the ready-mixed concrete plant.

Returned concrete RCA is different from standard RCA, which is made from controlled sources as well as construction debris that tends to have a high level of contamination (reinforcing bar, oils, deicing salts, and other building components). Returned concrete RCA on the other hand is prepared from concrete that has never been in service and thus likely to contain much lower levels of contamination.

The National Ready Mixed Concrete Association conducted a returned concrete RCA study at a ready-mixed concrete plant where three strength classes (1000, 3000, and 5000 psi) were produced (Obla and Kim 2009). The properties of coarse and fine RCA were compared to that of virgin aggregates. The RCA was not separated into coarse and fine size fractions when substituted at 300, 600, and 900 lb/yd$^3$ to evaluate its use in new RCA concrete. Some of the mixtures used the coarse fraction of the RCA (to replace virgin coarse aggregate) and a portion of the fine fraction of the RCA to replace virgin fine aggregate at different replacement levels. Compared to virgin aggregate, returned concrete RCA has lower specific gravity, higher absorption, higher percentage of minus 200 fines, and lower aggregate-weathering potential as measured by the sulfate soundness.
test. Both the coarse and fine fraction of the returned concrete RCA observed in this study satisfied most of the ASTM C33/C33M requirements for aggregates. In a series of studies by Butler et al. (2013, 2014, 2015), several RCA sources were compared, including one source of RCA produced from returned concrete. They found that the RCA produced from returned concrete demonstrated lower compressive strengths, modulus of elasticity, abrasion resistance, splitting tensile strengths, and bond strengths with reinforcing steel as compared to the other RCA sources derived from demolished older concrete structures. They noted that this may be due in part to the lower quality adhered mortar present on the RCA from hardened concrete. However, these research results are applicable only for the specific RCA sources evaluated.

5.4—Characteristics of recycled concrete aggregates

Recycled concrete aggregates (RCAs) are two-phase particles that consist of adhered mortar and the original virgin aggregate (Fathifazl et al. 2009; Kikuchi et al. 1998). Some particles may also be completely mortar phase or completely original virgin aggregate phase. The mortar phase consists of the original cement paste and the original virgin fine aggregate. The amount of adhered mortar contained in RCA, the manner in which it is adhered, and the interfacial transition zone between the adhered mortar and the natural aggregate significantly affect the texture, density, absorption capacity, soundness, and alkali-aggregate reactivity. The physical and mechanical properties of RCA are discussed in this section.

5.4.1 Particle size distribution—The particle size distributions produced when demolished concrete is crushed is generally independent of the quality of the concrete being crushed (Ravindrarajah 1996). Katz (2003) showed that concrete crushed in a jaw crusher set at a 1 in. opening, crushed at the different ages of 1, 3 and 28 days, with corresponding strengths of 1100
psi (7.4 MPa), 2100 psi (14.4 MPa), and 4100 psi (28.3 MPa), respectively, produced similar grading curves (Katz 2003). Once the materials have been processed, they should be sized for proper use.

Fine RCA with particle size predominantly below 0.18 in. (4.75 mm) can also be prepared. In such cases, the fine RCA tends to have a high amount of minus 0.003 in. (75 microns) material. In Obla et al. (2007), RCA produced from concrete that was returned to a ready-mix facility was prepared by sieving through a 38 mm sieve but without separating into coarse and fine fractions and found to have acceptable properties indicating that adequate grading can be achieved without overly complex grading and separating processes having to be involved.

5.4.2 Adhered mortar content—After crushing of old concrete, the resultant RCA is composed of both conventional aggregates and the old mortar, or adhered mortar. The adhered mortar portion can account for a significant portion of the RCA particle, with the exact amount being dependent on the properties of the original concrete demolished and the aggregate crushing and production process. In general, RCA with smaller nominal particle sizes have larger amounts of adhered mortar (Hansen and Narud 1983; Juan and Gutierrez 2009; Tu et al. 2006). The adhered mortar content can significantly impact aggregate properties such as absorption, density, abrasion resistance, and sulfate content. Etxeberria et al. (2007b) found that by using an impact crusher to crush old concrete, the adhered mortar content of the resulting RCA could be significantly lower compared to an RCA produced in a jaw crusher. It was also suggested that the adhered mortar on RCAs has a lower strength compared to the mortar produced in new concrete incorporating RCAs due to the presence of microcracks that can form during the crushing process.

The quality of the concrete being crushed will affect the amount of adhered mortar in each particle size. RCA sourced from concrete of lower strength will have more adhered mortar in the fine
fractions than RCA sourced from high-strength concrete. RCA sourced from higher strength concrete will have more adhered mortar attached to the conventional aggregates and in the coarser fractions of the material (Padmini et al. 2009). Additionally, the number of times that RCA is passed through crushing operations will affect the balance of adhered mortar to original virgin aggregate in the RCA. Crushing demolished concrete multiple times will result in reduced amounts of adhered mortar in the coarser fractions, and increased levels of adhered mortar in the finer fractions (Juan and Gutierrez 2009).

Several methods have been devised for measuring the amount of adhered mortar on RCAs. Hansen and Narud (1983) prepared RCA concrete cubes using red-colored cement. After being cut into slices and polished, the new red-colored mortar and old adhered mortar were clearly distinguished. A linear traverse method similar in principle to ASTM C457/C457M was used to determine the adhered mortar content. This method was also successfully employed by Abbas et al. (2008). This method is quite intensive, however, and requires skilled knowledge of image processing and analysis.

Other common removal methods for measuring the amount of adhered mortar on RCA involve immersing the RCAs in a solution of hydrochloric acid. This method works to dissolve the cement paste and has been shown to produce acceptable results (Gokce et al. 2004; Nagataki et al. 2004; Poon et al. 2004). However, this method cannot be used on RCAs containing original limestone aggregates, which are susceptible to acid dissolution (Juan and Gutierrez 2009).

Abbas et al. (2008) used a combination of sulfate attack and freezing-and-thawing treatment to remove adhered mortar from RCAs. A saturated sodium sulfate solution helped to chemically degrade the mortar-aggregate bond while the freezing-and-thawing action created internal stresses.
91 to assist in the further degradation of mortar-aggregate bond. The results of this study were also
verified by image analysis.

Another method used for the removal of adhered mortar from RCAs was proposed by Juan and
Gutierrez (2009). The RCA was subjected to temperatures in excess of 400°C for a period of 1
hour and then rapidly cooled in cold water. The sudden increase in temperature caused internal
thermal stresses that were able to weaken the mortar-aggregate bond. A study conducted by Butler
et al. (2011) evaluated several methods for removing adhered mortar, including hydrochloric acid
dissolution, freezing-and-thawing, sulfate attack, and the thermal treatment method. They
concluded that the thermal treatment method proposed by Juan and Gutierrez (2009) was the most
effective at removing the adhered mortar; however, it was also the most energy intensive.

5.4.3 Particle shape—RCA particles are generally coarse and angular compared to virgin
aggregate. Additionally, RCA produced from jaw crushers is generally coarser and have a higher
level of flat particles than RCA produced using impact crushers (Müller and Winkler 1998). Fine
RCA is generally coarser than the fine aggregates specified by ASTM C33/C33M. They are
coarser than generally all standard sands used in production of concrete (Obla et al. 2007). Hansen
(1986) concluded that the fine size fraction of RCA particles is somewhat coarser and more angular
than that needed to produce good quality concrete. The results of these studies also indicated that
this coarseness and increased angularity are part of the reason that concrete made with these
materials tend to reduce workability. Adding a portion of a finer natural blending sand to the fine
size fraction of RCA can produce materials with suitable concrete-making properties (Hansen
1986).

5.4.4 Texture—When recycled concrete is crushed using mechanical means, some of the natural
aggregate particles will split, causing fresh surfaces to form, not just in the adhered mortar, but

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also in the natural aggregate phase. Typically, jaw crushers produce a smaller proportion of split
particles than impact crushers. The surface texture of RCA is typically rough and porous
(Ravindrarajah 1996); however, this will depend on the amount of adhered mortar in a given
fraction size, and the surface texture of the original conventional aggregate. Butler et al. (2014)
measured the amount of adhered surface moisture on RCA particles at their saturated surface dry
condition for several RCA types. They postulated, through comparisons with visual observations,
that the larger the amount of adhered surface moisture on an RCA surface, the more roughened its
surface. They were able to find correlations between the amount of adhered surface moisture and
the slump of several RCA concretes proportioned with constant w/cm.

5.4.5 Density—The density of RCA will be variable depending on the original virgin aggregates
used in the source concrete, the density of the source concrete, and the amount of adhered mortar.
Densities are generally lower for RCA than for standard virgin aggregates (Dhir et al. 1999).
Additionally, the amount of processing performed on the RCA can have a significant effect on the
density. This is because as the aggregates successively undergo the various crushing procedures,
additional adhered mortar (which has a lower density than the virgin aggregate) is removed, and
the RCA density increases (Gokce et al. 2004).

5.4.6 Absorption—One of the most marked physical differences between RCA and virgin
aggregates is RCA’s higher water absorption. Hansen (1986) and Dhir et al. (1999) concluded that
the higher water absorption of the coarse RCA fraction is a result of the absorption of the adhered
mortar. Absorption values typically range from 3 to 10 percent for the coarse size fraction of RCA,
depending on the concrete being recycled, and from 3 to 8 percent for fine size fraction of the RCA
(Gómez-Soberón 2002; Poon et al. 2004; Shayan and Xu 2003; Tam et al. 2008). Absorption
capacity also increases as adhered mortar content increases (Gokce et al. 2004; Nagataki et al.
due to the porous nature of the adhered mortar. Dry RCA absorbs water during and after mixing. To avoid this, RCA should be prewetted or stockpiles should be kept moist (Environmental Council of Concrete Organizations 1990) just as if it were a lightweight aggregate. Adjusting dosages of water-reducing admixtures can also aid in workability problems caused by the high level of absorption from RCA.

5.4.7 Abrasion resistance—ASTM C33/C33M indicates that aggregates for use in concrete construction should have abrasion loss of less than 50. Abrasion resistance of RCA submitted to the Los Angeles abrasion loss test has been shown to be variable and highly dependent on the amount of adhered mortar. The applicability of the Los Angeles abrasion test to RCA is questionable considering the aggressiveness of the test and the nature of RCA. The Los Angeles abrasion test is performed by placing the aggregates in a steel drum with steel balls, the drum is then rotated for a period of time, and the mass loss of the aggregates after the test can be correlated to the abrasion resistance of the aggregates. Work using RCA in this test showed that much of the adhered mortar was ground to powder during the test, causing the aggregates to rate as having a low abrasion resistance (Juan and Gutierrez 2009). Therefore, when using RCA, the Los Angeles abrasion test should only be used in conjunction with other abrasion tests methods in which the concrete system (such as ASTM C944/C944M) and not just the abrasion resistance of the aggregates are recommended for determining the abrasion resistance of RCA concrete.

5.4.8 Freezing and thawing—Sulfate soundness tests (ASTM C88/C88M) are required by ASTM C33/C33M and fine and coarse size fractions of RCA may be tested by ASTM C88/C88M to ensure that appropriate freezing-and-thawing durability of the RCA. However, Obla et al. (2007) found the applicability of the sulfate soundness test to RCA questionable because other mechanisms such as sulfate attack might increase mass loss of the RCA in the test. Gokce et al.
performed a series of tests to determine the reliability of the sulfate soundness test (ASTM C88/C88M) relation to RCA. RCA was tested both in ASTM C88/C88M as well as in ASTM C666/C666M. The concrete used in ASTM C666/C666M was air-entrained concrete made with RCA. It was found that samples that met the performance requirements of ASTM C666/C666M could still fail the requirements of ASTM C88/C88M. This was because the chemical attack caused by the sulfate solution caused the bond between the adhered mortar and original virgin aggregates to breakdown, resulting in high mass loss and skewing the results of the test (Gokce et al. 2011). Therefore, it is not suggested that RCA be tested according to ASTM C88/C88M. Alternatively, aggregates should be tested according to ASTM C666/C666M to demonstrate satisfactory results in concrete subjected to freezing and thawing. Freezing-and-thawing resistance of RCA concrete is covered in Chapter 7.

5.4.9 Alkali-reactive aggregate—RCA used as aggregate in new concrete possesses potential for alkali-silica reaction (ASR) if the old source concrete contained reactive aggregate. Several scenarios exist that should be evaluated. The first is the case where the reaction has stopped due to either the unavailability of alkalis, consumed by the reaction, or the unlikely event that the reactive silica in the aggregate has been consumed. The second scenario is that the alkali content of the original concrete was too low to initiate ASR, but the alkali levels in the new concrete made with RCA may be high enough to activate ASR. The third scenario is a case where the original concrete did not have access to moisture to drive the reaction, but when demolished and used as an RCA, enough moisture is present to start the reaction. The fourth and final scenario is that the reaction is ongoing. The fourth case should be evaluated and properly mitigated. The first, second, and third scenarios are very problematic and should be given consideration prior to using the RCA in an RCA concrete. There is a high likelihood that the new portland cement used in the RCA
concrete will have a higher alkali content than the original concrete due to modern day cements having higher alkali contents. All scenarios should be considered in the petrographic and laboratory evaluation of the concrete that was used to produce the RCA.

RCA derived from concrete that has been predicted to be potentially reactive (due to ASR occurring in the original concrete or a reactive history of the original natural aggregate) should be evaluated for remaining ASR potential (Gress and Kozikowski 2000). Recent work has shown that current test methods may be valuable in assessing the ASR of RCA. It has been found that the ASTM C1260 and ASTM C1293 tests are both capable of registering reactivity of ASR susceptible RCAs (Adams et al. 2013; Obla et al. 2007; Shehata et al. 2010). It is important to note, however, the reactivity of RCA seen in the accepted test methods has not been correlated to performance in the field. Therefore, the limits of expansion imposed by the standard test methods may not be applicable for use with RCA. It is suggested that if potentially reactive RCA is used in the field, mitigation techniques should be employed to protect against potential damage.

Additionally work by Adams et al. (2013) showed that crushing of the aggregates had a significant effect on the reactivity of the aggregates. The more processed (more successive passes through a crusher) an RCA was, the more reactive it became. Further work by Beauchemin and Fournier (2012) found that this was due to the increased amount of original reactive virgin aggregate, and reduced amount of adhered mortar after successive levels of crushing. ASR in RCA concrete is discussed in Chapter 7.

5.4.10 Contaminants and Leaching—Concrete rubble often includes contaminants such as asphalt, chlorides, cladding, soil and clay balls, glass, gypsum board, hardboard, iron, joint sealants, lightweight brick and concrete, paper, plaster, plastics, rubber, steel reinforcement, tile, vinyl, wood, and roofing materials of various kinds. Maximum allowable limits on contaminants should

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be based on final use of the RCA. Generally, applications that require little processing to remove debris include:

a) Various general bulk fills  
b) Embankment stabilization  
c) Base or fill for drainage structures  
d) Road construction  
e) Noise barriers  
f) Architectural landscaping applications  

Contaminants are a concern when RCA is to be used in RCA concrete. However, dust and fines that cling to the coarse size fraction of the RCA are of little consequence in RCA concrete, and washing is not required. Contaminants usually are of no concern in non-concrete-aggregate applications, except in special cases of unbound base (Bruinsma and Snyder 1995), which is discussed in detail in Chapter 6. Soil and clay balls can be especially troublesome. The presence of clay in a concrete mixture increases water demand and reduces strength. Furthermore, clay balls can cause popouts if located near a concrete slab surface. Some recycling contractors use a 1 in. (25 mm) scalping screen ahead of the primary crusher to remove soil and clay balls from broken concrete. However, this step may not be necessary if care is taken by the loader operator to exclude soil or base material while removing old concrete in contact with the ground—foundations, floors, pavements, walks, curbs, and gutters.

Environmental Council of Concrete Organizations (1990) suggest limits for structural grade concrete for various contaminants as listed in the following:

a) Asphalt—1 percent by volume  
b) Gypsum—0.5 percent by mass of SO₃

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c) Organic substances—0.15 percent by mass

d) Soil—refer to limits in ASTM C33/C33M

e) Chlorides—refer to limits in ACI 318

f) Glass—none should be tolerated because conventional glass may cause ASR as well as cracking and popouts in concrete

Additional limits on various contaminants were also noted in 5.4.4 and 5.4.6.

RCA is typically stored in stockpiles or used as fill material or rip rap; all of which result in the material being are exposed to the elements. As rainwater washes through the stockpiled aggregates, it will run off and enter local ecosystems. The water runoff may cause the leaching of heavy metals from the concrete into the environment. A study performed by Sadeki et al. (1996) for the Minnesota Department of Transportation provided insight into the contaminants present in leachate from an RCA stockpile. In this study, the leachate pH and chromium concentration exceeded Minnesota standards for surface waters. Research by Müeller and Winkler (1998) has shown, however, that the heavy metals leached from RCA are extremely low and meet typical leaching environmental standards. Nevertheless, to protect the quality of ground and surface water, an RCA stockpile should be positioned some distance away from surface waters, and stockpile management should include measures for controlling runoff (such as berms, straw bales, and filter channels) (Sadeki et al. 1996).

5.5—Current guidelines and standards for RCA

There have been a number of national and international standards and guidelines that have been produced on the use of RCA in the production of new concrete. In particular, many of these...
standards limit the use of RCA in new concrete for specific applications based on specified measured aggregate properties.

5.5.1 ASTM International—Similar to the aggregate requirements in CSA A23.1/A23.2, ASTM C33/C33M does not contain specific provisions or evaluation criteria for the use of RCA in concrete, although it does permit the use of crushed hydraulic-cement concrete as aggregate. It provides a cautionary note regarding the possible effect of RCA on water demand, and possible durability concerns when using RCA; however, no specific limits are provided.

5.5.2 American Association of State Highway and Transportation Officials (AASHTO)—AASHTO M 80 does not contain specific provisions or evaluation criteria for the use of RCA in concrete, although it does permit the use of crushed concrete as aggregate. Any aggregate produced from crushed concrete should meet the requirements of AASHTO M 80. Prior to the addition of this provision in AASHTO M 80, AASHTO MP 16 controlled the use of RCA in concrete. AASHTO MP 16 was removed from the AASHTO standards in 2017, however.

AASHTO MP 16 presented mainly nonstructural uses for RCA in concrete (for example, sidewalks, curbs, median barriers, and cement-treated base courses). A classification system was used to categorize an RCA source according to deleterious substance limits and weathering exposure conditions. Three classes of RCA were proposed: Class A for severe exposure, Class B for moderate exposure, and Class C for negligible exposure. Table 5.5.2 presents the physical properties requirements of RCAs as outlined in AASHTO MP 16. Given the level of detail and guidance provided, AASHTO MP 16 appears to represent the most thorough standard/guideline that has been developed for use of coarse RCA in concrete in North America, though it no longer is part of the AASHTO specifications.

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Table 5.5.2—RCA physical properties limitations as per AASHTO MP 16

<table>
<thead>
<tr>
<th>Items</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum LA abrasion loss, %</td>
<td>50</td>
</tr>
<tr>
<td>Soundness loss, %</td>
<td>12 (using Na₂SO₄)</td>
</tr>
<tr>
<td></td>
<td>18 (using MgSO₄)</td>
</tr>
<tr>
<td>Amount of material passing test sieve 75µm, %</td>
<td>1.5</td>
</tr>
<tr>
<td>Chloride ion content</td>
<td>0.6 lb/yd³ concrete</td>
</tr>
</tbody>
</table>

*To convert from lb/yd³ to kg/m³ multiply values by 0.59.

5.5.3 Canadian Standards Association (CSA)—Current Canadian standards do not contain specific requirements or provisions for the use of RCA as aggregate in concrete. CSA A23.1/A23.2 recommends that RCA may be evaluated in a similar manner as normal-density aggregates. In addition, the following parameters should be assessed: durability characteristics, deleterious materials, potential alkali-aggregate reactivity, chloride contamination, and workability characteristics of resulting concrete. Acceptance criteria for use of an aggregate for a particular concrete application are the same as those used for natural aggregate.

5.5.4 European guidelines (RILEM)—The European specification for use of recycled aggregate in concrete (RILEM Technical Committee 121 1994) was published as a recommendation report. This report addresses coarse recycled aggregates derived from demolished masonry rubble (defined as Type 1), demolished concrete rubble (Type 2), and a combination of demolished concrete and natural aggregates (Type 3). Ranges for various aggregate properties are outlined and used to classify a particular RCA source as either Type 1, 2, or 3 and are presented in Table 5.5.4. In addition, based on the RCA type, provisions for use as concrete aggregate along with a set of strength limits and durability compliance criteria are provided.

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### Table 5.5.4—RCA properties limitations as per RILEM Technical Committee 121 (1994)

<table>
<thead>
<tr>
<th>Mandatory requirements</th>
<th>RCA Type I</th>
<th>RCA Type II</th>
<th>RCA Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum dry particle density, kg/m³</td>
<td>1500</td>
<td>2000</td>
<td>2400</td>
</tr>
<tr>
<td>Maximum water absorption (% m/m)</td>
<td>20</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Maximum content of material with SSD &lt; 2200 kg/m³ (% m/m)</td>
<td>-</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Maximum content of material with SSD &lt; 1800 kg/m³ (% m/m)²</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maximum content of material with SSD &lt; 1000 kg/m³ (% m/m and % v/v)</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum content of foreign materials (metals, glass, soft material, bitumen) (% v/v)</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maximum content of metals (% m/m)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maximum content of organic material (% m/m)</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum content of filler (&lt;0.063 mm) (% m/m)</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum content of sulfate (% m/m)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Water saturated-surface-dry condition (SSD).  
†If the maximum allowable content of sand is exceeded, this part of the aggregates should be considered together with the total sand fraction, refer to RILEM Technical Committee 121 (1994).  
‡Water soluble sulfate content calculated as SO₃.

#### 5.5.5 Japanese Industrial Standard—The Japanese Standards Association separates recycled aggregates into two separate categories: low-quality Class L and high-quality Class H recycled aggregates. However, it does not define RCA differently from other types of recycled aggregates (such as previously used natural aggregates or aggregates with all adhered mortar removed). Class L aggregate concrete includes backfilling, filling, and leveling concrete applications whereas Class H can be used for normal concrete applications. The standards for use of Class L and Class H recycled aggregates in concrete are JIS 5023 and JIS 5021. Table 5.5.5 outlines the physical properties requirements for Class H recycled aggregates. Additional provisions are provided on the limits of deleterious substance amounts in recycled aggregates. Limits presented in Table 3 are fairly comparable to those for conventional aggregates and, as a result, make the Japanese standards for high-quality coarse and fine RCA fairly stringent as compared to similar North American and European guidelines.

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Table 5.5.5—Physical aggregate properties requirements for Class H recycled aggregate

<table>
<thead>
<tr>
<th>Items</th>
<th>Coarse aggregate</th>
<th>Fine aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven-dry density, g/cm³</td>
<td>not less than 2.5</td>
<td>not less than 2.5</td>
</tr>
<tr>
<td>Water absorption, %</td>
<td>not more than 3.0</td>
<td>not more than 3.0</td>
</tr>
<tr>
<td>LA Abrasion, %</td>
<td>not more than 35</td>
<td>NA</td>
</tr>
<tr>
<td>Solid volume percentage for shape</td>
<td>not less than 55</td>
<td>not less than 53</td>
</tr>
<tr>
<td>determination, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of material passing test sieve 75 µm, %</td>
<td>not more than 1.0</td>
<td>not more than 7.0</td>
</tr>
<tr>
<td>Chloride ion content*</td>
<td>not more than 0.04</td>
<td>not more than 0.04</td>
</tr>
</tbody>
</table>

*Measured in percent weight of hardened concrete.

5.5.6 German Institute for Standardization—Updated in 2002, DIN 4226-100 allows the use of RCA in new concrete provided it satisfies the requirements of a particular aggregate class. Four separate classes of RCA are presented and classified according to Table 5.5.6.

Table 5.5.6—German standards on use of RCA in concrete (DIN 4226-100)

<table>
<thead>
<tr>
<th>Constituents, % by mass</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete and natural aggregates according to DIN 4226-100</td>
<td>≥ 90</td>
<td>≥ 70</td>
<td>≤ 20</td>
<td>≤ 80</td>
</tr>
<tr>
<td>Clinker, no porous clay bricks</td>
<td>≤ 10</td>
<td>≤ 30</td>
<td>≥ 80</td>
<td></td>
</tr>
<tr>
<td>Calcium silicate bricks</td>
<td></td>
<td></td>
<td>≤ 5</td>
<td></td>
</tr>
<tr>
<td>Other mineral materials (for example, porous brick, lightweight concrete, plaster, mortar, and porous slag)</td>
<td>≤ 2</td>
<td>≤ 3</td>
<td>≤ 5</td>
<td>≤ 20</td>
</tr>
<tr>
<td>Asphalt</td>
<td>≤ 10</td>
<td>≤ 30</td>
<td>≤ 1</td>
<td></td>
</tr>
<tr>
<td>Foreign substances (for example, glass, plastic, metal, wood, and paper)</td>
<td>≤ 0.2</td>
<td>≤ 0.5</td>
<td>≤ 0.5</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Oven dry density, kg/m³</td>
<td>≥ 2000</td>
<td>≥ 2000</td>
<td>≥ 1800</td>
<td>≥ 1500</td>
</tr>
<tr>
<td>Maximum water absorption after 10 minutes, %</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>No limit</td>
</tr>
</tbody>
</table>

CHAPTER 6—USE OF RECYCLED CONCRETE AGGREGATE IN UNBOUND

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APPLICATIONS

6.1—Introduction

Compacted unbound granular aggregate materials are used in many construction applications, such as bedding and backfill for pipe and precast elements (Taylor and van Dam 2012); backfill for structures and drainage applications (Bruinsma et al. 1997); and as subbase, base, and working platform applications for various types of pavements and slabs (Arulrajah et al. 2014; Poon and Chan 2006). In many cases, recycled granular materials, such as crushed recycled (or reclaimed) concrete aggregate (RCA), can be used in these unbound aggregate applications (Poon and Chan 2006). The two general types of granular aggregates used are dense-graded aggregates when mechanical strength and low permeability are desired, and open-graded aggregates when permeability is needed for drainage applications.

At a recent workshop (Lat-RILEM International Workshop on Recycled Aggregate. Santa Clara, Villa Clara, Cuba 2017), experts tackled the problems of source depletion and future supply issues related to this critical construction material.

RCA is an excellent material for use in unbound applications. This was shown by a survey conducted by the Federal Highway Administration (2004), which confirmed that many concrete pavements currently replaced are recycled as unbound base material. The economics of using RCA as unbound base improves significantly in metro areas due to disposal costs, higher cost of virgin materials, and increased transportation costs. Superior foundation support is easily obtained using RCA as unbound base material. The environmental benefits of using RCA as unbound base material are significant in many aspects including sustainability, lower CO₂ emissions, less fuel consumption, less use of higher value virgin aggregates, and sequestering of CO₂ from the atmosphere.
The source of RCA is generally not significant for unbound base applications. Even concrete showing distress from freezing and thawing, D-cracking, or alkali-silica reaction can effectively be used as unbound base material because any minor swelling or breakdown of particles after compaction in place will generally not be an issue. However, RCA should not be used where there is a potential for sulfate or acid exposure from subgrade soils, groundwater, or other external sources, unless it has been extensively evaluated for sulfate attack, acid attack, or both. The exposed cement paste in the RCA can be vulnerable to acids and sulfates.

Although RCA effluent can have increased pH, especially during the first flush cycle, it has no buffering capacity, and therefore has no significant environmental impact when used as unbound base and drainage material. RCA, like concrete, can deteriorate in acidic environments such as landfills and can decompose in such harsh environments into its original components.

It has already been found that the exposed calcium hydroxide in concrete can get carbonated under atmospheric conditions, and the generated calcium carbonate can help healing cracks (Li and Yang 2007). This mechanism is also viable for RCA materials. Moreover, it is possible for the RCA fines to accumulate and harden in the presence of CO$_2$ to create a material called tufa, which can be problematic in poorly designed filter fabric drainage designs (Kim et al. 2014).

Studies indicate that calcium-based compounds are present in RCA in sufficient quantities to be precipitated and leached in the presence of atmospheric carbon dioxide (Bruinsma et al. 1997; Dri et al. 2013; Grabiec et al. 2012). Selective grading and blending with virgin aggregates may reduce this precipitation potential significantly. It has been found that the precipitated and insoluble residue can reduce permeability of typical drainage filter fabric, but not that of most pipe drains. Using RCA fines (0.2 in. [4.75 mm] minus materials) should be avoided below any drainage layer (Snyder and Bruinsma 1996).

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Testing criteria for RCA are similar to those required for virgin aggregates, except for the sulfate soundness test, which can attack the paste fraction, as would be expected for portland cement products. This test, along with the aggressiveness of the Los Angles abrasion test, require special consideration when evaluating RCA for use as unbound material. Sulfate soundness testing is typically eliminated and the limit on Los Angeles abrasion is increased to up to 50 percent on RCA specifications (Kuo et al. 2001).

6.2—Chemistry

The chemistry of portland cement hydration should be considered in the discussion of the fate of a recycled concrete aggregate (RCA) particle subjected to the environmental conditions expected when it is used as unbound base and drainage material. The major components of portland cement clinker (C₃S and C₂S) produce calcium silicate hydrate (CSH) and calcium hydroxide (Ca(OH)₂ or CH) during cement hydration reactions. While the hydration reactions of C₄AF and C₃A consume some CH, when hydration reactions are complete, a significant amount of CH remains throughout the hydrated cement paste. The quantity of the CH varies depending on the type of portland cement and can be as high as 25 percent. The stability of the CSH is dependent on the pH of the pore water, which depends in turn on the presence of CH. If the pH of the pore water is significantly reduced, the CSH structure can be weakened.

A concrete mixture initially containing 600 lb (272 kg) of portland cement would result in the development of 150 lb (68 kg) of CH, which is dispersed in approximately 4000 lb (1810 kg) of concrete, resulting in approximately 4 percent CH on a weight basis of the concrete produced. CH is slightly soluble in water, approximately 0.18 percent at 32°F (0°C) (NIOSH 2016). The solubility of CH decreases with higher temperatures. CSH normally has an extremely fine pore

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system, with a surface area comparable to that of activated carbon. Hence, the coefficient of permeability of cement paste having small capillary voids with little connectivity can be of the order of $10^{-13}$ in./second ($10^{-12}$ cm/second) and even lower, of the order of $10^{-12}$ in./second ($10^{-11}$ cm/second), beyond 28 days of age. Thus, it is generally difficult for the CH phase inside concrete to get carbonated within the surrounding dense CSH gel. However, in crushed RCA materials, upon exposure to air, the CH can gradually react with the ambient CO$_2$ to form more stable calcium carbonate.

6.3—Leaching

As mentioned previously, recycled concrete aggregate (RCA) is obtained by crushing original concrete materials, which normally contain an abundant CH phase. During the crushing process, this CH phase will be exposed to the external environment. CH in the exposed or near-surface RCA particles would be available to go into solution during rainfall. The initial rain drops would rapidly supersaturate with 1.8 grams of Ca(OH)$_2$ per liter of water. The runoff water would have a pH of approximately 12.5 with no buffering capacity. However, the 12.5 pH would quickly neutralize to a pH of 7 when it encountered soil. If the rain continues, the flushing of the Ca(OH)$_2$ would quickly diminish because the low permeability of the CSH hinders any fast transport of pore fluid. The end result is that the large quantity of Ca(OH)$_2$ present in the RCA would not be quickly available to go in solution, but the process would slowly continue towards that goal, with a pH of somewhere around 8, slightly above neutral pH. A realistic time period to extract or carbonate of all the Ca(OH)$_2$, even if subjected to acid rain, would be in the order of several hundred years (Bruinsma et al. 1997; Pade and Guimaraes 2007), long after the design life of the base.
Studies on RCA leaching revealed different results. Earlier research showed that RCA brought from diverse sources had relatively high-pH leaching and heavy metal leaching including arsenic, chromium, lead, and selenium, which exceeded the maximum contaminant level of the U.S. drinking water standard as stipulated by the EPA (Chen et al. 2013). Former studies showed that the leaching of metals from RCA (that is, chromium, copper, iron, and zinc) was below permissible EPA limits for potable water (Chen et al. 2013). Also, alkaline leaching decreased over time (Abbaspour et al. 2016a). Stockpiling of RCA over a 1-year period decreased the adverse effect of corrosive leachate (decrease in pH from approximately 11.5 to 10) (Abbaspour et al. 2016b). Based on these results, it is still uncertain whether RCA materials will lead to pH elevation of groundwater and further investigation is still needed.

6.4—Hazardous waste

There is some misconception that concrete would leach hazardous waste under normal environmental exposure conditions. This misconception may have been created due to the nature of some of the EPA toxicity tests that were designed to simulate low pH conditions found in landfills. The results of such tests should not be directly transposed to concrete under normal field exposure conditions. The environmental conditions that exist in and around subsurface foundations (buildings, pavements, fill) are generally not as acidic and it is therefore unlikely for the CSH system to be destroyed allowing metals in RCA to be released and mobilized.

There is literature on hazardous waste solidification and stabilization using portland cement and other binders (Batchelor 2006; Li et al. 2001; Malviya and Chaudhary 2006). The levels of potentially hazardous leachates from RCA are much lower than those in applications of cementitious binders in hazardous and radioactive waste stabilization. Thus, it is expected that the...
cementitious matrix will continue playing a stabilization role of leachates in RCA. However, this aspect needs further investigation using RCA from different sources and grades.

6.5—Tufa and carbonation

It is possible under certain conditions to compromise the drainage ability of base drainage materials made from RCA. This is especially possible if the RCA grading is too fine and the geo-fabric filter material is improperly used in the drainage design. The reduced flow properties are caused by the contamination of fines and dust at flow restricted areas. The material that collects in these instances is referred to as Tufa. Naturally occurring Tufa is geologically defined as a rough, thick, rock-like calcium carbonate deposit that forms by precipitation from bodies of water with high dissolved calcium content. This process is both physical and chemical. Fines moving with moisture containing Ca(OH)₂ generated physically from RCA can accumulate in restricted flow areas and upon drying, while still in the presence of moisture and CO₂, can form a precipitate like material, known as Tufa.

RCA may effectively be used as a drainage material by properly designing the drainage system. Eliminating the minus sieve #4 material, if possible, is the most effective single strategy. Washing the RCA to remove dust and unwanted fines was shown by Snyder and Bruinsma (1996) to have a very positive effect on minimizing the creation of Tufa. The study showed that RCA can produce precipitate that could compromise drainage if the system was not properly designed. This becomes more problematic when geo-fabric filters and no conventional pipe drains are used. If a geo-fabric filter is used, the drainage system should be designed such that water flows parallel to the geo-fabric material and not through it. This design procedure should prevent clogging.

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6.6—Freezing-and-thawing resistance and D-cracking

A damage phenomenon can occur in some porous aggregates when they undergo freezing while its pores are critically saturated with water. Tensile stresses caused by hydraulic pressures when the water freezes cause cracking of the aggregate particles, which can radiate into the cement paste. The surface visible cracks develop a characteristic pattern of fine cracks paralleling slab joints and resembling a D and known as D-cracking. D-cracking is a function of the aggregate size and its pore structure. Each aggregate tends to have a unique critical size below which D-cracking ceases to occur. In many cases, recycling portland cement concrete inherently reduces the original aggregate size within a given RCA particle. It is therefore possible to eliminate D-cracking in RCA by controlling the crushing process such that RCA particles below the critical size are produced. This has been shown to be successful in some highway recycling projects (Snider 2004).

A classic case of a failure of an unbound RCA base originating from a concrete that had structural issues, but no materials-related distress, occurred at Holloman Air Force base in New Mexico (Rollings et al. 2006). The unbound base was subjected to a high water table with a high concentration of sulfate, typical of New Mexico. Shortly after construction, heaving from sulfate attack began and, in some cases, resulted in an upward movement of up to 3 in. (76 mm). The conclusions of the project suggested that sulfate attack should be of concern when considering the use of RCA for unbound base in the presence of sulfate rich groundwater (Rollings et al. 2006). The misinterpretation of this unbound base failure as being caused by the RCA versus the hostile environment it was placed in, has had a negative impact on the use of RCA base materials in airport facilities.

The resistance to freezing-and-thawing cycles of RCA is normally low compared to that of virgin aggregates due to the relatively high water absorption tendency of the RCA (Gokce et al. 2004).
Lowering the w/c can enhance the freezing-and-thawing resistance but may not reach acceptable levels. However, the use of entrained air can significantly increase the resistance to freezing and thawing of RCA (Salem et al. 2003).

6.7—Sulfate attack

Chemical sulfate attack in cement-based materials is a chemical reaction that can result in expansion and associated damage. The reaction between sulfates and calcium aluminate hydrate in the presence of water results in the creation of ettringite, which occupies a larger volume. If RCA is used in an environment having water rich in sulfate ions, sulfate attack of the RCA can occur. Conditions leading to sulfate attack are either the result of contamination of the recycled concrete by products containing sulfates, such as wallboard (from gypsum), or when an RCA unbound base is placed in an environment with external sulfate ions such as groundwater.

6.8—Alkali-silica reaction

Alkali-silica reaction (ASR) is a deleterious chemical reaction that occurs when aggregates incorporating reactive silica are in contact with high pH pore water in cementitious matrixes. The silica combines with alkalis in the presence of calcium and forms a gel that swells in the presence of external moisture, creating internal stress within the aggregate and surrounding cementitious matrix. The high pH is normally a result of soluble alkalis, which increases OH\(^-\) to the point that the high energy silica in aggregates disassociates and goes into solution. Depending on the properties of the expansive gel, it can induce cracks in both the cement paste and aggregate particles (Mehta and Monteiro 2017).

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RCA obtained from concrete with active ASR requires special consideration prior to its further application. For instance, if the ASR-active RCA is to be used as an unbound base material, then no special testing needs be considered. Even though the unbound base is in an environment conducive to continuing ASR expansion, the total possible expansion is trivial relative to the available void space within the base itself. Hundreds of miles of ASR RCA base have been used over the last 20 years by various state highway agencies without ASR-related problems. It should also be noted that sequestering of CO$_2$ on the surface of RCA tends to lower the pH, which protects the surface of RCA from ASR. Conversely, if RCA is to be used in new concrete, then additional testing should be conducted, as discussed in Chapter 7.

6.9—Summary

State-of-the-art practice demonstrated that RCA can be a suitable construction material in subbase applications owing to its appropriate strength and similar size distribution to normal aggregates. The application of RCA in unbound subbase allows effective recycling practice and sustainable construction. However, environmental concerns regarding the use of RCA materials have not been fully resolved. Moreover, the effect of RCA on the durability of the subbase needs further investigation. Based on the noted research and discussion of existing practice, the application of RCA in subbase is summarized in the following:

a) The used RCA can possibly increase the pH of groundwater due to leaching of Ca(OH)$_2$ from the DCA, especially in the case of freshly produced RCA. Rain water along with released Ca(OH)$_2$ can lead to the formation of Tufa materials, which can block drainage. The leaching of Ca(OH)$_2$ can be mitigated by the carbonation of the RCA.
b) The leaching of any hazardous trace content, such as heavy metal ions from RCA, is generally insignificant and would be observed in most cases.

c) Subbases built using RCA can generally have similar or even better durability performance compared to that of similar subbases made with normal aggregates, including resistance to sulfate attack, alkali-silica reaction, and damage by freezing-and-thawing cycles.

CHAPTER 7—PRODUCTION AND PROPERTIES OF CONCRETE WITH RECYCLED CONCRETE AGGREGATES

7.1—Introduction

The use of recycled concrete aggregate (RCA) is beginning to reach maturity in many countries. Nations including Canada, the United Kingdom, Germany, China, and Japan have developed specifications and guides for use of RCA in concrete (refer to 5.5 for further details). In the United States, ASTM C33/C33M acknowledges the use of RCA as aggregate in concrete as being acceptable, provided appropriate precautions and considerations are taken. Benefits of using RCA in concrete include reducing dependency on nonrenewable natural aggregate reserves; diverting demolished concrete debris from waste disposal sites; and, provided RCA sources are in close proximity to building sites, reducing carbon emissions and traffic congestion associated with hauling natural aggregates over large distances. This chapter is intended as a comprehensive overview of the current state-of-the-art in RCA concrete research. The following sections include a discussion of production and mixture proportioning methods, fresh concrete properties, and hardened concrete properties.
Although there have been numerous laboratory and field studies that have investigated the use of RCA in concrete, there has been little consistency among the chosen test variables investigated in these studies. Typical test variables have included the percent replacement of natural aggregate with RCA (that is 10, 30, and 50 percent); the RCA type (source); use of fine RCA as a percent replacement for natural sand and in various combinations with coarse RCA; RCA processing method (single- or two-stage crushing and methods of removing adhered mortar); and the moisture state of the RCA prior to concrete batching (dry, prewetted, or saturated). Therefore, as this chapter will highlight the test variables mentioned and present many options available for producing RCA concrete for a variety of applications. The case studies presented in Chapter 9 will further demonstrate the many varieties of RCA concrete that have been used in real applications.

7.2—Mixture proportioning and production

Recycled concrete aggregate (RCA) concrete can be batched, mixed, transported, placed, and compacted in the same manner as concrete containing natural aggregate; however, special considerations may be required. The higher porosity of RCA as compared to natural aggregate leads to a higher absorption (refer to 5.5.6 for additional information). It is recommended that RCAs be batched in a prewetted and close to a saturated-surface-dry (SSD) condition. To achieve the same workability, slump, and $w/cm$ concrete with natural aggregates, the paste content or amount of high range water reducer may have to be increased.

7.2.1 Water-cementitious materials ratio—As with concrete incorporating natural aggregates, the $w/cm$ of RCA concrete will affect the strength and workability of the mixture significantly. Typically, concrete made with RCA may have lower strengths as compared to concrete made with natural aggregates given the same $w/cm$ (refer to Table 7.2.1 for references). However, as recent
studies have indicated, depending on the RCA source, similar or even higher compressive strength (for similar w/cm) can be achieved using RCA as a coarse aggregate (Butler et al. 2012).

Table 7.2.1—Summary of findings from previous researchers on compressive strength of RCA Concrete (tested at 28 days)

<table>
<thead>
<tr>
<th>Researcher(s)</th>
<th>Number of RCA sources studied</th>
<th>% change in compressive strength from control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahal (2007)*</td>
<td>1</td>
<td>10% decrease</td>
</tr>
<tr>
<td>Padmini et al. (2009)</td>
<td>3</td>
<td>10 to 35% decrease</td>
</tr>
<tr>
<td>Etxeberria et al. (2007)†</td>
<td>1</td>
<td>20 to 25% decrease</td>
</tr>
<tr>
<td>Rakshvir and Barai (2006)</td>
<td>3</td>
<td>5 to 10% decrease</td>
</tr>
<tr>
<td>Chen et al. (2003)</td>
<td>2</td>
<td>30 to 40% decrease</td>
</tr>
<tr>
<td>Katz (2003)</td>
<td>1</td>
<td>25% decrease</td>
</tr>
<tr>
<td>Topcu and Sengel (2004)</td>
<td>1</td>
<td>33% decrease</td>
</tr>
<tr>
<td>Tu et al. (2006)†</td>
<td>1</td>
<td>10% decrease</td>
</tr>
</tbody>
</table>

*Measured using cube specimens.
†RCA concrete with 100 percent RCA replacement.
‡Compared to high performance natural aggregate concrete.

7.2.2 Mixture design guidelines—Most studies in the literature have adopted the absolute volume mixture proportioning method when proportioning RCA concrete mixtures (ACI 211.1). The following are guidelines for developing mixture proportions using RCAs:

a) To determine a target mean strength on the basis of a required strength, a higher standard deviation should be used when designing a concrete with RCAs of variable quality than when RCAs of uniform quality or natural aggregates are used.

b) At the design stage, it may be assumed that the w/cm for a required compressive strength will be the same for RCA concrete as for a natural aggregate concrete when coarse RCA is used with natural sand. If trial mixtures show that the compressive strength is lower than assumed, an adjustment to a lower w/cm should be made.
c) Given the same slump, the water requirement of RCA concrete is higher than for natural aggregate concrete.

d) Specific gravity, unit weight, and absorption of aggregates should be determined based on a minimum of five test samples prior to mixture proportion studies and should be based on the properties of the RCAs intended for use in the particular application on site.

e) The sand to aggregate volume ratio for RCA concrete can be the same as when using natural aggregates.

f) Trial mixtures are strongly recommended to achieve desired RCA concrete mixture performance prior to in-place placement. If the placing will include confined spaces and irregular form shapes, trial placements should also be included.

In addition to the absolute volume mixture proportioning method, Abbas et al. (2008) developed a new mixture proportioning method known as the equivalent mortar volume (EMV) method specifically for the proportioning of RCA concrete. This method works by ensuring that the total amount of mortar in an RCA concrete mixture is equal to its companion natural aggregate concrete mixture. The residual (adhered) mortar content (RMC) on the RCA is included as part of the total mortar. This new mixture proportioning method has been shown to improve the RCA concrete workability, fresh and hardened mechanical properties, and to reduce the amount of fine aggregate and cement required.

7.2.3 Concrete production considerations—Although concrete production (batching, mixing, transporting, and placing) of RCA concrete is similar to concrete with natural aggregates, additional care should be taken when producing RCA concrete. The following items are recommended for production of RCA concrete:

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a) An important requirement of all RCA concrete is prewetting the RCAs to offset the high water absorption of the recycled aggregates (Butler 2012; Hansen and Narud 1983).

b) Coarse RCA should meet the gradation requirements for natural aggregates as per ASTM C33/C33M.

c) Trial mixtures should be produced to test the new concrete’s quality and to determine proper mixture proportions.

d) Perform frequent monitoring of the properties of the RCA that is being used. One potential problem with using RCA concrete is the variability in properties of the old concrete that may in turn affect the properties of the new concrete. Depending on the particular source and batch of RCA being used, adjustments in the mixture proportions may then be required.

A study using commercially produced RCA concrete conducted by Obla et al. (2007) reported that concrete containing crushed returned concrete (refer to 5.3.4) had approximately 30 to 60 minutes lower initial and final setting times as compared to the control mixture containing natural aggregates. They also reported higher slump loss particularly when the finer fractions of RCA were used.

7.3—Fresh concrete properties

7.3.1 Workability—The majority of the research studies have found that as the percent of natural aggregate replacement with RCA increases in a concrete mixture, the slump value decreases. Topcu and Sengel (2004) attributed this observation to the higher water absorption rate of the mortar adhered to the RCA. Specifically, they found that RCA concrete produced with 50 percent RCA replacement or more had significantly reduced workability. In a comprehensive study that looked at both laboratory and commercially-produced RCA concrete, Sagoe-Crenstil et al. (2001)
found that plant or commercially produced RCA is relatively smoother than laboratory-produced RCA and found this to improve workability. Due to the high absorption capacity of RCA, mixing water can be lost to aggregate absorption. If the aggregates are not preconditioned appropriately, this can greatly affect the w/cm and subsequent strength of the concrete. It is recommended to pre-wet aggregates to achieve a state of saturated-surface-dry so mixing water is not lost to aggregate absorption. Additionally, the particle shape and surface texture of RCA can affect the workability of concrete requiring more water to achieve a similar workability (Buck 1976; Butler et al. 2013; Mukai et al. 1979). Depending on the quality and resulting properties of the RCA used, it may be necessary to incorporate water-reducing admixtures in RCA concrete mixtures to achieve similar workability as equivalent natural aggregate concrete mixtures (Butler et al. 2012).

7.3.2 Density (unit weight) and air content—Some of the earliest studies on the use of RCA in concrete performed by Mukai et al. (1979) and Hansen and Narud (1983) concluded that unit weights of concrete made using RCA were within 85 to 95 percent of the original hardened concrete from which the RCAs were derived. In terms of fresh air content, Mukai et al. (1979) found that fresh RCA concrete had higher and more variable air contents as compared to the control mixtures. Specifically, Hansen and Narud (1983) found that air contents of RCA concrete are up to 0.6 percent higher compared with natural aggregate concrete. Hansen (1986) concluded that the air contents of RCA concrete are slightly higher and that densities can be 5 to 15 percent lower. More recent studies have continued to confirm reductions in unit weight of RCA concrete compared to natural aggregate concrete on the order of 10 percent (Katz 2003). This reduction is the result of both the lower density of the RCA and the increased air content of the fresh RCA concrete. Another study conducted by Malešev et al. (2010) found that as percent replacement of RCA increased, the air content also increased by up to 13 percent (for 100 percent RCA mixtures).
as compared to the control (natural aggregate) concrete mixtures. Katz (2003) used the gravimetric method for determining air content and noted that this method is very sensitive to slight changes in bulk specific gravity of the aggregate, which can be difficult to determine accurately. They suggested that a ±1 percent absolute error in the measured air content is present when using the gravimetric method for measuring air content of RCA concrete. Therefore, in considering past research in this area, it is important to note that as the absorption capacity of RCA can be significantly higher than natural aggregates and the pressure method for determining air content may not be valid in some cases. When using RCA with high absorption capacities, it is recommended that the volumetric air content method be employed (ASTM C173/C173M). The variation in density and the effect on air content will vary based on the amount of adhered mortar attached to each particle; therefore, test batches should be made to determine these properties carefully.

7.4—Hardened concrete properties

7.4.1 Compressive strength

7.4.1.1 Coarse RCA and natural sand—The compressive strength is affected by a wide number of factors including the w/c, type of cement, workability, addition of admixtures, supplementary cementing materials, aggregate size and type, moisture conditions during curing, temperature conditions during curing, age of concrete, maturity of concrete, and rate of loading (Jayasuriya et al. 2018a; Neville 2005). With regard to the aggregate used, its strength, surface texture, and grading all determine its impact on the concrete compressive strength. The bond between the aggregate and the cement paste will directly influence the compressive strength. Crushed, angular, and well-graded aggregates tend to promote better bond between cement paste and aggregate, and
higher concrete strengths. Extensive testing has been carried out over the past three decades to determine the compressive strength of various RCA concrete mixtures. Table 7.2.1 presents and summarizes the findings of previous researchers on the compressive strength of RCA concrete and how they compared to equivalent control (natural aggregate) concrete mixtures.

In addition to the findings summarized in Table 2.9, some of the seminal research on RCA concrete was carried out by Hansen and Narud (1983) who reported that RCA concrete obtained approximately the same strengths as the original concrete from which they were made. They also concluded that the compressive strength of RCA concrete depends on the strength of the original concrete and it is largely controlled by a combination of the \(w/cm\) of the original concrete and the \(w/cm\) of the RCA concrete. Furthermore, they hypothesized that higher strength concrete could be made from RCA derived by crushing of lower strength concrete.

In general, it has been found that the compressive strength of RCA concrete decreases with an increase in percent of RCA replacement (Xiao et al. 2005). In some cases, RCA concrete with strengths over 11,500 psi (80 MPa) have been produced using a combination of RCA replacement percentages, supplementary cementing materials, and chemical admixtures (Ajdukiewicz and Kliszczewicz 2002). In this case, the RCAs were obtained from an original concrete with compressive strengths of approximately 8700 psi (60 MPa). In the research conducted by Sagoe-Crenstil et al. (2001), there was no significant difference between the strength of portland cement concretes, as a function of aggregate type, for the grade of concrete investigated. Etxeberria et al. (2007b) reported compressive strengths that were 20 to 25 percent less than natural aggregate concrete for 25, 50, and 100 percent RCA replacement. They recommended that RCA concrete could be used in medium strength applications only (3000 to 6500 psi [20 to 45 MPa]). In higher

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strength mixtures (6500 to 8700 psi [45 to 60 MPa]), they found RCA concrete strength to be limited by the strength of the RCA particle and the amount of adhered mortar.

7.4.1.2 *Coarse and fine recycled concrete aggregates*—Concrete manufactured from both coarse and fine recycled concrete aggregates has been investigated in past studies. Sani et al. (2005) concluded that the compressive strengths of concrete made with 100 percent recycled coarse and fine aggregate was approximately 40 percent lower than for concrete using natural aggregates. They also found that the compressive strength of the concrete appeared to be inversely related to the porosity of the RCA. They demonstrated that this reduction in strength may be compensated for by incorporating fly ash into the mixture. Another study incorporated blends of 50 percent natural and 50 percent recycled sands that they found produced resulting concrete compressive strengths that were 10 to 20 percent less than RCA concrete made with all natural sands (Building Contractors Society of Japan 1978). Obla et al. (2007) used crushed returned concrete with size fraction varying from 38 mm to the ASTM C33/C33M No. 200 sieve (75 micrometer size opening) and reported negligible change in concrete fresh and hardened properties as long as the amount used was less than 10 percent of the total aggregate amount. The fine fraction (smaller than No. 4 sieve [4.75 mm]) of the crushed returned concrete was approximately 5 percent of the total aggregate weight.

7.4.2 *Splitting tensile and flexural strength*—The tensile strength of concrete made with natural aggregates varies between 8 and 15 percent of the compressive strength (MacGregor and Bartlett 2000). It is strongly affected by the type of test carried out to determine the tensile strength, the type of aggregate, the compressive strength, and the presence of a compressive stress that is transverse to the tensile stress (MacGregor and Bartlett 2000). Typical tests for measuring the tensile strength of concrete include the direct tension test, the splitting tensile test using cylindrical
specimens, and the flexural-tensile test using prismatic beam specimens. According to Neville (1997), the ratio of splitting tensile strength to compressive strength may be influenced by coarse aggregate properties. In general, as compressive strength increases, the tensile strength increases at a decreasing rate. In addition to the coarse aggregate properties, the method for measuring the tensile and compressive strength will affect the compressive to tensile strength (that is, $f_{ct}/f_{ct}$) relationship. Etxeberria et al. (2007b) found the splitting tensile strength of RCA concrete to be higher that the concrete with natural aggregates. They attributed these findings to the absorption capacity of the adhered mortar on the RCA and the new interfacial transition zone formed between the RCA and the new cement mortar. Sagoe-Crenstil et al. (2001) found the splitting tensile strength to be a function of binder strength rather than aggregate type. They also measured the splitting tensile-to-compressive strength ratio, which is an indicator of the concretes resistance to tensile strain and is a function of coarse aggregate size and type, concrete voids, and curing and testing conditions. This ratio for RCA concrete was found to be in the range of natural aggregate concrete (between 0.89 and 1.21). Ajdukiewicz and Kliszczewicz (2002) observed that high performance concrete mixtures with natural aggregates always produced higher tensile strengths than high performance RCA concrete; however, the difference was never more than 10 percent.

Table 7.4.2a summarizes and presents additional findings of previous researchers on the tensile strength of RCA concrete.

### Table 7.4.2a—Summary of findings on splitting tensile strength of RCA concrete (tested at 28 days)

<table>
<thead>
<tr>
<th>Researcher(s)</th>
<th>Number of RCA sources studied</th>
<th>% Change in Tensile Strength from Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etxeberria et al. (2007)</td>
<td>1</td>
<td>18 percent increase,* 2 percent decrease†</td>
</tr>
</tbody>
</table>

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Generally, concrete made from coarse RCA and natural fine aggregates has been found to have reductions in tensile strength between 10 and 20 percent (Hansen 1986). The flexural strength or modulus of rupture of concrete is commonly used in design calculations for pavements and other slabs on ground. Abou-Zeid et al. (2005) found the flexural-compressive strength ratio for the RCA concrete to be slightly higher than for natural aggregate concrete (Abou-Zeid et al. 2005). They attributed this to the superior bond between the RCA and the cement binder, which is due to the rough surface and angularity of the aggregate. They also postulated that it may be due to a chemical reaction between the RCA concrete and the surrounding cement paste. Table 7.4.2b presents and summarizes the findings of previous researchers on the flexural strength of RCA concrete.

\[\text{Table 7.4.2b—Summary of findings on flexural strength of RCA concrete (tested at 28 days)}\]

<table>
<thead>
<tr>
<th>Researcher(s)</th>
<th>Number of RCA sources studied</th>
<th>Percent change in flexural strength from control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen et al. (2003)</td>
<td>2</td>
<td>10 to 25 percent decrease</td>
</tr>
<tr>
<td>Rakshvir and Barai (2006)</td>
<td>3</td>
<td>10 percent decrease</td>
</tr>
<tr>
<td>Safiuddin et al. (2011)*</td>
<td>1</td>
<td>No change</td>
</tr>
<tr>
<td>Katz (2003)</td>
<td>1</td>
<td>15 percent decrease</td>
</tr>
<tr>
<td>Topcu and Sengel (2004)</td>
<td>1</td>
<td>13 percent decrease</td>
</tr>
</tbody>
</table>

*RCA concrete was considered to be high workability.

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7.4.3 Fracture energy—In general, the total amount of energy absorbed in a tensile test to failure is represented by the area under the load-deformation curve for the specimen. This area also represents the amount of energy absorbed within the fracture process zone and is referred to as the fracture energy, fracture toughness, or work of fracture. Specifically, it represents the fracture energy per unit area of the fracture surface (projected area on a plane perpendicular to the stress direction) (Hillerborg et al. 1976).

The fracture process zone is created when microcracks in concrete originate from strain localization, which develops ahead of the crack tip (Mehta and Monteiro 2017). Numerous analytical models have been developed to attempt to model the fracture process zone. Hillerborg et al. (1976) developed the fictitious crack model that essentially modeled the fracture process zone as a tied-crack with a specified crack width, \( w \), and a specified stress-elongation (\( \sigma - w \)) relation. The model attempts to capture the complex behavior of concrete in tension.

As concluded by Darwin et al. (2001), the fracture energy of concrete is mainly governed by the properties of the coarse aggregates. ACI 408R further summarizes these points by stating that as aggregate strength increases, an increase in bond strength is observed that appears to be related to the aggregates’ effect on the tensile strength and fracture energy of the concrete.

Given the unique nature of RCA concrete, the effect of specific RCA properties on the fracture energy is still relatively unknown as very few studies have been conducted on measuring the fracture energy of RCA concrete. With the increasing use of nonlinear finite element analyses, which use complex constitutive models for design of concrete structures, the fracture energy and post-peak softening response of RCA concrete are important input parameters for facilitating the future design of RCA concrete-based structures. Ong and Ravindrarajah (1987) studied fracture...
energy of low- and high-strength concrete produced using natural aggregates, RCAs, and a combination of natural aggregates and RCAs (Ong and Ravindrarajah 1987). They tested four 2 x 2 x 26 in. (50 x 50 x 650 mm) prisms with 1 in. (25 mm) notches cut at their midspans and recorded the load-displacement response and calculated the fracture energy of each specimen. They found that the greater the volume of aggregate used, the larger the area of the cracking surface. In general, they concluded that the concrete produced using natural aggregates had higher fracture energies than the RCA concretes. They attributed this difference to the weaker bond between the cement paste and the RCAs, which causes less complex micro-cracking and consumes less energy during crack propagation. Casuccio et al. (2008) noted similar trends with the RCA concrete having lower stiffness (13 to 18 percent) and significantly lower fracture energies (27 to 45 percent) than natural aggregate concrete. This difference was attributed to a decrease in elastic compatibility between the mortar and the coarse RCAs.

7.4.4 Modulus of elasticity and Poisson’s ratio—Several studies have been done on the modulus of elasticity of RCA concrete. Rahal (2007) evaluated one type of RCA source and produced RCA concrete with compressive strengths between 2900 and 7300 psi (20 and 50 MPa). The study found that for concrete between 3600 and 4400 psi (25 and 30 MPa), the modulus of elasticity of the RCA concrete was 3 percent lower than the natural aggregate concrete. Xiao et al. (2005) were able to measure the complete stress-strain behavior of RCA concrete at several aggregate replacement levels (0, 30, 50, 70, and 100 percent). They found that as the percent replacement increased, the modulus of elasticity decreased by up to 45 percent for the 100 percent RCA replacement mixtures. The researchers were also able to derive a constitutive relation for the RCA concrete tested and used regression to create a predictive model incorporating the percent of RCA replacement. Another study by Katz (2003) measured the modulus of elasticity of cube specimens.
and used a correction factor to normalize the results to equivalent cylinder values. Compared to natural aggregate concrete, the RCA concrete had very similar elastic modulus values however; the ACI 318 equation \(E_c = 0.043W_c^{1.5}(f'_c)^{1/2}\), still over-predicted the modulus of elasticity values by 25 percent. They noted that the effect of the RCA on the modulus of elasticity is similar to that of lightweight aggregate. Bekoe et al. (2010) measured the elastic modulus of RCA concrete while investigating its use in pavement applications. The research used one source of RCA at several replacement levels (0, 25, and 50 percent) in concrete. They concluded that the elastic modulus decreases with an increase in replacement percentage and found, at 50 percent replacement level, a reduction of up to 10 percent compared to the control concrete. Chen et al. (2003) studied two sources of RCA and investigated the effect of washing the RCAs prior to batching on the mechanical properties of RCA concrete (Chen et al. 2003). They found that the RCA concrete mixtures, on average, had elastic moduli that were 70 percent of the natural aggregate concrete for a given w/cm. Another study by Etxeberria et al. (2007a) evaluated a single RCA source in multiple replacement percentages in new concrete and found an 11 percent reduction (for 100 percent RCA replacement mixtures) in modulus of elasticity compared to the natural aggregate concrete. Building Contractors Society of Japan (1978) investigated the change in modulus of elasticity of concrete made using RCA. They reported that the reductions in modulus of elasticity made with coarse and fine RCA varied from 25 to 40 percent. They also reported that the reductions in modulus of concrete made with coarse RCA varied only from 10 to 33 percent.

Poisson’s ratio is defined as the ratio between the lateral strain and the axial strain and generally remains constant within the linear-elastic range of a material. In concrete, the Poisson’s ratio is mainly dependent on the properties of the aggregate and ranges between 0.15 and 0.22 and is generally the same under compressive or tensile loading (Neville 1997). There have been a limited

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number of research studies on the Poisson’s ratio of RCA concrete. Ajdukiewicz and Kliszczewicz (2002) studied six different RCA types and produced high strength RCA concrete. There was no significant difference in Poisson’s ratio between the natural aggregate and RCA concretes for a range of compressive strengths (5600 to 12,900 psi [38.7 to 89.2 MPa]). They reported 28-day Poisson’s ratios that ranged between 0.17 and 0.22.

7.4.5 Bond with reinforcing steel—There have been very few studies conducted on the bond performance with reinforcing steel in RCA concrete. Ajdukiewicz and Kliszczewicz (2002) performed pull-out tests on high performance RCA concrete using both plain round and deformed reinforcing bars and concrete mixtures with and without chemical admixtures. They found that in concrete with 100 percent coarse and fine RCA replacement, the bond stress value at failure was up to 20 percent lower than for natural aggregate concrete. In the case where 100 percent coarse RCA with river sand was used; only an 8 percent reduction in bond stress was measured. Xiao and Falkner (2007) performed a series of both pull-out and bond beam tests for several RCA replacement percentages and for both plain round and deformed reinforcing bars (Xiao and Falkner 2007). They found the bond and development deterioration process for RCA concrete to be similar to natural aggregate concrete. Five stages were observed: micro-slip, internal cracking, pullout (peak stress), complete steel bar pullout, and residual (load is approximately half the peak value). Xiao and Falkner (2007) observed that for plain bars, \( \tau_{max} \) decreased by 12 percent and 6 percent for 50 percent RCA replacement and 100 percent RCA replacement, respectively (Xiao and Falkner 2007). For deformed bars, \( \tau_{max} \) was very close to those for the control specimen. They postulated that the bond between the RCA concrete and the deformed bars is governed by the anchorage and friction resistance and therefore the percent of RCA replacement had little effect. However, the bond strength between RCA concrete and plain bars is governed by adhesion and,
in this case, the aggregate type and percentage has an influence. Xiao and Falkner (2007) also
developed an analytical expression that sufficiently models the entire bond-slip relationship
between RCA concrete and plain and deformed reinforcing bars and concluded that the anchorage
length for RCA concrete incorporating 100 percent RCAs could be the same as for natural
specimens and several different RCA replacement percentages (Choi and Kang 2008). They found
for a w/cm of 40 percent and with RCA replacement percentages of 50 percent, the bond stress-
slip relationship was similar to natural aggregate concrete. With a w/cm of 0.5, the bond stress-slip
relationship becomes much more sensitive to the quality of the RCA and appears to be better than
for natural aggregate concrete. They suggested that the ACI 408R expression for bond strength
over-estimated the experimental values obtained, whereas the CEB-FIP expression underestimates
the bond strength. Fathifazl (2008) tested 12 beam-end specimens and found in general that RCA
concrete specimens had lower bond strengths than natural aggregate concrete specimens (Fathifazl
and Razaqpur 2013). They found, however, that the overall bond behavior of specimens was
independent of aggregate or concrete type. In a study by Butler et al. (2014), 48 beam-end
specimens were tested and the bond strength was found to be related to the crushing properties of
the aggregate. In general, bond strengths of natural aggregate concrete were found to be 21 percent
higher than for RCA concrete. They used regression models to provide estimates of the theoretical
development lengths for RCA concrete and found that the RCA concrete members required
development lengths to be up to 9 percent longer than for the NA concrete members. However,
when compared to both ACI 318 and CSA A23.3 development length equations, the estimated
development lengths were 50 percent shorter, highlighting the conservativeness of the design

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equations. Table 7.4.5 presents and summarizes the findings of previous researchers on the compressive strength of RCA concrete.

**Table 7.4.5—Summary of findings on bond strength of RCA concrete with reinforcing steel**

<table>
<thead>
<tr>
<th>Researcher(s)</th>
<th>Number of RCA sources studied</th>
<th>Bond specimen type(s)</th>
<th>Maximum percent change in bond strength from control</th>
<th>Age of specimens at testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butler (2012)</td>
<td>3</td>
<td>Beam-ends</td>
<td>21 percent decrease</td>
<td>Between 28 and 48 days</td>
</tr>
<tr>
<td>Fathifazl (2008)</td>
<td>2</td>
<td>Beam-ends</td>
<td>Similar</td>
<td>28+ days</td>
</tr>
<tr>
<td>Choi and Kang (2008)*</td>
<td>3</td>
<td>Pull-out</td>
<td>Similar</td>
<td>28 days</td>
</tr>
<tr>
<td>Ajdukiewicz and Kliszczewicz (2002)*</td>
<td>6</td>
<td>Pull-out</td>
<td>20 percent decrease</td>
<td>28 days</td>
</tr>
<tr>
<td>Xiao and Falkner (2007)</td>
<td>1</td>
<td>Pull-out</td>
<td>12 percent decrease</td>
<td>28 days</td>
</tr>
</tbody>
</table>

*Used high-strength (800 MPa) 16mm diameter reinforcing bars.
†Investigated high-strength RCA concrete up to 80 MPa.

**7.4.6 Shear strength**—There have been relatively few studies that have investigated the effect of RCA on the shear strength of concrete. Gonzalez-Fonteboa and Martinez-Abella (2007) tested eight reinforced concrete beams using one RCA source and that was used to replace 50 percent of the natural aggregate content. Mixtures were proportioned such that the RCA concretes had similar compressive strengths and workability as the natural aggregate concrete. Load-deflection behavior, reinforcing bar, and concrete strains were all measured. The structural behavior of the RCA and natural aggregate concrete beams was observed to be similar and both ACI 318 and CSA A23.3 code equations yielded conservative predictions of shear strength.

Fathifazl et al. (2009) tested reinforced concrete beams incorporating RCA as coarse aggregate. Concrete mixtures were proportioned according to the equivalent mortar volume (EMV) method (Abbas et al. 2007). In total, 32 beams were tested involving a number of different parameters.
including, aggregate type, with or without stirrups, shear span-to-depth ratio, and longitudinal reinforcement. Two RCA types derived from crushing of various demolished concrete structures were used for the research. In general, no significant difference in shear failure mode or cracking patterns was observed between the RCA and natural aggregate concrete beams. The tested ultimate shear strength values were compared to the design values provided in ACI 318, CSA A23.3, and Eurocode 2, and code values were found to provide conservative estimates of the shear strength. The findings presented by Fathifazl et al. (2009), however, are applicable to only those RCA concretes that have been proportioned by the EMV method.

**7.4.7 Interfacial transition zone (ITZ)—**Given that RCAs are heterogeneous materials, the microstructure of concrete incorporating RCAs becomes even more complex than for natural aggregate concrete. Figure 7.4.7 depicts the microstructure for RCA concrete, which contains three ITZs: one between the original aggregate and the old adhered mortar (old ITZ), one between the original aggregate and the new mortar, and one between the new mortar and the old adhered mortar.

**Fig. 7.4.7—**Interfacial transition zone in RCA concrete. (Note: adhered mortar + original aggregate = recycled concrete aggregate) (from Butler 2012).

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Nobuaki et al. (2003) used the Vickers micro-hardness test to evaluate the ITZ characteristics in natural aggregate and RCA concrete. They concluded that the Vickers micro-hardness increases as the \( w/cm \) decreases. In the case of the old ITZ formed on the RCAs, the compressive strength decreases with a decrease in adhered mortar strength because the strength of the old ITZ governs the strength of the RCA concrete. In concrete types with low \( w/cm \) (0.25 or lower), Nobuaki et al. (2003) found the old ITZ to have lower Vickers micro-hardness. The opposite result was observed in concrete with high water-binder ratio (0.55) as the new ITZ had lower Vickers hardness values.

Poon et al. (2004) used scanning electron microscopy to study the densities of both natural aggregate and RCA concrete. A higher density ITZ was observed in both the high-strength natural aggregate and RCA concretes. The porosity of RCAs was found to be higher than the natural aggregates and resulted in different ITZ microstructures. Etxeberria Larrañaga (2004) also used scanning electron microscopy to study the microstructure of RCA and observed that the quality of the ITZ for RCA concrete was better than that of the adhered mortar (Etxeberria Larrañaga 2004). Therefore, the adhered mortar may be considered as the weakest point in RCA concrete. Consequently, the strength of the adhered mortar will greatly influence the overall resulting concrete strength and behavior.

7.4.8 Creep—Research (Hansen 1986, 1992) has found creep for concrete manufactured from RCA aggregates to be 30 to 80 percent greater than for concrete manufactured from natural materials. These results are not surprising as concrete containing RCA has up to 50 percent more paste volume, and creep of concrete is proportional to the content of paste or mortar in concrete.

In addition, Knaack and Kurama (2015) investigated the creep of concrete containing 50 and 100 percent direct volume replacement of natural aggregate with RCA. They used three different RCA sources and all mixtures were proportioned based on aggregates in a saturated condition. It was
found that the replacement of NA with RCA significantly increased the amount of creep in the resulting concrete. RCA concretes with lower compressive strengths also experienced higher creep. Adjustment factors that can be applied to NA concrete-based models for estimating creep deformations of RCA concrete were proposed based on their results. Fathifazl and Razaqpur (2013) also studied the creep of RCA concrete considering two sources of RCA and proportioned mixtures using ACI 211.1 and equivalent mortar volume methods (refer to 7.2.2). They investigated five different rheological models for NA concrete and proposed modifications factors to be applied to the ACI Committee 209 model for estimating creep deformations. Based on their results, they found that the modified 209 model could be used in practical applications for estimating creep of RCA concrete.

7.4.9 **Coefficient of thermal expansion**—As temperature rises, concrete expands and the coefficient of thermal expansion (CTE) is a measure of the percent change in length of concrete under a 1°C change in temperature. Typically, for normal-density concrete this value is approximately $10 \times 10^{-6}/°C$. Factors influencing the thermal expansion and contraction of concrete include aggregate type, cement content, $w/cm$, temperature range, concrete age, and relative humidity. Overall, aggregate type has the greatest influence (Kosmatka and Wilson 2016). A very limited number of studies have investigated the CTE of RCA concrete and the influence of aggregate properties on the CTE. Smith and Tighe (2009) performed CTE tests on concrete pavement cores containing concrete of several RCA replacement levels (0, 15, 30, and 50 percent) using a simplified testing method. They found that, as the percent replacement increased, the average CTE value decreased. Bekoe et al. (2010) also investigated the CTE of concrete for pavement applications at several replacement levels. Overall, they concluded that there was no clear difference between the natural aggregate concrete and the RCA concrete with various replacement percentages.

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7.4.10 Drying shrinkage—Research has shown that drying shrinkage in concrete produced with RCA is significantly higher than concrete containing only natural aggregates (Domingo-Cabo et al. 2009; Kikuchi et al. 1998; Ravindrarajah 1996). This increase may be attributed to the higher paste content of RCA due to the amount of adhered mortar in an RCA particle. The higher paste content of RCA concrete compared to concrete with natural aggregates, provides less restraint because there are fewer natural aggregates, thus causing higher levels of shrinkage. However, there have also been other studies that have pointed out that the fine portion of RCA may potentially serve as internal curing agents and help to reduce drying shrinkage (Hu and Kim 2013; Kim and Bentz 2008; Yildirim et al. 2015).

The drying shrinkage of RCA concrete will increase as the amount of RCA included in the mixture increases. This is due to the increased adhered mortar content that is introduced as more RCA is incorporated into the mixture (Domingo-Cabo et al. 2009; Khatib 2005).

Concrete made with recycled coarse and fine aggregates produced shrinkages that are 70 to 100 percent greater than that of corresponding natural aggregates (Building Contractors Society of Japan 1978). Ravindrajah and Tam (1987) found that shrinkages were greater for higher-strength concrete than for lower-strength concrete (Sriravindrarajah and Tam 1987). More recent research has shown that the higher levels of free-drying shrinkage observed in concrete made with RCA did not necessarily correspond to higher-cracking susceptibility (Corinaldesi and Moriconi 2012; Jeong 2011). A study by Adams et al. (2016) and Jayasuriya et al. (2018b) showed that concrete made with RCA that had similar levels of drying shrinkage as concrete made with natural aggregates actually had reduced levels of cracking risk compared to the natural aggregate concrete.

7.4.11 Permeability—Concrete made from recycled aggregates with w/cm 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 \( w/cm \) of the recycled concrete by 0.05 to 0.10 (Rasheeduzzafar 1984). Obla and Kim (2009) found that the rapid indication of chloride ion penetrability (RCPT) (as per ASTM C1202) test results of concrete containing crushed returned concrete was very similar to concrete containing natural aggregate when the fines fraction of the crushed returned concrete was used. However, when the coarse fraction was used to replace all of the natural coarse aggregate, the RCPT value was found to increase by as high as 50 percent.

7.4.12 Freezing-thawing resistance—Many studies of freezing-and-thawing resistance indicate that there is almost no difference between that of concrete made with natural aggregates and with recycled aggregates (Dhir et al. 1999; Gokce et al. 2004, 2011; Hansen 1986). It is important, however, as with natural aggregate concrete that proper amounts of air entraining admixtures are used in the new concrete. Additionally, Gokce et al. (2004, 2011) determined the air entrainment of the original concrete plays a significant role in the freezing-and-thawing resistance of RCA concrete.

7.4.13 Carbonation, chloride penetration and reinforcement corrosion—Katz (2003) performed carbonation tests on several RCA concrete prism specimens and found that the carbonation depths of the RCA concrete specimens were between 1.2 and 2.5 times greater than those of the natural aggregate concrete specimens. The Building Contractors Society of Japan (1978) concluded that the rate of carbonation of a recycled aggregate concrete made with concrete that had already carbonated was 65 percent higher than the control concrete made with natural aggregates. They also concluded that reinforcement in recycled concrete may corrode faster than in natural aggregate concrete. However, this accelerated corrosion could be offset by reducing the \( w/cm \) of the RCA
concrete and by the use of supplementary cementitious materials like fly ash, silica fume, and slag cement.

**7.4.14 Alkali-silica reaction**—Recycled concrete used as coarse aggregate in new concrete possesses some potential for alkali-silica reaction if the old concrete contained alkali-reactive aggregate. The reactivity of the aggregates is dependent on the source material used to produce the recycled concrete. Natural aggregates that are reactive may continue to be reactive once incorporated into new concrete as a part of RCA. Additionally, the RCA itself can contribute alkalis to the system (depending on the condition of the original concrete from which it was derived), exacerbating ASR in new concrete made with RCA. Therefore, it is very important to understand the reactivity and alkali content of the source material used for the original concrete prior to its consideration as a source of RCA (Scott and Gress 2004). Typical test methods for determining the reactivity of natural aggregates can also be used for RCA (Adams et al. 2013; Li and Gress 2006; Shayan and Xu 2003; Shehata et al. 2010). However, when using the accelerated mortar bar method, care should be taken to understand the effect of crushing the aggregates. Adams et al. (2013) found that higher levels of processing produced higher levels of reactivity in concrete made with RCA produced with reactive aggregates. It was determined that this was due to removal of adhered mortar and increased natural aggregate content that will occur after successive levels of crushing (Beauchemin and Fournier 2012). Therefore, it is recommended that prior to testing RCA for reactivity, producers should understand the amount of processing that will occur prior to use, and try to replicate this level during testing. However, it is important to understand that the limits put forth in standard test methods used for determining the degree of reactivity of aggregates may not be applicable for use with RCA, as long-term field studies have yet to be completed (Adams et al. 2013).

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For highly reactive aggregates made from recycled concrete, ASR guidance should be followed. The use of SCMs can help reduce expansions seen in concrete made with reactive ASR, though the effectiveness of the SCM may be affected by how much adhered mortar is attached to RCA particles (Shehata et al. 2010). Also, even if expansive ASR did not develop in the original concrete, it cannot be assumed that it will not develop in the new concrete if special control measures are not taken. This is due to the fact that crushing of the RCA may expose more reactive particles in the natural aggregates that were not previously exposed. Petrographic examination and remaining ASR potential expansion tests are recommended to make this judgment (Gress and Kozikowski 2000).

### 7.5—Summary

This chapter provided a comprehensive summary of the current state-of-the-art of RCA concrete research around the world. Several recommendations were also made in this chapter with respect to RCA concrete production and mixture proportion methods. The results of the studies presented emphasize the various test variables used to evaluate the properties of RCA concrete. Based on the current state-of-the-art, it is evident that a wide variety of RCA concretes can be produced for use in various applications. This chapter also reinforces the need to properly categorize and assess an RCA source that is being considered for use as a full or partial replacement of natural aggregate in concrete. Chapter 5 provided several national and international resources for selecting suitable RCA sources based on physical properties test results; however, given the vast range of RCA types and variables to consider, additional research in this area is still required.
CHAPTER 8—CASE STUDIES

8.1—Introduction

Previous chapters have highlighted the extensive recycled concrete aggregate (RCA) experimental research that has been conducted over the past several decades. However, one of the major barriers to the widespread adoption of recycled materials in concrete is being able to demonstrate their performance under full-scale real operating conditions. Therefore, research studies and construction projects involving field investigations of RCA materials are critical to further advancing their use.

Most case studies to date have involved the reuse and recycling of concrete in granular fill and base layer applications. Case studies involving the use of RCA in new concrete applications are still limited. Several transportation departments and the U.S. Federal Highway Administration have sponsored a limited number of demonstration projects that incorporate the use of RCA as new aggregate in new concrete pavements (Federal Highway Administration. 2004). Even more limited are case studies involving the use of RCA as aggregate in reinforced (structural) concrete applications. The following sections highlight various national and international case studies where RCA has been used either as a base material under pavements, as aggregate in new concrete pavements, as aggregate in architectural and nonstructural concrete, or as an aggregate in reinforced concrete structures. These case studies are intended to provide engineers, concrete suppliers, asset managers, and other stakeholders with an overview of real-world applications, which are possible when concrete is recycled and reused.
8.2—Concrete roadways

The recycling of portland cement concrete pavements for use as unbound base material is a very mature industry compared to its use as aggregate in new concrete pavements. Its use as base material and as RCA in new concrete pavements as well as other construction applications have been evaluated (Cuttell et al. 1997; Smith 2009; Snyder and Bruinsma 1996; Wade et al. 1997). In addition, many transportation departments across the U.S. have been using RCA as base material in concrete pavements for several decades (Federal Highway Administration. 2004). While most recycled pavements have performed reasonably, some have received national attention for their poor performance. The present preferred and most frequent application, especially near metropolitan areas, is using RCA as unbound base material under new pavements.

8.2.1 Unbound base material

Case Study #1: Interstate 5 Improvement Route 22 to 91 Freeway, California

Project background

In 2008, the Interstate 5 Improvement Route 22 Freeway to Route 91 Freeway project in Anaheim, CA, was completed. The 6-year project was designed to widen the freeway from three to six lanes, as this represents a critical section of interstate freeway with its proximity to Disneyland, Angel Stadium, and Arrowhead Pond. Because the project involved portable recycling, several challenges existed. Because bridges were also demolished as part of the project, a large quantity of reinforcing steel had to be separated from the concrete and processed separately. In addition, a number of logistical challenges had to be overcome, such as working in confined areas adjacent to on and off ramps, freeway medians, detour routes, and travel paths of portable crushing plants traversing the site.

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Recycled materials application

Approximately 700,000 tons of RCA was used as road base and as aggregate in nonstructural concrete elements including gutters, curbs, and sidewalks (Construction and Demolition Recycling Association 2019). The recycled materials were stockpiled and, according to Caltrans, met the specifications.

Performance results and cost benefit

It was estimated that using the RCA from the demolished pavements on this project saved Caltrans approximately $5 million when compared to traditional construction methods and materials (Construction and Demolition Recycling Association 2019).

Case Study #2: Heathrow Airport Terminal 5, United Kingdom

Project background

London's Heathrow Airport is the busiest airport in the world. Its Terminal 5 expansion project was the largest in Europe at the time of its construction, with an overall cost of £4.2 billion (approximately $5.5 billion). The overall project consisted of 16 separate major projects and 147 separate subprojects. The new terminal was designed to cater to over 30 million passengers. It officially opened in March 2008 (Constructing excellence: Demonstration project-Heathrow terminal 5 2005).

Recycled materials application

In total, over 88,000 tons (80,000 tonnes) of RCA from both on- and off-site sources were reused in the project (Constructing excellence: Demonstration project-Heathrow terminal 5 2005).
Approximately 48,500 tons (44,000 tonnes) of RCA was used as a base material under a temporary (10-year design life) building structure that formed part of the main Terminal 5 project and was completed in 2002. The decision to use RCA for this application was joint between the British Airports Authority (owner) and Laing O'Rourke (contractor) based on superior performance, lower cost, and environmental impact (WRAP 2003).

The RCA supplied was derived from crushed concrete and was considered of high quality, free from deleterious substances and materials such as steel, wood, or plastics (WRAP 2003). The RCA source met the specifications of Class 6F1 and 6F2 capping material as specified under the UK Specification for Highways Works, Series 600.

*Performance results and cost-benefit*

The cost of the RCA used in this project was approximately 25 percent less than that of the equivalent virgin material, which equated to overall project savings of £80,000 (approximately $110,000). In addition, the use of RCA was in accordance with the British Airports Authority environmental policies for the Terminal 5 site (WRAP 2003).

8.2.2 RCA in new concrete pavement

*Case Study #3: FHWA – University of New Hampshire Research Test RCA Pavements*

*Project background*

In 1994, the Federal Highway Administration (FHWA) sponsored research to combine field site evaluations with related laboratory and petrographic examinations to determine why some RCA concrete pavements performed well, while others did not (Sturtevant 2007). The test sections were originally constructed in Kansas, Connecticut, Wyoming, Minnesota, and Wisconsin. In 2006, the
FHWA, through the University of New Hampshire Recycled Materials Resource Center (RMRC), sponsored research to revisit the 1994 study project sites (Gress et al. 2009; Sturtevant 2007).

Recycled materials application

RCAs were used as aggregate in new concrete pavement mixture designs. Efforts were made during the crushing and processing stages to minimize the amounts of adhered mortar. This contributed to the success of project by producing concrete with higher-than-expected compressive strength values (Cuttell et al. 1997).

Performance results

The 2006 evaluation data provided a better indication of RCA pavement long-term performance trends (the study projects were 18 to 26 years old in 2006) and offered further insight into the factors that affect RCA pavement performance. As would be expected, any pavement that was recycled had already incurred deterioration caused by various mechanisms. For instance, it was shown that eight out of 10 of the pavements evaluated had underwent deterioration due to ASR (Gress et al. 2009). Some of the pavements were improperly designed with excess joint spacing and many without load transfer dowel bars. Overall, the pavements were shown to have had equivalent performance to that of the control sections, even though materials-related distress was found to be a contributing factor. It was shown that recycled pavements could be very effectively rehabilitated by milling and dowel bar refitting to produce exceptional riding quality.

Case Study #4: University of Waterloo RCA Pavement Test Site, Waterloo, Canada

Project background

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Research conducted at the University of Waterloo investigated the use of recycled concrete aggregates (RCAs) in concrete pavements and road structures (Smith 2009). A pavement test site at the Region of Waterloo's Waste Management Facility was used to construct several pavement sections that incorporated a variety of RCA concrete mixtures. The test sections were subjected to heavy truck traffic loading and the pavements were monitored for 2 years.

Recycled materials application

Four 164 x 28 ft (50 x 8.5 m) wide sections were paved with concrete that incorporated 0, 15, 30, and 50 percent replacement of virgin aggregate with RCA. The coarse RCA used as part of this project was derived from the crushing of decommissioned sidewalk, curb, and gutters from the surrounding region. Aggregate testing results indicated that this was a particularly high-quality RCA with low deleterious substance content. Butler (2012) used RCA from the same source and compared it with two other RCA sources and also deemed this particular RCA to be of high quality.

Performance results

The concrete mixtures with 30 percent RCA as coarse aggregate displayed mechanical and durability performance (that is, compressive strength, flexural strength, freezing-and-thawing durability, and coefficient of thermal expansion) that were comparable to or better than that of the conventional concrete mixtures. After 2 years in service and approximately 3,000,000 equivalent single axle loads, all test sections were in excellent condition with performance index values of 90 or greater.

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Case Study #5: Long-Term Performance Evaluation of Concrete Pavements Containing Recycled Concrete Aggregate, Oklahoma

Project background

During the 1980s, the Oklahoma Department of Transportation constructed several sections of portland cement concrete pavement where the coarse aggregate fraction in the mixtures was replaced by 100 percent RCA. The motivation for using RCA in this project was that the nearest natural aggregate source was a quarry located more than 50 miles away. Researchers at Texas A&M carried out a study to evaluate these pavements (Mukhopadhyay et al. 2018; Shi et al. 2019) which, to the researchers’ knowledge, had never been systematically evaluated. In this study, two of the pavements, one jointed plain concrete pavement (JPCP) and one continuously reinforced concrete pavement (CRCP) were selected for detailed lab and field investigations. The work involved conducting a performance evaluation of the existing RCA concrete pavements, including laboratory testing of mechanical properties, petrographic examination of the concrete microstructure with specific emphasis on the nature of crack propagation, and field evaluation using a falling weight deflectometer (FWD) test to assess the structural behaviour of the pavement.

Recycled materials application

The original pavement was found to have undergone moderate D-cracking near the transverse joints. The reconstruction of the 7.75 mile (12.5 km) long I-40 section began on March 10, 1983. The existing pavement was first removed and delivered to a standard crushing plant that used hammer mills. Small quantities of reinforcing steel were removed by suspending a magnet over the conveyor and the wire cages that held the dowel bars in place were skillfully extracted by the loader operator. The plant was able to convert 42 percent of the broken pavement into coarse RCA.

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However, using hammer mills in the crushing process produced more fine materials than expected. The resulting RCA concrete used 100 percent RCA as coarse aggregate in the new concrete layer.

Performance results and cost-benefit

The average laboratory 7-day compressive strength of five specimens determined in 1983 was 3850 psi (26.6 MPa) for the control concrete and 3600 psi (24.9 MPa) for the RCA concrete. The field RCA concrete samples for I-40 in 1983 had 1.5 to 2.0 in. (3.8 to 5.1 cm) slump, 4.6 percent air content, and 3160 to 4580 psi (21.8 to 31.6 MPa) 7-day compressive strength. These results satisfied Class A concrete requirements. During a field survey conducted in 2017, researchers drilled core samples and tested in the lab a variety of mechanical properties (compressive strength, splitting tensile strength, and elastic modulus). These results indicated an overall reduction (up to 11 percent in compressive strength, 19 percent in elastic modulus, and 13 percent in splitting tensile strength) in the mechanical properties of the RCA concrete pavements as compared with that of the conventional concrete pavements. Only the cores extracted from an RCA concrete pavement on the I-40 JPCP yielded compressive strengths that were 7 percent higher than that of the conventional PCC sections.

Shi et al. (2019) also conducted FWD tests and the Oklahoma Department of Transportation provided distress survey data on the pavement sections. This field data indicated that the RCA JPCP section exhibited lower performance compared to the control JPCP section; the lower performance of the RCA JPCP was manifested by its lower equivalent thickness and lower coefficient of friction from the FWD analysis, and its higher IRI and faulting from the surface condition survey. However, CRCP has greater resiliency than JPCP, so the difference between the RCA section and the control section was not as significant as in the JPCP case.
Using RCA as replacement for virgin coarse aggregate in concrete yielded reduced elastic modulus. Based on previous simulation work and the FWD results from this study, PCC slabs with lower elastic modulus yield increased differential energy. The results of coefficient of friction infer that the RCA section already developed high level of base damage compared to the control section. The RCA was reported to have less detrimental effect on the CRCP section because the latter was resting on a much stronger asphalt base compared to the relatively weak soil base supporting the JPCP.

Replacing natural aggregate with RCA in this project allowed to avoid purchasing and delivering 60,500 tons (63,000 tonnes) of natural aggregate, with reported savings of approximately $0.8 million. The cost of this concrete recycling project was $0.7 million less than that of the alternative rehabilitation plan with an asphalt concrete overlay. Therefore, the concrete recycling approach represented the best bid option (Mukhopadhyay et al. 2018).

8.3—Architectural and low-strength concrete

8.3.1 Architectural concrete—Another innovative use of recycled concrete is as a green architectural landscaping building material. Reuse of portland cement concrete in such landscaping projects with relatively low risks of structural integrity and performance loss is another viable application of RCA. For instance, several landscaping projects have used large chunks of crushed concrete as rough paving stones or in landscaping retaining or accent walls.

Case Study #6: Enviroblock Concrete Blocks, Carbon Neutral Business Zone, United Kingdom

Project background
A new business development block located in Lincolnshire, UK, was built to provide commercially viable carbon-neutral office space. The £1,300,000 ($1,700,000) project included several office buildings, an eco-café, a classroom, and a demonstration eco-house. The entire development was designed to be carbon neutral and require no heating (Aggregate Industries 2019).

Recycled materials application

The primary walls of the office buildings and main structures were partially constructed using a proprietary concrete product called Enviroblock. These blocks contain a minimum of 80 percent RCA and achieve compressive strengths of 1050 to 1500 psi (7.3 to 10.4 MPa). They were manufactured in the UK and produced in lightweight (1450 kg/m$^3$) and dense (1950 kg/m$^3$) varieties. Performance and cost-benefit information were unavailable for this project and product.

8.3.2 Low strength concrete

Case Study #7: Coarse and fine RCA in Municipal Concrete Sidewalks, Ontario, Canada

Project background

In 2014, Lafarge Canada carried out field trials of using a combination of coarse and fine RCA in new municipal sidewalk construction in Ontario, Canada. The goal of this project was verifying the use of recycled pavements in-place to gain acceptance and develop specifications for the use of RCA in concrete.

Recycled materials application

The pilot project included the development of four RCA concrete mixtures and one control natural aggregate concrete mixture all satisfying the requirements of CSA A23.1/CSA A23.2 for C-2 32 MPa air-entrained concrete for use in sidewalk applications. Three RCA concrete mixtures were...
designed for 10, 20, and 30 percent volumetric replacement of natural aggregate by coarse RCA and the other RCA mixture used fine (granular) RCA to replace 20 percent of the total aggregate volume.

Performance results
The measured fresh properties (air content and slump) of all the RCA concrete mixtures were comparable to that of the control mixture. Compressive strength and compressive strength gain of the RCA concrete and control concrete were also similar. Both the laboratory surface scaling and chloride permeability tests revealed marginal differences between the RCA and control concrete mixtures. After 1 year of exposure to freezing and thawing and deicing salts in the field, no significant difference in visual performance was observed between the RCA and control concrete test sections.

8.4—Concrete structures
8.4.1 Tilt-up concrete construction
Case Study #8: Enterprise Park at Stapleton

Project background
In 2008, Etkin Johnson Group, general contractor Murray and Stafford, Inc., concrete contractor CAL Construction Inc., and Forest City Development used RCA mixture designs for their office and industrial development located within the borders of what was once Denver’s Stapleton International Airport. The foundations and tilt-up panel construction are shown in Fig. 8.4.1. ReCrete Materials Inc. of Arvada, CO (Construction and Demolition Recycling Association 2019) provided approximately 7900 yd$^3$ (6000 m$^3$) of ready mixed concrete containing RCA for use in

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foundations and tilt-up panels at the Enterprise Park at the Stapleton project in Denver, CO (Fig. 8.4.1).

The developer, Etkin Johnson Group, sought Leadership in Energy and Environmental Design (LEED) certification for this project, which included three buildings with 441,000 ft\(^2\) of office and industrial space within the Stapleton Redevelopment. The decision to use RCA in the concrete for this project was based on several factors:

a) The material was readily available at nominal additional costs
b) The end product met all quality standards
c) The use of recycled material allowed the concrete mixtures to be tailored to the needs of each part of the project
d) The use of RCA had a positive environmental impact.

The proximity of the recycled material, in this case, offered additional points toward LEED certification, as did the fact that RCA qualifies for both pre- and post-consumer LEED points.
Recycled materials application

Approximately 2305 tons of RCA from the runways of the former airport was used in the construction of three high-end office/warehouse buildings. The 2200 yd$^3$ (1700 m$^3$) of concrete used in the foundations contained approximately 560 tonnes of RCA and 105 tonnes of fly ash for a total weight of recycled material in the foundations of 665 tonnes. The 5700 yd$^3$ (4350 m$^3$) of concrete used in the tilt-up panels contained approximately 1420 tons of RCA. Fly ash was not used in the tilt-up panels.
allowed in the tilt-up panel mixture design, therefore only RCA qualified as a recycled product for LEED certification. According to the Tilt-Up Concrete Association, the 1420 tonnes of recycled concrete used in the tilt-up panel concrete mixture design in this project is the largest use of RCA concrete in a tilt-up application on record.

Performance results

The tilt-up contractor noticed little, if any, difference in the performance of the recycled material compared to conventional concrete materials, including the pumpability and finishability. Higher compressive strength values could be achieved than if conventional concrete had been specified. The contractor identified several advantages of using the RCA concrete, which included a reduction in plastic shrinkage cracking and initial set times, higher 7- and 28-day compressive strength, improved concrete finishing, diversion of useable RCA from the waste stream, and a reduction in the number of truck trips from distant aggregate quarries (Construction and Demolition Recycling Association 2019).

8.4.2 Reinforced concrete structures

Case Study #9: I-5 Willamette River Bridge, Oregon, United States

Project background

Constructed in 1961, the I-5 Willamette River Bridge experienced significant deterioration, which was discovered in 2002, leading to weight restrictions on heavy traffic. A temporary detour bridge was constructed in 2004 to handle the additional traffic until a new bridge could be constructed. Construction began in May 2008 on two new twin arch bridges, which opened in August 2013 (Oregon Department of Transportation 2015).
The new bridges span over a local highway, railroad tracks, an off-ramp, and two multi-use paths. The north and southbound segments span 1759 and 1984.7 ft, respectively. The bridges are considered to be the longest concrete arch spans in Oregon. The main bridge structure consists of one cast-in-place post-tensioned concrete girder span, two concrete deck arch spans over the Willamette River, three cast-in-place, post-tensioned box girder spans over a roadway, and three cast-in-place post-tensioned box girder spans (refer to Fig. 8.4.2a).

![Fig. 8.4.2a—Willamette River Twin Arch Bridges spanning over the Willamette River (photo courtesy of Oregon Department of Transportation).](image)

**Recycled materials application**

Using crushed concrete from the demolished detour bridge, recycled concrete aggregate was produced for use in concrete mixtures of the new bridge foundations. Class 4500 mixtures incorporating 30 percent RCA were developed for use in the mass concrete shaft caps in two of the bents on the north and south banks of the river. A testing program comprising compressive strength, shrinkage, permeability, resistance to freezing-and-thawing cycles, and modulus of elasticity testing, demonstrated very similar performance of the RCA mixtures to that of the Class

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4500 mixtures with virgin aggregate (Bollman 2012). In total, 150 tons of RCA was used as aggregate in concrete for the new bridges with plans for using additional RCA in the surrounding park pathways (ODOT 2012). Figure 8.4.2b shows a typical shaft cap.

Fig. 8.4.2b—Typical shaft cap, arch, and column junction (Bollman 2012).

Case Study #10: Bridge over Turia River, Valencia, Spain

Project background

Completed in 2009, the Turia River Bridge located in Valencia, Spain, is a 145 m cable-stayed bridge with a steel-concrete composite deck. The 22.4 m wide bridge replaced an older 9 m wide bridge that was demolished. The new structure has improved commuting between the neighboring cities of Manises and Paterna from 11,500 to 14,000 vehicles per day with a total construction cost.
of $14 million (12 million euros) (Dywidag Systems Inc. (2017)). This project was also used as a pilot project for using recycled concrete aggregates in new bridge construction. Concrete materials from the old structure were used in the new one and an extensive concrete materials testing and mixture design study was carried out at the Structures and Materials laboratory at CEDEX (Sanchez et al. 2009). The completed cable-stayed bridge is shown in Fig. 8.4.2c.

Fig. 8.4.2c—Bridge over the river Turia, Valencia, Spain (image courtesy of Dwyidag-systems.com).

Recycled materials application

Crushed concrete from the old bridge structure was processed into coarse RCA for use in new concrete to be used in a 90 m long reinforced-concrete deck. Mixture designs with 35 MPa compressive strength incorporated 20 percent replacement of natural coarse aggregate with RCA. Prior to undertaking RCA concrete mixture designs, an extensive survey of the old bridge concrete, which included performing durability and mechanical properties tests on core samples, was completed.
Performance results

A series of laboratory tests were carried out on the RCA concrete, including compressive strength, flexural strength, workability (slump), modulus of elasticity, shrinkage, water penetration, and rate of carbonation. The measured compressive strength for all tested batches was greater than the project specified compressive strength of 35 MPa. In terms of durability characteristics, the depth of water penetration was found to satisfy the criteria for concrete exposed to the most aggressive environments as set out in the Spanish Code on Structural Concrete (EHE08). The shrinkage during the curing process closely matched the shrinkage predictions set out in EHE08. This pilot project concluded with a set of technical specifications for using RCA in new bridge deck construction with a view to applying similar principles on future projects.

Case Study #11: Samwoh Eco-Green Park, Singapore

Project background

Completed in 2009, the Eco-Green Park Building was constructed by the building material and supply company Samwoh Corporation in Kranji, Singapore, to showcase the use of recycled materials in new construction. Given that Singapore currently imports the majority of its natural aggregates from neighboring countries, more sustainable long-term alternatives in the form of exploring the use of construction and demolition waste in new concrete were sought (Ho et al. 2014). Figure 8.4.2d shows the completed Eco-Green Park Building.
Recycled materials application

An extensive laboratory testing program was carried out prior to construction of the building to develop and evaluate suitable RCA concrete mixtures. The concrete used in the new Eco-Green Park building contained up to 100 percent RCA as coarse aggregate in all its structural elements. The RCA was obtained from a local recycling facility and a two-stage crushing process was employed to reduce the amount of adhered mortar. Strict quality control and screening measures were used not to exceed a maximum deleterious substance content of 6 percent.

Performance results

A wide variety of concrete mechanical and durability properties were tested including compressive strength, splitting tensile strength, flexural strength, creep, initial surface absorption, sulphate resistance, water permeability, and chloride ions ingress. RCA concrete with similar mechanical properties to that of the control concrete was produced without adjustment of the w/c. In addition, it was concluded that, while the durability performance of the RCA concrete mixtures was not on
par with the control mixtures, the RCA mixture designs could be effectively modified to achieve similar performance.

A unique component of this case study was the integration of an extensive fiber-optic based structural health monitoring system to monitor the in-place behavior of the structure. Ho et al. (2014) reported that the deformation of the building had stabilized and that no abnormality in the building response had been observed.

**Case Study #12: Resource Access Centre (Bud Clark Commons), Portland, Oregon**

**Project background**

Completed in 2011, the $47,000,000 Portland Resource Access Centre serves as a day center and permanent housing for homeless persons. Originally planned to serve 1000 Portland residents per day, it consists of eight floors and more than 107,000 ft² of useable space. The building achieved LEED Platinum status and incorporated recycled concrete materials in its foundation. Concrete materials were supplied by CalPortland.

**Recycled materials application**

RCA was used in all mass footings and foundations and in some slabs to increase the recycled material value to obtain LEED certification. RCA was produced from returned concrete to CalPortland’s plant that would have otherwise been taken to a dump site. The material was crushed by a portable crusher to ASTM C33/C33M No. 57 coarse aggregate specification. RCA was incorporated at 30 percent of the coarse aggregate weight for the foundation and mass footings in the 27.5 MPa (4000 psi) and 34.5 MPa (5000 psi).
Performance results and cost-benefit

A variety of laboratory and field tests were performed on the RCA concrete mixtures. All mixtures were found to exceed their targeted 28-day design compressive strength with values between 35.5 and 44.1 MPa (5150 and 6400 psi).

During batching, all mixtures were reported to perform very well and there were no significant issues during pumping and finishing operations. Finishers noted negligible differences between the RCA and conventional concrete mixtures.

Slight cost savings were recorded, however, which was counterbalanced with the costs of transporting the demolished concrete to off-site crushing plants and then transporting the RCA back to the concrete batching plant. The primary benefit of using RCA in this project was in its recycled content value (that is, as a post-consumer product), which provided additional LEED credits. Based on their experience with this project, CalPortland recommended that the location of RCA stockpiles should be carefully considered as there is potential for high-pH runoff (leachate) due to moisture or rain coming into contact with the stockpile.

8.5—Conclusions

This chapter highlights a variety of case studies around the world in which RCA was used in new concrete applications. It discusses the various reasons for using RCA and outlines the cost-benefit of using RCA in various projects. Considering that the list of case studies presented herein is not exhaustive, it is important to note that, while many other real-world projects where RCA has been used may exist, adequate documents detailing these projects seem to be lacking. The construction industry and government organizations need to continue documenting their concrete recycling projects and making them easily accessible to make coverage of case studies more informed and
more comprehensive. Furthermore, additional studies investigating the use of RCA in new concrete structures, where long-term monitoring of their performance under real operational conditions is conducted, will be essential for establishing the viability of structural RCA concrete.

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CHAPTER 9—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Association of State Highway and Transportation Officials

AASHTO M 80-13 Standard Specification for Coarse Aggregate for Hydraulic Cement Concrete


American Concrete Institute

ACI 117.1R-14 Guide for Tolerance Compatibility in Concrete Construction

ACI 201.2R-16 Guide to Durable Concrete


ACI 221R-96(2001) Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete

ACI 228.2R-13 Report on Nondestructive Test Methods for Evaluation of Concrete in Structures

ACI 301-16 Specifications for Structural Concrete

ACI 318-19 Building Code Requirements for Structural Concrete and Commentary

ACI 364.1R-19 Guide for Evaluation of Concrete Structures Before Rehabilitation

ACI 408R-03(12) Bond and Development of Straight Reinforcing Bars in Tension

ACI 546R-14 Guide to Concrete Repair

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ACI 562-19    Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary

ACI 546.1R-19  Guide to Concrete Repair

ACI 546.2R-10  Guide to Underwater Repair of Concrete


Concrete Removal using Hydrodemolition

ASTM International

ASTM C33/C33M-18 Standard Specification for Concrete Aggregates

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3 ASTM E1155-14 Standard Test Method for Determining FF Floor Flatness and FL Floor
4 Levelness Numbers
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6 *Canadian Standards Association*
7 CSA A23.2-28A:2014 Standard Practice for Laboratory Testing to Demonstrate the
8 Effectiveness of Supplementary Cementing Materials and Lithium-Based Admixtures to Prevent
9 Alkali-Silica Reaction in Concrete
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21 Resulting from Reinforcing Steel Corrosion
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