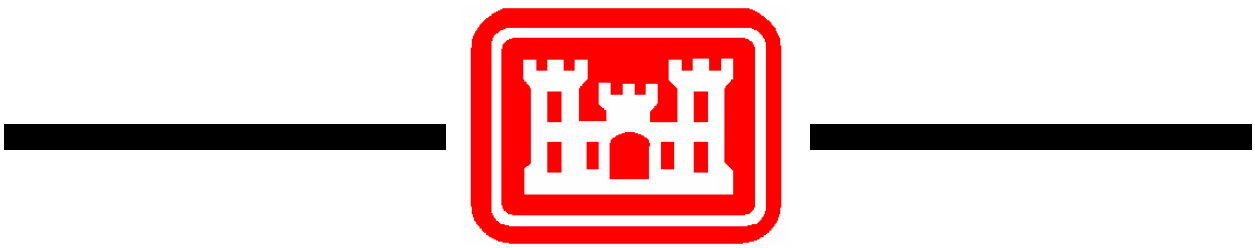
PUBLIC WORKS TECHNICAL BULLETIN 200-1-27
14 SEPTEMBER 2004

REUSE OF CONCRETE MATERIALS FROM BUILDING DEMOLITION



Public Works Technical Bulletins are published by the U.S. Army Corps of Engineers, Washington, DC. They are intended to provide information on specific topics in areas of Facilities Engineering and Public Works. They are not intended to establish new DA policy.

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
441 G Street, NW
Washington, DC 20314-1000

CEMP-CE

Public Works Technical Bulletin 14 September 2004
No. 200-1-27

FACILITIES ENGINEERING
ENVIRONMENTAL

REUSE OF CONCRETE MATERIALS FROM BUILDING DEMOLITION

1. Purpose. The purpose of this Public Works Technical Bulletin (PWTB) is to transmit information on the state of practice for recycling/reuse of concrete materials from building demolition.

2. Applicability. This PWTB applies to all U.S. Army facilities engineering activities.

3. References.

a. Army Regulation (AR) 200-1, Environmental Protection and Enhancement, 21 February 1997.

b. Army Regulation (AR) 420-49, Utility Services, 28 April 1997.

c. Army TM 5-822-10/AFM 88-6, “Standard Practice for Pavement Recycling” (26 August 1988).

4. Discussion.

a. Army Regulation (AR) 200-1, para. 5-10 contains policy for solid waste management, including participation in recycling programs and the sale of recyclables.

b. AR 420-49 contains policy and criteria for the operation, maintenance, repair, and construction of facilities and systems, for efficient and economical solid (nonhazardous) waste

management including source reduction, re-use, recycling, collection, transport, storage, and treatment of solid waste.

c. Construction and demolition (C&D) waste is a major contributor to Army installations' solid waste burden. Landfill space is diminishing, no new landfills are being built on installations, and there is a growing need to reduce the amount of waste. As part of the Department of Defense (DOD), the Army is encouraged to meet the P2 Measures of Merit goal to divert 40% (by weight) of solid waste from landfills or incineration. This, coupled with the fact that the supply of natural materials is limited, has encouraged the public and Government to use recycled materials, especially with material with high potential for reuse such as concrete.

d. By weight, concrete makes up the largest portion of the solid waste stream. A DOD survey of all installations has identified 8,000 buildings, totaling 50 million square feet, as candidates for removal. If these buildings are removed using traditional demolition techniques, hundreds of thousands of tons of waste will be generated and disposed of in landfills. The recycling of these concrete waste materials from building demolition can provide a solution to the problem of diminishing landfill space.

e. This PWTB outlines ways in which recycled concrete may provide a suitable substitute for more expensive virgin materials. Recycled concrete waste creates a product that can be sold or used for fill, bank stabilization, pavement for trails, and other purposes, reducing environmental burdens by substituting recycled (crushed) concrete for natural virgin aggregates.

f. Concrete recycling appears to be profitable. In most cases, it can meet demand requirements of lower value product applications such as road base, thereby freeing up higher quality material for higher value applications. Wherever good aggregates are not available locally, where aggregate costs are excessive, or where disposal of existing pavement of structures would be a problem, the use of recycled concrete aggregate (RCA) should be considered.

g. Appendix A contains information pertaining to the recycling/reuse of concrete aggregate.

h. Appendix B gives case studies of successful efforts involving the recycling of building concrete.

5. Poi Points of Contact. HQUSACE is the proponent for this document. The POC at HQUSACE is Mr. Malcolm E. McLeod, CEMP-II, 202-761-0632, or e-mail: malcolm.e.mcleod@usace.army.mil

6. Questions and/or comments regarding this subject should be directed to the technical POC:

U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
ATTN: CEERD-CN-E (Stephen D. Cosper)
2902 Newmark Drive
Champaign, IL 61822-1072
Tel. (217) 352-6511, X-5569
FAX: (217) 373-3430
e-mail: Stephen.D.Cosper@erdc.usace.army.mil

FOR THE COMMANDER:

DONALD L. BASHAM, P.E

Chief, Engineering and

Construction

Directorate of Civil Works

Appendix A:

Reuse of Concrete Materials From Building Demolition

CONTENTS

1. INTRODUCTION

a. General.

Construction and demolition (C&D) waste is a major contributor to Army installations' solid waste burden. Landfill space is diminishing, no new landfills are being built on installations, and there is a growing need to reduce the amount of waste. As part of the Department of Defense (DOD), the Army is encouraged to meet the P2 Measures of Merit goal to divert 40% (by weight) of solid waste from landfills or incineration. This, coupled with the fact that the supply of natural materials is limited, has encouraged the public and Government to use recycled materials. One such material with high potential for reuse is concrete.

By weight, concrete makes up the largest portion of the solid waste stream. Billions of tons of concrete have been used since World War II to construct buildings, bridges, dams, roads, and other structures. When the useful life of these structures is over, the materials from which they were built will find their way into the waste stream as rubble. Throughout the United States, many military installations will close and convert to civilian use over the next several years. Thousands of structures on those installations will be removed. A DoD survey of all installations identified 8,000 buildings, totaling 50 million square feet, as candidates for removal. If these buildings are removed using traditional demolition techniques, hundreds of thousands of tons of waste will be generated and disposed of in landfills.

Landfills are becoming increasingly difficult to find, are too remote from the demolition site, or are too costly to maintain. At the same time, sources of supply of suitable aggregate for making concrete are continually being exhausted. The recycling of building demolition waste materials into new buildings can provide a solution to these problems (De Pauw).

Grinding reinforced concrete buildings can reduce the volume of landfilled debris by roughly 80%. While volume reduction itself is beneficial, recycling the waste creates a product that can be sold or used for fill, bank stabilization,[1] pavement for trails, and other purposes, thereby reducing further environmental

[1] Recycled concrete (or quarried material) used for stream bank protection should be crushed in appropriate gradations, like rip-rap. Using slabs of concrete could actually increase erosion due to high localized water velocities and may hide voids.

burdens by substituting recycled aggregates for natural virgin aggregates.

b. Scope of Work.

This PWTB contains guidelines for the use of recycled concrete as an aggregate. Most previous research covers the recycling of concrete pavements. Much of the information here pertains to all-Portland cement recycling. However, Army installations have been reluctant to reuse rubble from buildings. Information is needed to identify the behavior of building rubble when used in variety of applications and to maximize the reuse of concrete rubble from buildings.

c. Methodology.

Much of the information for this study was obtained by literature review. (Many data sources were Internet web pages.) A phone survey of Army installations was also conducted.

d. Use of Aggregate Throughout the United States.

About 10 tons of aggregate per person are consumed annually in America. Every mile of Interstate highway consumes 38,000 tons of aggregate. Approximately 400 tons of aggregate are used in construction of the average home (NSSGA).

Probably the most recycled material in the United States is concrete. In 1997, C&D Debris Recycling and Vanderbilt University conducted a survey of North American aggregate producers to determine the status of the concrete recycling industry. Survey results showed that concrete was being recycled in 32 states; current recycling rates may be higher. The volume of recycled concrete processed by individual firms varied widely. (An average of 174,000 tons was recycled per year.) The main sources for this concrete rubble are demolition work and road/highway rehabilitation projects: 46% comes from demolition, 32% from road work, and the rest from a number of other sources including construction, waste concrete, and debris (Figure 6).

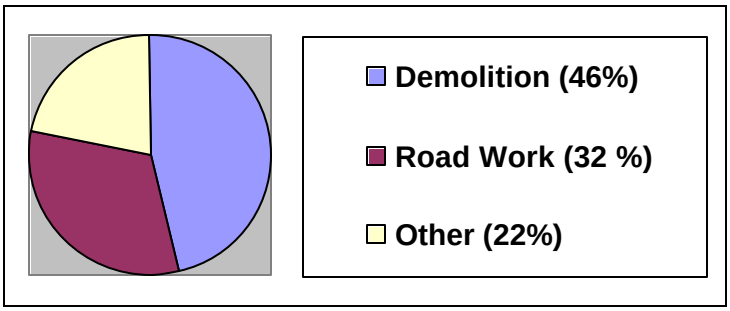


Figure 1. Sources of Concrete for Recycling (Deal 1997).

U.S. Highway agencies have been using recycled materials with varying degrees of success for the past 20 years. The use of RCA in base or sub-base applications has been widely accepted and is covered by conventional granular aggregate specifications in a number of jurisdictions. Many state, regional, and local public works may have additional specifications and test requirements that must be followed. Links to these specifications can be found on the Recycled Materials Resource Center website at http://www.rmrc.unh.edu under the heading “Resources” and then by selecting, “External Specification Links” from the pull down menu.

The United States does not have national standards for the use of recycled C&D waste. The Federal Highway Administration (FHWA)has conducted research on the suitability and economics of reusing recycled concrete and has recently published a detailed report as part of a Federal initiative to reduce barriers to recycling and to facilitate the migration of successful practices across state boundaries.

e. Natural Versus Recycled Aggregates.

Aggregates are required for construction projects and are defined by the U.S. Geological Survey as rock fragments that may be used in their natural state or after mechanical processing such as crushing, washing, and sizing. Aggregate can be naturally occurring sand and gravel or crushed stone. Recycled aggregates consist mainly of crushed concrete (Wilburn and Goonan 1988).

i. Natural Aggregates.

Natural aggregates consist of both sand and gravel, stones and crushed stone. Construction aggregates make up more than 80 percent of the total aggregates market, and are used mainly for road base, rip-rap, cement concrete, and asphalt. In 1998,

roughly 3,400 U.S. quarries produced about 1.5 billion tons of crushed stone, of which about 1.2 billion tons was used in construction applications (Wilburn and Goonan 1988).

Aggregates are divided into two distinct categories – fine and coarse. Fine aggregates are those that generally consist of natural sand or crushed stone in which most particles can pass through a 3/8-in. (9.5mm) sieve. Coarse aggregates are those with particles greater than 0.19 inch (4.75 mm), but that generally range between 3/8 and 1.5 inches (9.5 mm to 37.5 mm) in diameter (PCA).

ii. Recycled Aggregates.

Recycled aggregates originate from C&D debris and consist mainly of crushed concrete and crushed asphalt pavement. In the United States, demolition of roads and buildings generates large quantities of demolition wastes, which generates more than 200 million tons of recycled aggregates annually (USGS Fact Sheet FS-181-99, February 2000).

f. Cement Versus Concrete.

Although the word “cement” has been in use since the 14th century, the term “concrete” was not applied to the building material until the 19th century. Although the two words “concrete” and “cement” are often used interchangeably, cement is actually a finely ground powder that is just one ingredient of concrete. Cement constitutes only 10-15% by weight of concrete’s total mass, but is the essential binding agent in concrete.

Concrete is made by mixing Portland cement (a mix of limestone, clay, and sand) with aggregates comprised of sand, gravel, and crushed stone, together with water to form a rock-like substance (Figure 1). Eighty percent of concrete is aggregate. It influences the way both fresh and hardened concrete perform. Once concrete is mixed, poured, and set, it cannot be reused, except as a recycled raw material. Historically, it has been discarded (most likely in a landfill) and replaced with new concrete.

In residential construction, concrete is used primarily for foundations. In larger complexes, it is used more extensively in walls, and in floor and roof slabs because of its strength and non-combustibility.

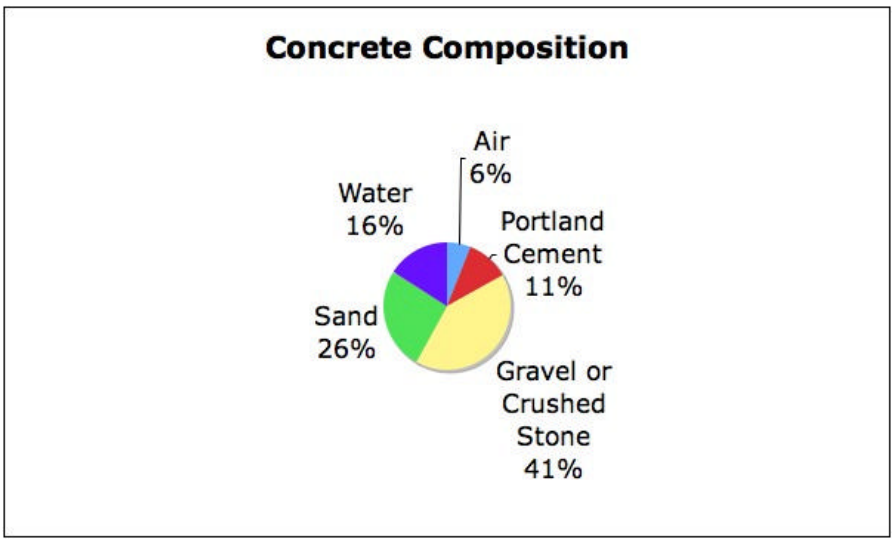


Figure 2. Composition of Concrete (Environmental Council of Concrete Organizations (ECCO).

g. Recycled Concrete Aggregate (RCA).

i. Definition.

Recycled concrete originates from C&D debris that has been removed from pavement, foundations, or buildings, and that has been crushed to produce Recycled Concrete Aggregate (RCA) (Figure 2). Recycled concrete aggregates account for roughly 5 percent of the total aggregates market (more than 2 billion tons per year) while the rest is being supplied by natural aggregates.

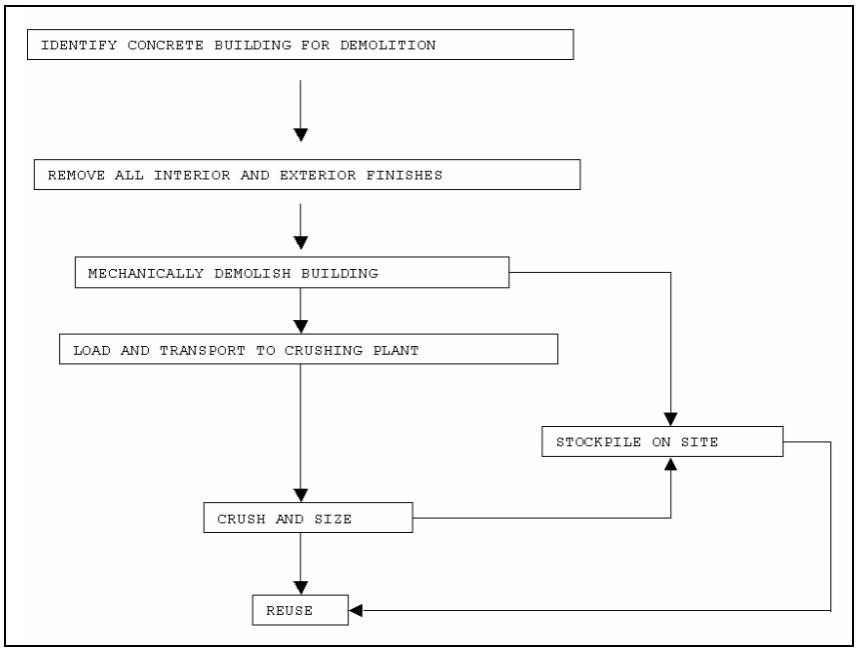


Figure 3. Concrete Building Recycling Flow Process.

ii. Physical Properties.

Recycled concrete aggregate looks like crushed stone (Figure 3). However, crushed concrete has many physical properties that vary from those of natural aggregates. In general, crushed concrete particles are more angular have a rougher surface texture than natural aggregate. Roughly textured, angular, and elongated particles require more water to produce workable concrete than smooth, rounded compact aggregate.

Figure 4. Crushed Concrete Aggregate.

The lightweight, porous cement mortar attached to recycled concrete aggregates causes crushed concrete aggregates to have a lower specific gravity and higher water absorption than comparatively sized natural aggregates.

The lower compacted unit weight of RCA compared with conventional mineral aggregates results in higher yield (greater volume for the same weight), and is therefore economically attractive to contractors.

USACE and Department Of Transportation (DOT) specifications have shape requirements for aggregates. For example, at least 70% of the material should have two or more crushed (flat) faces. Increased angularity of the aggregate increases asphalt and concrete stability.

iii. Chemical Properties.

Concrete recycled from buildings may be contaminated by sulfates from plaster and gypsum wallboard, which creates a possibility of sulfate attack if the recycled aggregates used in concrete are accessible to moisture (Buck 1972a).

One of the main issues surrounding the use of recycled concrete aggregate in concrete production is the potential for reaction between the RCA and alkaline water. Alkali-silica reaction results in volumetric expansion, in which there is a high probability of internal fracturing and premature deterioration of the concrete. Where alkali-silica reactivity is of concern, the potential for deterioration should be evaluated (Recycled materials Resource Center, URL: http://www.rmrc.unh.edu/).

Chloride ions from marine exposure can also be present in RCA. Because of the use of deicing salts as a mechanism to control development of ice on pavement, there is a strong possibility that chloride ions will be present in recycled concrete aggregate. The presence of chloride ions in Portland cement concrete can adversely impact the reinforcing steel within concrete. Reinforcing steel in the presence of chloride ions will react to form iron oxide or rust. If the formation of iron oxide persists, there is a high probability of delamination of the concrete structure.

Since total elimination of all deleterious contaminants is not practical, experimentation is required to determine acceptable levels and to eliminate unnecessary processing cost while providing a quality product. These issues are currently under investigation by the Federal Highway Administration (FHWA),

DOTs, etc. Until more definitive specs are commonplace, users will have to “do their homework” to see if RCA can be used in their particular application.

These chemical-related cautions apply largely only to use of RCA in new concrete mixes or asphalt concrete. Many, perhaps most, of the uses for RCA (such as a roadbase or erosion control) are not subject to these limitations.

h. Quality Control.

Recycling may slightly degrade high quality aggregate, but recycling generally produces good quality aggregate. Quality, however, varies significantly due to large variation in type and impurities of debris sources. Care must be taken to prevent contamination of the concrete by dirt or other undesirable materials from buildings that would restrict the recycling, such as gypsum plaster products.

Excluding the possible concerns regarding chloride salts (discussed above), contamination is usually not a problem when recycling concreted taken from highways or other pavements. Concrete building recycling, though, requires more concern for contaminants such as plaster, soil, wood, gypsum, asphalt, plastic, vinyl, or rubber. While contaminants are usually not a problem for recycled aggregates used as a pavement base course, strict control must be used for recycled aggregates in concrete to ensure that there are no more contaminants than are allowed for virgin coarse aggregate (ECCO). In general, the degree of contamination and potential reactivity of RCA should not exceed limits permitted for virgin aggregates (AASHTO Designations: M147-70, M80-77, M6-81; M 319-02; ACPA 1993; ASTM Standard Specification D2940-92, 1996).

The degree of contamination can be limited by a short inspection of the incoming trucks at the rubble-processing plant aided by the knowledge about the origins of the demolished concrete. Concrete that is reclaimed may come from a variety of sources, and therefore may be subjected to natural variation in properties. If reclaimed concrete did not perform well in its original application, it is not likely to make a good aggregate for use in a secondary application.

Recycled aggregate materials can and should be subject to the same testing requirements as virgin materials for a specific application. Construction or highway specifications for concrete often include freeze-thaw cycle resistance, wetting and

drying, and abrasion resistance. Material used for riprap will have minimum density requirements. See Section 6 below.

i. Composition of C&D Waste.

Concrete rubble from highways, pavements, and other civil engineering works contains few materials other than steel and concrete. On the other hand, C&D waste from building renovation, demolition and construction contains many building materials, so the recycling of building rubble presents a much greater challenge. C&D waste consists of concrete, asphalt, wood, fixtures, rebar, metals, drywall, roofing, and other materials. Many of these materials and the majority of concrete waste can be recycled. By weight and volume, C&D recycling is the biggest recycling industry in the United States. Probably the most recycled material in the United States is concrete The Construction Materials Recycling Association (CMRA) estimates that more than 100 million tons of concrete are recycled every year.

To produce good quality recycled aggregate, proper separation of unsuitable materials from the aggregate feedstock is important. Contaminants are mostly a concern when recycled aggregates are to be used in new concrete. Standard specifications for recycled aggregates should include maximum allowable limits on contaminants such as asphalt, gypsum, organic substances (wood, textile fabric, paper, joint sealants, paints, etc.), soil, chlorides, and glass. Limits are suggested for various contaminants, usually by volume or weight percentage of the recycled material. For building demolition, the separation of the various waste materials can add significantly to the demolition cost, but provide higher market value for the aggregate.

j. Portland Cement Concrete.

The use of crushed waste concrete as concrete aggregate began in Europe at the end of World War II. Research by the German Committee of Reinforced Concrete carried out from 1996 to 1999, identified important properties of recycled aggregate concrete in comparison with concrete made with natural aggregates (Concrete Technology Today/July 2002). The results of this research may provide valuable guidance for the U.S. concrete industry to make the next step into using recycled aggregates in building construction.

Because it is more difficult to control the quality of the source aggregate materials when reclaimed concrete is used in

the production of Portland cement concrete, recycled aggregates are not commonly used for production of new Portland cement concrete. There is the potential that the final concrete product may exhibit properties that differ from concrete produced with natural aggregates. As a result, Portland cement concrete manufactured using reclaimed concrete aggregate may not be appropriate for all concrete applications.

The reuse of crushed concrete as aggregate in high-grade concrete has up to now been restricted by a lack of standards, experience, and knowledge. It would require extensive (and prohibitively expensive) screening and testing of the recycled material to produce recycled aggregate that would potentially meet the technical specifications and performance expectations for structural Portland cement concrete. However, laboratory research and experience at several recent projects have proven that it is feasible to use recycled concrete as aggregate for new concrete mixtures.

k. Physical Properties.

Some of the physical properties of particular interest when RCA is used in Portland cement concrete applications include aggregate grading, particle shape, drying shrinkage, absorption, strength, and durability.

Grading refers to the determination of the particle-size distribution for aggregate. Grading limits and maximum aggregate size are specified because grading and size affect the amount of aggregate used, as well as cement and water requirements, workability, and durability of the concrete. Generally, up to 30% of the conventional aggregate in concrete may be replaced by recycled aggregate without significantly affecting the mechanical properties of the new concrete. This may be the simplest, most economical, and least controversial way of getting wider use of recycled aggregates in new concrete (ECCO). The recycled concrete aggregate shall meet the same particle size distribution as that specified for natural aggregates. If the RCA is found to fail the specified grading requirements, the crushing operation maybe adjusted or the RCA may be combined with natural aggregates to obtain the desired grading.

Aggregate particle shape influences the properties of both fresh and hardened concrete. Ideally, crushed aggregate particles should have a cubical shape. As the number of flat and elongated particles increases, concrete workability decreases and the amount of and water needed to achieve a given slump

increases (Concrete Producer, April 1996). The crushing process needs to be carefully controlled. RCA, being 100 percent crushed material, is highly angular in shape. While this shape helps increase the strength of the mix, it can reduce its workability.

Drying shrinkage and creep of concrete significantly increases with the use of recycled, and in particular, fine aggregate. It may be prohibitive to use crushed concrete aggregates in reinforced concrete because of its significant impact on drying shrinkage and creep. Critical applications where this would not be acceptable include bridges and airfield pavements. However, the modulus of elasticity decreases with increasing quantities of recycled aggregate. With 100% recycled aggregate, the modulus of elasticity of the concrete is about 35% lower than that of natural aggregate concrete.

When RCA is used for recycled concrete, the resulting aggregate is characterized by absorption up to eight times that of natural aggregate fines. The workability of recycled concrete is reduced because recycled aggregate contains a higher fine content than natural aggregate; the mortar from the original concrete makes the RCA more porous and absorptive than its natural counterpart. The additional absorption requires more water be added to the RCA stockpile to reach saturation before it can be added to the concrete mix.

The use of recycled aggregate does not substantially affect the compressive strength and splitting tensile strength of the concrete when only the coarse aggregates were replaced by coarse fragments of demolition debris. When the fines are also replaced by recycled fines, the strength drops by between 35 and 50% compared with natural aggregates. When using 100% recycled aggregate, no significant differences from the natural aggregate concrete were found in freeze-thaw resistance, the progress of carbonation, and oxygen permeability.

Table 1 lists the effects of recycled aggregate on concrete properties compared to the properties of concrete containing natural aggregate with the same water-to-cement ratio.

Table 1. Effect of Recycled Aggregate on Concrete Properties in Comparison to Virgin Aggregate.

Compressive strength	**Tensile strength**	**Modulus of elasticity**	**Drying shrinkage**	**Creep**	**Permeability**	**Freeze-thaw resistance**
No effect	No effect	Decrease	Increase	Increase	No effect	No effect

Some properties of concrete from recycled aggregates can deviate from those of comparable concrete mixes with natural aggregates. These differences need not impair the suitability of recycled concrete. Investigations on crushed concrete from demolition work have proven that it is possible to produce high-grade aggregate with reused concrete. High quality can be produced by pre-separation, processing, and screening of the content for impairing constituents

l. Federal Highway Administration RCA Survey.

Together with the Construction Materials Recycling Association, the FHWA is conducting a National Review on Recycled Concrete Aggregate. Because the management and regulation of recycled materials use in the highway environment are the responsibility of a state’s department of transportation (DOT) and its environmental protection agency (EPA), these agencies are working together to develop a consensus-based approach to RCA use.

The purpose of this review is to capture for technical deployment the most advanced uses of recycled concrete aggregate and then to transfer the knowledge to all state transportation agencies. Specific uses or applications will be identified along with their barriers and benefits to implementation. Specifications, construction practices and challenges will also be documented and disseminated to all state transportation agencies through technical guidance, training, and guide specifications as necessary. Five states – Minnesota, Utah, Virginia, Texas and Michigan – have been chosen for an in-depth review of their recycled concrete aggregate programs.

FHWA has a longstanding position that any material used in highway or bridge construction, be it virgin or recycled, shall not adversely affect the performance, safety or the environment of the highway system. The FHWA policy is that:

- Recycling and reuse can offer engineering, economic, and environmental benefits.
- Recycled materials should get first consideration in materials selection.
- Determination of the use of recycled materials should include an initial review of engineering and environmental suitability.
- An assessment of economic benefits should follow in the selection process.
- Restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications.

m. General Uses Of Aggregates.

In the United States, recycled concrete aggregates have been primarily used as fill or sub-base materials, and less often, as aggregates in new concrete pavements (Figure 4). Most (70%) of this recycled concrete aggregate went to construction firms while government agencies and contracts account for nearly all of the rest (Deal 1997). In most areas, there is a ready supply of rubble and a good demand for recycled materials as fill and base for construction projects such as buildings, parking lots, roads and streets, and pipe and drain ducts.

Crushed concrete can be reused in new construction as road and railroad base material, fill, or pavement constituents. In some applications, recycled concrete may be used in place of aggregate for drainage layers and sub-bases. Other potential uses include ballast, sub-ballast, drainage, erosion control and filter material. Finely crushed concrete can also be used as a neutralizing agent in a variety of applications. The reuse of crushed concrete as aggregate in high-grade concrete, however, has up to now been restricted by a lack of standards, and a lack of experience and knowledge in working with the materials.

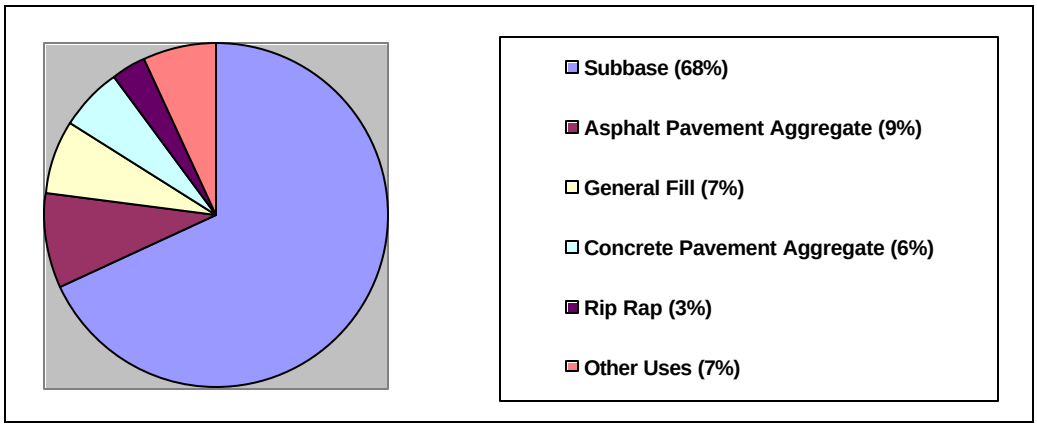


Figure 5. Uses of Recycled Concrete Aggregate (Deal 1997).

i. Granular Base.

A base course is defined as the layer of material that lies immediately below the wearing surface of a pavement. The base course must be able to prevent overstressing of the subgrade and to withstand the high pressures imposed on it by traffic. It may also provide drainage and give added protection against frost action when necessary.

Recycled aggregates can be (and are) used as granular base and sub-base in road construction (Figure 5). In many applications, recycled aggregate will prove to be superior to natural aggregate for use as granular base. An estimated 85 percent of all cement concrete debris that is recycled is used as road base due to its availability, low transport cost, and good physical properties.

Figure 6. RCA Used for Granular Base.

Granular base materials typically contain more than 50 percent of the recycled coarse aggregate particles. (The amount of fine aggregates is limited to promote drainage.) In fill applications, the fines content of RCA may restrict drainage, particularly in road sub-base applications. However the fines also facilitate compaction in some jurisdictions. The use of recycled materials is often preferred for this reason.

Forty-four States allow recycled concrete in road base applications (Wilburn and Goonan 1998). Specifications for these applications are developed by a variety of Federal and State agencies. Specifications often vary considerably by local climatic conditions and product availability because the quality of the recycled materials varies from location to location and is fairly difficult to control. Specifications for crushed stone are developed by State departments of transportation (DOTs) and organizations such as:

- The American Society for Testing and Materials (ASMT), URL: http://www.astm.org
- American Association of State Highway and Transportation Officials (AASTHTO), URL: http://www.aashto.org
- U.S. Department of Transportation, Federal Highway Administration (FHWA), URL: http://www.fhwa.dot.gov
- U.S. Army Corp of Engineers, URL: http://www.usace.army.mil

Processed RCA is covered by conventional granular aggregate specifications in a number of jurisdictions. AASHTO Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course, AASHTO M319-02, covers the use of reclaimed concrete aggregate as an unbound granular base course material. This specification was developed to aid the use of recycled materials in highway transportation applications. When properly processed, hauled, spread, and compacted on a prepared grade to appropriate density standards, reclaimed concrete aggregate can provide adequate stability and load support for use as road or highway base courses, whether used alone or blended with natural or crushed aggregate. The properties of processed RCA generally exceed the minimum requirements for conventional natural aggregates for granular base.

ii. Embankment Fill.

Crushed rock fill is specified where necessary to control embankment erosion, to prevent capillary action from saturating embankments, and to prevent the entrapment of water by the embankment.

RCA is not commonly used to construct fill embankments because, in most cases, the cost of the aggregate will be significantly higher than that of common fill. Recycled concrete aggregate in embankments or fill may not make the best use of the high quality aggregates associated with RCA. Where no other applications are readily available, RCA can be satisfactorily used in this application. It requires minimal processing to satisfy the conventional soil and aggregate physical requirements for embankment or fill material.

Desirable attributes of RCA for use in embankments or fill include high friction angle, good bearing strength, negligible plasticity, and good drainage characteristics. The design requirements for RCA in embankment construction are the same as for conventional aggregates. There are no specific standard specifications covering RCA use as embankment or fill and design procedures are the same. Fines should be screened out before this type of use.

Due to its high alkalinity, RCA in contact with aluminum or galvanized steel pipes can cause corrosion in the presence of moisture. Additionally, the presence of water percolating through reclaimed concrete aggregate has the potential to increase the pH to produce a corrosive solution. Therefore, recycled concrete aggregate should not be used in the vicinity

of metal culverts that are sensitive to highly alkaline environments (AASHTO M319-02).

iii. Railway Ballast.

Ballast is a select material placed on the subgrade to distribute the load of the tract and trains to prevent overstressing of the subgrade and to restrain the track laterally, longitudinally, and vertically under the dynamic loads imposed by trains and the thermal stresses induced in the rails by changing temperatures. Ballast also provides adequate drainage of the track (TM 5-628/AFR 91-44). Ballast produced for use on main lines is generally governed by standard specifications.

Ballast should meet the gradation requirements specified in the AREA Manual for Railway Engineering, chapter 1, part 2.

It is very desirable that the gravel contain a large volume of crushed stones. Otherwise, the ballast will not hold the ties in place under high-speed traffic, increasing maintenance costs. One requirement of good ballast is that it quickly drain water away from the track.

One of the most demanding applications for crushed stone is railroad ballast. Railway ballast consists of a coarse aggregate that provides a free-draining foundation for the track. The aggregate used must be strong, angular material, with a high resistance to abrasion. Select crushed rock aggregate is generally used, though crushed slag or gravel is also used. Recycled aggregates are not commonly used for railway ballast because of concerns about strength, abrasion resistance, and durability (Crawford 2001).

iv. Drainage and Filter Material.

A relatively small volume of aggregate production goes to provide drainage or filter media for various applications, including sub-drains for buildings, dams, and other engineered structures, as well as filters for sewage and water treatment. Recycled aggregates are not commonly used for filter or drainage material because of concerns about durability, particularly with respect to chemical attack from impurities in the groundwater or leachate being filtered (Market Development).

Recycled fine aggregates are not suitable for use in drainage layers beneath the pavement because soluble mineral rich in

calcium salts and calcium hydroxide can be transported with the water as it percolates through and plugs sub-drains. If the RCA is located above such porous drainage systems, the calcium minerals tend to precipitate out of solution and bind to the drainage structure. The mineral deposits formed are sometimes referred to as tufa-like or portlandite deposits. Over time, the permeability of the drainage system can be reduced. If the RCA is intended for use as a drainage layer, then the processed coarse aggregates should be washed to remove the dust and fines.

v. Concrete Block.

Concrete block are made by mixing Portland cement, sand, and other aggregates with a small amount of water and then blowing the entire mixture into molds. The major component material of concrete block (sand and various coarse aggregates) account for as much as 90% of its composition. Recycled material such as crushed concrete and by-products of other industrial processes such as blast furnace slag, can be used for some portion of the aggregate in block. Concrete block offers an advantage because there is little waste. Any unused block can be recycled or saved for future projects rather than being disposed of.

ASPHALT CONCRETE

Recent laboratory studies to determine the feasibility of using RCA in asphaltic concrete have indicated that RCA mixes had 1.5 to 2.0 times the stability of crushed stone-natural sand mixes (Petrarca and Galdiero). In two controlled test strips, the RCA mixes are performing better than the standard paving mixes. If properly designed and constructed, recycled concrete-asphalt mixes are capable of providing a strong, economical, stable pavement that will yield low deflections. The RCA mixes are also approximately 15 percent lighter than standard mixes, and therefore will cover 15 percent more volume for the same tonnage.

2. CONCRETE RECYCLING ON ARMY INSTALLATIONS.

Much of the infrastructure that has been constructed since the 1950s, particularly roads and barracks within the Army, has become obsolete and is in need of replacement or repair. As Americans tear up roads and tear down buildings, they generate large quantities of demolition wastes. Demolished infrastructure can be either landfilled or recycled.

Currently, the Army has concrete barracks that were built in the mid 1950s during the Korean-War era that have outlived their

usefulness and have been slated for removal, either to make room for new construction, or to satisfy Base Realignment and Closure (BRAC) program requirements. Two of typical barracks buildings constructed with reinforced concrete are commonly known as “Hammerhead” and “Rolling Pin” barracks (Figures 7 and 8).

Figure 7. Hammerhead Barrack.

Figure 8. Rolling Pin Barrack.

A 3-story “Hammerhead” barrack is approximately 38,000 square feet and contains roughly 2000 tons of concrete. Another concrete construction typical of Army installations is the 3-story “Rolling Pin” barrack. These structures are approximately the same size (38,000 sq ft). Each also contained around 2000 tons of concrete. Reinforcing steel in these buildings alone totals 75 tons.

As buildings like these approach and pass their average 50-year life-span (and eventual demolition) in the decades to come, increasing amounts of concrete rubble will need to be disposed of. Records of the history of old concrete buildings or pavement (such as those detailing quality and composition), if available, will be valuable documents that may facilitate recycling. Such records may indicate the strengths and mixture designs of the original concrete, information useful in determining the recycling potential of the concrete (ECCO). For example, the concrete from barracks at one military base was tested. In all instances, the level of lead present was below allowable EPA standards. The concrete was acceptable for recycling (Turley).

a. Uses of RCA.

On most Installations, there is a ready supply of rubble and there are many uses for recycled materials as fill and base

course for construction projects such as buildings, parking lots, roads and streets, and pipe and drain ducts.

Areas of the United States where aggregates occur in abundance include the western part of the country (especially Colorado and Wyoming), upper New England through Maine, New Hampshire and Vermont, and Northern Michigan, Minnesota, and Wisconsin. Areas where aggregates are scarce include the Gulf coast regions from Texas to Florida and the Southeastern and Mid-Atlantic shorelines. Although nature dictates the location of natural aggregates, other factors influence the development of the resources. Prime aggregate sources can be lost if parking lots, houses or other buildings are constructed over the resources. Zoning and permits may restrict development of other sources. Yet, for economic reasons, aggregate operations must be within reasonable distances of the market area.

The reuse of concrete, which is readily available from old buildings and pavements, avoids the costs and environmental problems associated with landfill disposal. Using recycled materials instead of natural materials provide environmental and economical benefits (conservation of resources, better performance, and lower materials and transportation costs).

b. Army Installation Survey.

A survey was conducted of select Army Installations to profile the aggregate use on Installations and to compare that use to the typical uses of recycled concrete aggregate available from the building or pavement demolition. This survey was used to define the demand for aggregate products on Army Installations and identified what agencies or offices use aggregate products. Where the demand matches the RCA capabilities, the potential exists to replace natural, purchased aggregate products with RCA generated on post.

Installations were contacted by phone and asked to identify the types and quantities of aggregate products used. Some of the uses for crushed aggregate included: rip-rap, construction fill, erosion control, road work, tank trails, ballast, and bank stabilization. In all of these applications it was determined that where aggregate products are used, recycled aggregates from construction or demolition waste could be substituted.

The main concerns voiced were the problems of sizing the crushed concrete, and the concern that the material be free from all rebar. Stockpiled crushed concrete may not be suitable for any application if the sizing and grading does not meet required

specifications. However, if prior to crushing, the intended use of the RCA is known, it can then be crushed to the required size. Any rebar or steel in the crushed concrete would tend to damage tracks and tires, and must be removed (commonly done by electromagnet).

It was found that the use of on-site crushers was not predominant. Typically, concrete crushing is done off-site by the contractor. Some companies will also bring portable crushers on site, crush the material, and leave it for use at the base. Leasing a crusher for a specific project is another alternative. (Fees will vary.) Since C&D work at an installation is usually performed for a specific project, the work may not require year-round use of a crusher. It may be appropriate to contract for crushing services, as required. Additionally, it is possible to stockpile the material for extended periods of time provided land is available for stockpiling.

c. Stockpiling.

When possible, all excess recycled aggregate should be stockpiled for use on future Government projects (Figure 9). However, state solid waste regulations may not permit stockpiling for more than a specified amount of time. After such time, the crushed aggregate is considered to be a waste and would need to be disposed of.

Figure 9. A Front-End Loader Is Used To Stockpile Recycled Concrete.

To ensure uniformity of RCA properties, sources or types of concrete feedstock should be processed separately and placed in separate stockpiles. Stockpiles should also be kept from contamination by foreign materials. Although there do not appear to be any environmental problems associated with leachate from RCA, some jurisdictions require that stockpiles be separated (a minimum distance) from water courses because of the alkaline nature of RCA.

d. Environmental Issues.

In a study on the environmental impact produced by the recycling of concrete originating from C&D, recycling processes involving mobile crushing plants were compared with the environmental impact produced during the extraction process of natural resources. It was concluded that the processes of quarrying, crushing, and grinding of natural aggregates produces a greater environmental burden than the processes of crushing and recycling of concrete. This is due to the fact that, in producing natural aggregates, the extraction processes (and their implicit consumption of energy) must also be considered (Estevez).

The amount of high quality aggregate available for construction is limited. Most natural aggregates are obtained by quarrying, which produces a number of environmental problems. Quarrying creates large cavities in the traditional landscape and produces noise and dust pollution. Traditionally, quarries

are located on the outskirts of developing cities, where their environmental effects will not affect surrounding communities. As cities expand, however, producers of natural aggregates face stronger environmental pressure and are forced to relocate farther away. Unfortunately, as the distance between aggregate producers and urban centers increases, so does the cost involved in transportation of the aggregates.

Transportation is a major part of the environmental burden because it is responsible for the most energy usage and emissions of gases and particulates (Figure 10).

There is also a fixed amount of areas in which to dump waste materials. As landfill costs for C&D debris continue to rise and the landfills become more heavily regulated, it makes economic sense to seek alternative means of disposal of concrete from C&D projects. Disposal of C&D waste at many military installations is usually the responsibility of a contractor. More contractors are incorporating recycling into their operations to decrease disposal costs.

Figure 10. Transportation of Heavy Aggregate Materials Can Have Environmental Consequences.

e. Equipment.

The increased interest in recycling concrete pavements and structures has brought about the development of technology and equipment for recycling that results in an overall reduction of cost when recycled materials are used. Most of the equipment used in the recycling process can be considered standard in

heavy construction. The same basic equipment used to process virgin aggregates also is used to crush, size and stockpile recycled concrete aggregates. Although most recycling plants have both primary and secondary crushers, some plants produce aggregates by primary crushing only.

In the United States, 61 percent of recyclers use jaw crushers for primary crushing and 43 percent use cone crushers for secondary crushing. Recyclers often prefer a jaw crusher because it can handle large pieces of concrete. Secondary crushers are also popular among recyclers. Following the initial crushing of concrete rubble and removal of any steel, the larger material is fed into a secondary crusher that breaks the particles down to the maximum size required which varies depending on specification.

f. Steel Reinforcement.

Several advances in recent years have made recycling more economical for all types of concrete including the development of equipment that can accommodate steel reinforcement for breaking up plain, mesh-and-dowel, or continuously reinforced concrete. Methods have also been developed to minimize hand labor in the removal of steel.

If the concrete contains steel reinforcement, which most concrete structures do, it is necessary to remove this reinforcement (Figures 12 and 13). All reinforcing steel should be removed from the salvaged concrete either before or during the crushing operation. Any reinforcing steel not removed previously must be separated from the recycled concrete after it is processed through the primary crusher.

After initial crushing, the pieces of reinforcing steel are removed either by electromagnet, suspended above the conveyer belt leading from the primary crusher, or removed manually from the conveyer belt by one or two men. Once the reinforcement is separated from the concrete, most recyclers sell this material for scrap.

Because there is good demand for recycled steel, very little steel ends up in landfills. Demolition contractors nearly always extract and sell the reinforcing bars in the concrete as ferrous scrap. The reinforcing bars are then melted down to create new steel products, which can include new reinforcing bars. The Steel Recycling Institute estimates that now over 45 percent of reinforcing bars are recycled. More than 7 million tons of steel is recycled into reinforcing bars every year.

Figure 11. Steel Reinforcement from Concrete Waste.

Figure 12. When a Road or Structure Is Demolished, the Rebar can Often Be Seen Protruding from the Broken Chunks of Portland Cement Concrete.

g. Economic Issues.

An inflated economy, along with the fact that natural resources are limited, has caused a substantial increase in the cost of construction materials. This, as well as the rising cost of fuel and equipment required to haul the concrete has encouraged recycling.

Proximity to market is critical due to high transportation costs. Transporting concrete to the landfill can cost as much as $0.25 per ton/mile (http://www.ConcreteNetwork.com). For large reconstruction projects, on-site processing and recycling of RCA is likely to result in economic benefits through reduced aggregate hauling costs. Since the need for processing will remain common to conventional aggregates and to recycled concrete, the energy reduction will come largely through the elimination or reduction of transportation costs. This can also reduce the overall cost for recycled aggregates. In some regions, RCA may cost 20 to 30% less than natural aggregate.

Below is an economic analysis of the cost of recycling C&D concrete waste compared to landfill disposal. Landfill costs for concrete, asphalt and brick will vary greatly depending on the location, but the best all around estimate is $1/ton (P2 Opportunity Handbook).

Other assumptions are that:

- Recycle crushed concrete on base at 240 ton/yr.
- Crushing costs: $4/ton (includes labor and crusher rental)
- Landfill costs (inert wastes): $1/ton
- Hauling costs: $5/ton
- Avoided new fill material costs: $12/ton

Table 2. Annual Operating Cost Comparison for Diversion and Disposal of (240 tons/yr) C&D Wastes.

	Diversion	**Disposal**
Operational Costs		
Crusher Costs (Labor & Rental)	$1000	$0
Waste Disposal	$0	$240
Hauling	$0	$1,200
Total Operational Costs	$0	$1,440
Total Recovered Income	$2,900	$0
Net Annual Cost/Benefit	+$1,900	-$1,440
Source: *METRO Solid Waste Management Division of Portland Oregon* (P2 Opportunity Handbook, Naval Facilities Engineering Service Center [NFESC]).		

The cost of recycling can be up to $4.00 per ton to crush, and may include other expenses. But, by eliminating the cost of removing the old concrete and factoring in savings on disposal costs, potential use of recycled aggregates, and potential income generated from the sale of scrap rebar, annual savings are approximately $3340 (Table 2). Recycling concrete makes sense for the cost benefits, the conservation of resources, and for the redirection of material that would otherwise be waste.

h. Technical Issues.

The processing of recycled concrete materials is relatively simple, but requires expensive, heavy-duty equipment, capable of handling a variety of materials. The technology basically involves crushing, sizing, and blending to meet the required product mix. Much C&D concrete contains metal and waste materials that must be detected and removed at the start of processing by manual or magnetic separation. Processing equipment must be versatile yet efficient for a handling a variety of materials of non-uniform size or composition.

The crushing plants can be either a portable type and located on the job site or a stationary plant situated at an existing pit or landfill. The main reasons for using portable plants include the ease of moving the equipment for cleaning and maintenance, as well as the ability to go to the job site. Portable plants must be small enough to fit on existing roads and under overpasses. Demolition project sites may also have space limitations. Recycling concrete at a demolition site is different than recycling on a paving job or at a stationary plant; the contractor usually has several pieces of mobile equipment at the site, mostly excavators with concrete breakers or pulverizing attachments.

a.

b.

Figure 13. Concrete Rubble Is Loaded into Crusher for Processing.

Demolished concrete is brought to the crushing operation where it is reduced to the maximum size called for in the specifications (Figure 11). Crushing is usually performed in two steps: a primary crusher reduces the larger incoming debris, and a secondary crusher further reduces the material to the desired particle size. Magnetic ferrous metal recovery can take place after both stages. The two main types of equipment are jaw and impact crushers. Jaw crushers are best suited to reduce large or odd-shaped debris quickly from C&D projects to a manageable size. Impact crushers are more effective than jaw crushers at freeing rebar encased in rubble.

i. Policy Issues.

Federal agencies are required under Executive Order 13101, *Greening the Government Through Waste Prevention, Recycling and Federal Acquisition*, to purchase environmentally preferable products and services. Recycling concrete from C&D waste will help Army facilities to meet the requirements of Executive Order 13101, which calls for executive agencies to incorporate waste prevention and recycling into their daily operations.

Policy implementation for C&D waste recycling varies considerably between jurisdictions. Some States and local governments, notably Texas, Washington, Oregon, California and Colorado have well-developed mechanisms to encourage diversion of C&D waste from landfills. Texas, Washington, Colorado and Oregon have provisions within state road construction specifications to allow the use of recycled materials. The CalTrans and Green Book specifications used in California, for example, have standard special provisions to allow recycled materials in roadbase construction.

Currently, 44 states allow the use of RCA in road bases, 15 states allow use in backfill applications, 8 states allow use in concrete, and 7 states allow use in asphalt. Of the states that allow applications in roadbase, only 27 have formal specifications in place. In general, what seems to be more common is that jurisdictions will accept RCA use in applications where lower quality products are used and where RCA meets or exceeds technical specifications applied to non-recycled material. RCA is not used in higher-quality applications often because of long-term performance considerations and because most professionals are hesitant to use a relatively untested material with no developed guidelines or specifications for its use (Wilburn and Goonan 1998).

A survey of various U.S. Highway agencies shows that many states recognize the great potential for using recycled concrete aggregate in highway construction. The American Concrete Pavement Association (ACPA) offers links to state Department of Transportation web sites as a public service. The ACPA website is http://www.pavement.com.

The biggest challenge facing recyclers today are Government regulations. These regulations relate to plant permitting issues, the exclusion of recycled material from project specifications, specifications that disallow fair competition of recycled with virgin aggregate, and disposal regulations that allow for free dumping of waste concrete.

Such Federal agencies as the Federal Highway Administration have made the effort to reduce the barriers to the use of recycled materials in highways and to allow for successful practices to easily cross state boundaries. The reauthorization of the next highway bill in Congress, Transportation Equity Act for the 21st Century (TEA-21), provides an opportunity to promote appropriate recycling, partnerships, technology transfer, and research and development.

3. CONCLUSION/FUTURE WORK.

As natural resources diminish, the demand for recycled concrete aggregate is likely to increase, making concrete recycling the economically and environmentally preferable alternative to traditional “smash and trash” demolition. Wherever good natural aggregates are not locally available, where natural aggregate costs exceed RCA costs, or where disposal of existing concrete pavement or concrete structures is problematic, concrete recycling should be evaluated.

In the future, procedures need to be developed for the quality control of recycled aggregates. Quality materials will also create competitive markets and higher grade outlets for secondary materials. Concrete recycling appears to be profitable. In most cases, it can meet demand requirements of lower value product applications such as road base, thereby freeing up higher quality material for higher value applications. While studies have shown that RCA can be used as aggregate for new concrete, there is a need to obtain long-term in-service performance and life cycle cost data for concrete made with RCA to assess its durability and performance. If additional research supports the use of concrete buildings – especially barracks – then existing specification should be revised to permit and encourage the use of recycled concrete as

aggregate, to conserve existing supplies of natural aggregates and to reduce the amount of solid waste that must be disposed of in landfills.

Further research should focus on: (1) the economic aspect of concrete processing and recycling; (2) the influence of contaminants in the demolished concrete from buildings; (3) the long-term feasibility of recycling; (4) the durability of RCA in new concrete, and its creep and shrinkage characteristics; and (5) the use of recycled fines.

4. ADDITIONAL SOURCE MATERIAL.

American Association of State Highway and Transportation Officials, Standard Specification for Materials, "Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses," in *AASHTO Designation: M147-70* (1980), *Part I Specifications*, 14th ed. (1986).

American Association of State Highway and Transportation Officials, Standard Specification for Materials, "Coarse Aggregate for Portland Cement Concrete," *AASHTO Designation: M80-77*, *Part I Specifications*, 14th ed. (1986).

American Association of State Highway and Transportation Officials, Standard Specification for Materials, "Fine Aggregate for Portland Cement Concrete," *AASHTO Designation: M6-81*, *Part I Specifications*, 14th ed. (1986).

American Association of State Highway and Transportation Officials, Standard Specification for Materials, "Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course," *AASHTO Designation: M 319-02*.

American Concrete Paving Association (ACPA), *Concrete Paving Technology: Recycling Concrete Pavement* (ACPA, IL, 1993).

American Society for Testing and Materials. Standard Specification D2940-92, "Graded Aggregate Material for Bases and Subbases for Highways or Airports," *Annual Book of ASTM Standards*, vol 4.03 (West Conshohocken, PA, 1996).

Army TM 5-822-10/AFM 88-6, "Standard Practice for Pavement Recycling" (26 August 1988).

Arnold, C.J., "Recycling Concrete Pavements," *Concrete Construction* (July 1993).

Brown, Reid H., and Charles R. Marek. "Effect of Crusher Operation on Coarse Aggregate Shape." *The Concrete Producer* (April 1996).

Buck, Alan D., *Recycled Concrete* (U.S. Army Engineer Waterways Experiment Station, 1972).

Buck, Alan D., *Recycled Concrete as a Source of Aggregate* (U.S. Army Engineer Waterways Experiment Station, 1976).

Buck, Alan D., *Recycled Concrete. Report 2, Additional Investigations"* (U.S. Army Engineer Waterways Experiment Station, 1976).

Buck, Alan D., *Use of Recycled Concrete as an Aggregate* (U.S. Army Engineer Waterways Experiment Station, 1972).

Chesner Engineering, P.C., *Draft White Paper for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Portland Cement Concrete* (University of New Hampshire Recycled Materials Resource Center, 30 October 2001).

Chini, Abdol R., and Filiipe M.B. Romero Monteiro, "Use of Recycled Concrete Aggregate as a Base Course," *ASC Proceedings of the 35th Annual Conference* (7-10 April 1999), pp 307-318.

Concrete Crushing and Sampling, a Methodology and Technology for the Unconditional Release of Concrete Material from Decommissioning (Belgoprocess, Inc.).

Crawford, H.S., *Market Development Study for Recycled Aggregate Products* (18 May 2001).

Davenport, Robert, "Recycling Hardened Concrete," *The Concrete Producer* (August 1995).

De Pauw, Carlo, and Henri Motteu "Recycling of Demolished Reinforced Concrete," *CIB 83*.

Deal, Tara A., "What It Costs To Recycle Concrete," *C&D Debris Recycling* (September/October 1997), pp 10-13.

"Dig That Broken Concrete," *Concrete Construction* (February 1973).

Eighmy, Taylor, and Bryan Magee, "The Road to Reuse," *Civil Engineering* (September 2001).

Estevez, Beatriz, Antonio Aguado, and Alejandro Josa, "Environmental Impact of Concrete Recycling, Coming from Construction and Demolition Waste (C&DW)," Deconstruction and Materials Reuse CIB Publication 287, *Proceedings of the 11th Rinker International Conference* (7-10 May 2003).

Federal Register (FR), vol 68, No. 117, Rules and Regulations, Environmental Protection Agency, 40 CFR Parts 257 and 258. *Criteria for Classification of Solid Waste Disposal Facilities and Practices and Criteria for Municipal Solid Waste Landfills: Disposal of Residential Lead-Based Paint Waste, Final Rule* (18 June 2003).

Forster, Stephen W., Sean P. Moore, and Marcia J. Simon, "Behavior of Recycled Concrete as Aggregate in Concrete," *Third CANMET/ACI International Conference on Durability of Concrete* (Nice, France, 1994).

Freymuller, Jack, "Duo Awarded Second Strength-Based Patent," *Rock Products* (01 December 2001).

Freymuller, John J., "Recycled Concrete Mix Patent May Blanket Most Applications," *Rock Products* (01 August 2000).

Garvey, Charlotte, "Concrete & Asphalt Recycling," *Rock Products* (01 October 2001).

Hanna, Amir, "Concrete in the Railroad Roadbed," *Concrete Construction* (March 1984).

Hooker, Kenneth A., "Masonry Materials and Environmental Concerns," *Masonry Construction* (April 1994).

Hull, John, "Concrete Scores For Environment," *The Concrete Producer* (April 1992).

Kuennen, Tom, "TRB Draws A Crowd," *Rock Products* (01 March 2002).

Kuhar, Mark S., "A Concrete Profit Center," *Pit & Quarry* (January 2000), pp 60-62.

Mabin, Stephen M., "Recycled Concrete Aggregate – New York State's Experience," *Symposium Proceedings: Recovery and Effective Reuse of Discarded materials and By-Products for Construction of Highway Facilities* (Denver, CO, 19-22 October 1993).

Maultzsch, M., and G. Mellmann, "Properties of Large-Scale Processed Building Rubble With Respect to the Reuse as Aggregate in Concrete," *Int. Symp. Sustainable Construction: Use of Recycled Concrete Aggregate* (London, 11-12 November 1998), pp 99-107.

Mellmann, G., U. Meinhold, and M. Maultzsch, "Processed Concrete Rubble for the Reuse as Aggregates," R.K. Dhir, and T.G. Jappy, eds., *Exploiting Wastes in Concrete. Proceedings of the International Seminar* (Dundee [UK], London, 07 September 1999), pp 171-178.

Mellmann, G., U. Meinhold, and M. Maultzsch, "The Performance of High-Grade Concrete With Full Substitution of Aggregates by Recycled Concrete," V.M. Malhortra, ed., *Proc. Int CANMET Symp. Sustainable Development and Concrete Technology* (San Francisco, CA, 16-19 September 2001), pp 85-95.

"Mitigating Alkali Silicate Reaction in Recycled Concrete," *Research Project: The Recycled Materials Resource Center*, available through URL:
www.rmrc.unh.edu

Muller, C., *Requirements on Concrete For Future Recycling* (Aachen University of Technology, Germany).

National Stone, Sand and Gravel Association (NSSGA), website (International Concrete & Aggregates Group, ©2002), accessed August 2003 through URL:
http://www.icagevents.com/NSSGA.htm

New Survey Shows Economic Benefits of Recycling Construction Debris, NJDEP News Release (06 September 2001).

Non-Hazardous Solid Waste Project Task No. 303, Draft Final Summary, Technical Report CDRL No. A016, *Recommended Army Practices: Reducing, Reusing, and Recycling Construction & Demolition Debris* (National Defense Center for Environmental Excellence [NDCEE], 11 April 2003).

P2 Opportunity Handbook, Section 7, Solid Waste Management, 7-1/A-8, Construction and Demolition Material Recycling (Rev. October 2002), available through URL:
http://p2library.nfesc.navy.mil/

The Joint Service P2 Opportunity Handbook was designed to identify available "off-the-shelf" pollution prevention (P2) technologies, management practices, and process changes that

will reduce the amount of hazardous waste and solid waste being generated at joint service industrial facilities. The handbook was prepared by the Naval Facilities Engineering Service Center (NFESC), under the direction of the Office of the Chief of Naval Operations (CNO-N45) and the Naval Facilities Engineering Command (NAVFAC), the Air Force Center for Environmental Excellence (AFCEE), the Army Environmental Center (AEC), Headquarters Marine Corps (HQMC), the Defense Logistics Agency (DLA), and the Coast Guard (USCG).

Petrarca, Richard, and Vincent Galdiero, *Summary of Testing of Recycled Crushed Concrete* (Transportation Research Record, 1989).

Quality Control for Recycled Concrete as a Structural Fill Material, accessible through URLs:
www.cwc.org
http://www.cwc.org/wood/wd975fs.PDF

Ray, Gordon K., "Quarrying Old Pavements To Build New Ones," *Concrete Construction* (October 1980).

"Recycled Aggregate for Reinforced Concrete?", *Concrete Technology Today* (July 2002), pp 5-6.

Recycled Aggregates—Profitable Resource Conservation, USGS Fact Sheet FS-181-99 (U.S. Geological Survey, February 2000).

Recycled Materials Resource Center, Research Project 13/14, *The Development and Preparation of Specifications for Using Recycled Materials in Transportation Applications*.

"Recycling Concrete Pavement" (American Concrete Pavement Association), available through URL:
www.pavement.com

Recycling Concrete Saves Resources, Eliminates Dumping (Environmental Council of Concrete Organizations, Skokie, IL, 1997).

"Recycling Concrete," available through URL:
ConcreteNetwork.com

Reusser, Richard R., *Recycling Portland Cement Concrete Pavement at the Contractor's Option* (OMMNI Associates, Inc.).

Rinker Conference Proceedings (May 2003).

Salem, Rohi M., Edwin Burdette, and N. Mike Jackson, "Interrelationship of Physical Properties of Concrete Made with Recycled Aggregates," *TRB 2003 Annual Meeting* (25 July 2001).

Schmitt, James W., "Concrete Aggregate—Not Just Any Old Rock," *The Concrete Producer* (September 1993).

"Steel Reinforcing Bars: Recycled," *Concrete Reinforcing Steel Institute*, Special Report (2002), available through URL: www.crsi.org

Suarez, C.J., and R.E. Malave, "Recommendations for the Use of Aggregates from Recycled Construction and Demolition Waste in Venezuela," Deconstruction and Materials Reuse CIB Publication 287, *Proceedings of the 11th Rinker International Conference* (7-10 May 2003).

Talend, Don, "What's TLC?", *The Concrete Producer* (September 2001).

Taylor, Brian., "The Urban Quarry," *C&D Recycler* (November/December 2002), pp 12-16.

"The Technologies of Recycling Edition," *Construction in Europe Quarterly Digest*, No. 9 (European Network of Building Research Institutes [ENBRI], Spring 1998).

TM 5-628/AFR 91-44, "AREA Manual for Railway Engineering," *Railroad Track Standards*, ch 1, pt 2. (Headquarters, U.S. Department of the Army [HQDA], 08 April 1991)

Toto, DeAnne, "Armed & Ready," *Recycling Today* (July 2003).

Transportation Equity Act for the 21st Century (TEA 21) hearing examining the reauthorization, testimony of Mr. Richard J. Feltes before the Senate Environment & Public Works Committee, Chicago, IL (07 April 2003).

Turley, William, "Building the C&D Recycling Industry," *Resource Recycling* (February 1999), pp 21-26.

User Guidelines for Waste and Byproduct Materials in Pavement Construction (Turner-Fairbank Highway Research Center, Federal Highway Administration), available through URL: http://www.tfhrc.gov/hnr20/recycle/pubs.htm

Vangeem, Marcha G., and Medgar L. Marceau, "Using Concrete To Maximize LEED Points, *Concrete International* (November 2002).

Wilburn, David R., and Thomas G. Goonan, *Aggregates from Natural and Recycled Sources: Economic Assessments for Construction Applications—A Materials Flow Analysis*, U.S. Geological Survey Circular 1176 (Department of the Interior, U.S. Geological Survey, Central Region, Denver, CO, 1 June 1998).

Wilburn, David R., and Thomas G. Goonan, *Aggregates From Natural and Recycled Sources: Economic Assessments for Construction Applications – A Material Flow Analysis* (U.S. Geological Survey Circular 1176, 01 June 1998), available through URL: http://greenwood.cr.usgs.gov/pub/circulars/c1176/c1176.html

Yelton, Rick, "Breaking Concrete for Bucks," *The Concrete Producer* (September 1998).

Yelton, Rick, Taking an Anvil to Recycling," *The Concrete Producer* (November 1998).

APPENDIX B

EXAMPLES OF CONCRETE BUILDING RECYCLING

1. Case Study: King County: Regional Justice Center, Kent, WA[2]

This project involved the development of a new regional justice center, including courthouse and detention facilities. The project manager required that materials be recycled on the project site and used in place of new material. Recycled concrete aggregate from the building demolition was used for backfill, general fill, pipe-bedding and as aggregate base course for pavement construction in new construction. Crushed concrete was also stockpiled on site for use during future site work.

1. Case Study: Sears Department Store, Portland, OR[3]

This recycling project in Portland, OR demonstrated that non-pavement concrete can be usefully recycled as well. An abandoned Sears department store was demolished and recycled, diverting 77 percent of its waste materials from the landfill. More than 7000 tons of brick, concrete, sand and dirt were processed into on-site and off-site fill. Some RCA was used as clean capping layer for a closed landfill. The dumping costs were much lower than if the entire building's waste were landfilled.

2. Case Study: Tennessee NFL Stadium, Nashville, TN[4]

The new Tennessee NFL Stadium was built on property previously occupied by a mixture of building structures. Most had concrete foundations, retaining walls and slab on grade with masonry load-bearing exterior walls and steel roof structures. The project was completed in phases because not all of the property could be purchased and the existing tenants relocated at the same time. In Phase I, the concrete recycling plan was to process the concrete for constructing temporary roads on site in lieu of purchasing crushed stone for that purpose. However, since construction on the stadium itself had not started, there

---

[2] http://www.metrokc.gov/procure/green/rjcconag.htm

[3] http://www.metro-region.org/

[4] http://www.smartgrowth.org/casestudies/demolitionstudy.htm

was no immediate use for the material; it needed to be stored for later use. A total of 40,356 tons of material was produced and stored. When the time came to construct temporary roads, the gradation of this stored material was not suitable to stand up to heavy construction traffic. It was used instead for structural fill. This proved to be beneficial since the first month of construction was extremely wet, and dry fill dirt could not be found. The concrete product was used to help dry the compacted structural fill areas and keep the project on schedule.

During Phase II, there was an immediate need for the processed material as structural fill to backfill the basement walls. Crushed stone was required because suitable soil was not available after wet winter conditions prevented proper compaction. Specifications were also prepared ahead of time so that the crushed rock being produced would be suitable for the backfill of the foundation walls. A total of 23,849 tons of material was produced. All of it was used in lieu of purchasing crushed stone. Additionally, it did not have to be stored. Steel from the processed concrete was collected and sold for steel scrap.

One important lesson learned was that it is important to plan the purpose and use for the recycled product early in the project. Project design engineers should write a specification for the recycled concrete material and have it tested when it is first produced to make sure that it meets the specifications. Doing this ensures that the product that can be used on the project. It was also found that not everything can be recycled. Some concrete, such as beams, etc., with a large amount of reinforcing steel, was not worth trying to crush.

3. Case Study: Fort Campbell, KY[5]

Fort Campbell, KY, was faced with the problem of diminishing landfill space and the disposing of thousands of tons of concrete from the demolition of their Hammerhead barracks. It was predicted that with all of the demolition that had to be done, landfill expansion would cost $20 million over 20 years. A concrete crushing operation was set up to grind up the concrete building debris to reduce the volume of materials for disposal. By crushing the concrete aggregate, the volume of debris was reduced by 80 percent. If they continue to grind

[5] Public Works Technical Bulletin (PWTB) 420-49-12, *Army Recycling Lessons Learned* (HQDA, 15 July 2000).

debris from the remaining reinforced concrete barracks to be demolished, annual benefits are estimated to be roughly $50,000 in reinforcing steel salvage, reuse of over 50,000 tons of aggregate/year, and a cost avoidance of approximately $500,000 per year by substituting recycled material for quarried aggregate. The Fort would save both money and landfill space.

PWTB 200-1-27
14 September 2004