

# Reappraisal of Recycled Concrete Aggregate as Coarse Aggregate in Concretes for Rigid Pavements

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State departments of transportation began using recycled concrete aggregate (RCA) as aggregate in portland cement concrete pavement in the United States in the late 1970s. Although RCA is rarely used in current U.S. rigid pavement slabs, the impetus for its continued use remains the same: a lack of landfill space, a shortage of nearby quality natural aggregates, or both. However, as American pavement engineers and researchers place a greater emphasis on sustainable, reusable roadways, the status quo for RCA in American roadways should be reconsidered along with these new priorities. This study proposes to revisit the use of recycled concrete as aggregate in rigid pavement slabs by using overlooked research to address the concerns that prevented the wide-scale adoption of recycled concrete as an aggregate in pavement slabs by state departments of transportation. Experiences encountered in countries (mostly restricted to Europe) where the use of RCA in rigid pavement is more common are also described. New opportunities for the use of RCA as a structural component in pavement concretes are detailed.

State departments of transportation began using recycled concrete aggregate (RCA) in the structural layers of portland cement concrete (PCC) pavement in the United States around the late 1970s. Although RCA is rarely used in the United States as a structural component of PCC pavements, the impetus for its continued use is the same now as it was then: a lack of landfill space and a shortage of quality natural aggregates. However, as American pavement engineers and researchers continue to place a greater emphasis on sustainable, renewable roadways, the conventional uses for RCA in American roadways should be reconsidered along with these new priorities.

After the early 1990s, the same states that had been using recycled concrete as a coarse aggregate in rigid pavements began finding alternative uses for it. Currently in the United States, RCA is often implemented into a base layer or its fines are used to stabilize a subbase or frost protection layer. It has also been incorporated into concrete mixes for curbs and gutters, sidewalks, concrete barriers, driveways, shoulders, riprap, and fill and as coarse aggregate in hot-mix asphalt. Although an ideal use of RCA would be as a component of a structural layer for new concrete pavements, that application is rarely pursued in the United States. At the time of a 2004 FHWA national review of RCA applications in the United

States, no states were using RCA as a structural component of rigid pavements (1).

However, if U.S. aggregate supplies are depleting as fast as is argued and new landfills become more difficult to zone, the United States may not be able to continue its current practices with RCA much longer. In addition, recent sustainability initiatives could be the impetus needed to once again look at RCA as a resource rather than a waste product. The Green Roads Initiative, a recent project from the University of Washington, aims to create a national standard for constructing and labeling sustainably built roads. This standard mirrors the form of the United States Green Building Council Leadership in Environmental Energy and Design (LEED) rating standard. Interestingly, Green Roads rating points can be earned for using RCA in the subbase only if the RCA is primarily used in the pavement's structural layer (2).

Though insufficient attention to sustainability in the past is in part to blame for the relegation of RCA to the base layers of American rigid pavements, one of the main obstacles to its use in rigid pavements is the stigma from a few bad experiences. The Michigan Department of Transportation (MDOT) experience with RCA in rigid pavement officially ended in 1991 when MDOT issued a moratorium on its use (3). Although not being as explicit, other states, especially those that were the early pioneers of using RCA in rigid pavements, have followed MDOT's example. These actions have blocked many pavement engineers from considering RCA as a constituent of rigid pavements and have restricted uses of RCA to unbound base layers. However, recent interest in composite pavement challenges these long-standing attitudes in pavement engineering. The second Strategic Highway Research Program (SHRP 2) R21 Composite Pavement Project and Transportation Pooled Fund Study TPF(5)-149 present new opportunities for unconventional uses of recycled materials, including RCA.

This study revisits the use of recycled concrete as an aggregate in rigid pavements by using overlooked research to address the concerns that prevented the wide-scale adoption of RCA as a structural component of rigid pavements by state departments of transportation. Since this study was in part motivated by FHWA and SHRP2 tours of European pavements, the literature reviewed is mainly European studies that have received little U.S. attention. Furthermore, in Europe the use of RCA in the concrete pavement structural layer is more common. To begin, past American research on RCA in rigid pavements is detailed briefly, followed by a review of the properties of concrete containing RCA, recycling of old PCC pavements, field performance of rigid pavements containing RCA as a structural component, and new opportunities for adoption of RCA in rigid pavement.

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*Transportation Research Record: Journal of the Transportation Research Board*, No. 2113, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 149–155.  
DOI: 10.3141/2113-18

## RCA IN RIGID PAVEMENTS: PAST U.S. RESEARCH

In the 1980s through the early 1990s, state departments of transportation and university researchers teamed to study RCA in PCC pavements in both laboratory and field settings. In 1989, an NCHRP study reported some of the first field observations of single-layer rigid pavements containing RCA that were placed in Iowa, Michigan, Minnesota, and Wisconsin between 1981 and 1986 (4). In 1997, researchers at the University of Minnesota surveyed the condition of rigid pavements containing RCA that were designed and constructed in the early to late 1980s in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming (5, 6). A follow-up study was done in 2006 and published in 2009 (7). After the early 1990s, no documented studies indicate that RCA was used as an aggregate in a structural layer of newly constructed rigid pavement.

As the use of RCA in the structural layer of PCC pavement declined, the topics of American research switched from a focus on implementation to a focus on laboratory testing concrete mixes with RCA for such properties as strength and freeze–thaw durability and documenting case studies of alternative RCA use. For instance, the American Concrete Institute sponsored a comprehensive special report reviewing government agency roles in using RCA, the economics of RCA, and the reasons why the U.S. pavement community remains skeptical of RCA durability and performance (8). The conclusion of these publications is that although laboratory research aims to prove RCA's credibility for use in new rigid pavement, practitioners have found other ways to use the aggregate, particularly as a pavement base material.

In other examples of this trend, three FHWA-sponsored papers published this decade either discuss or mention RCA but do not include a new case study of its use in the structural layer of rigid pavement in the United States. A 2000 case study on recycled materials in the European highway environment favors recycled asphalt pavement (RAP) and reviews implementation policy (9). A 2003 study concludes that RCA PCC can be used for secondary structures such as curbs and gutters or sidewalks but is not suitable—for strength reasons—for use in pavement structures (10). A 2004 review on the state of RCA use in the United States reports on the implementation of RCA by selected states and reviews environmental policy decisions (1). Surprisingly, this report also found that only 32 out of the 50 states recycle concrete rubble in any kind of application. The other 18 states still find it acceptable to landfill a majority of their concrete construction debris. The recent increase in attention on sustainable practices by the American public may steer the pavement community toward aggressive use of RCA in the concrete layer of rigid pavements. The following sections introduce additional research that can be considered alongside the more well-known American studies just detailed.

## PROPERTIES OF CONCRETES CONTAINING RCA

### Accommodating RCA in PCC Pavements

Using recycled materials in new construction requires the user to understand the variations found in recycled materials that are not present in the more conventional materials they replace. RCA's primary difference from natural aggregate is its absorption capacity due to the existing mortar surrounding the original aggregate. Concrete that incorporates the more porous RCA can require more water than a conventional concrete, depending on the saturation state of the RCA.

If this water is not supplied, the workability of the concrete is reduced, which complicates placement. Since crushing processes and virgin aggregate characteristics vary by region, one solution cannot be prescribed for this problem. Rather, many contractors find that familiarity with the RCA in a PCC mix makes the material much easier to work with (11). Another challenge to using RCA in PCC pavement is the fines. Although studies have confirmed that the use of coarse RCA in PCC yields durable and strong pavements, incorporating RCA fines into mix designs has resulted in unpredictable pavement behavior. A third challenge of incorporating RCA into a pavement's structural layer is a historical fear that RCA has a proclivity for alkali–silica reactivity (ASR) and D-cracking.

### RCA Absorption

RCA is more absorptive than natural aggregate because of its recycled mortar content, and it differs from natural aggregate in two consequential ways. First, it is less dense (6). Second, it requires more attention to mix design since each batch of recycled aggregate requires a unique adjustment to satisfy the absorption of the aggregates (4). The absorption of both natural aggregate and sand is around 1.0% or less. According to laboratory studies, the absorption of coarse RCA is around 2% to 5% and that of fine RCA between 6% and 12% (12, 13). Researchers have discovered methods to decrease the negative effects of increased aggregate absorption on concrete performance. One such discovery indicates that fly ash is an agent that reduces hardened concrete's overall permeability (14). Another involves accommodating the increased water demand of RCA. If the increased water demand of RCA is not accommodated, either not enough water causes a decrease in workability that prohibits placement or a high water-to-cement ratio compromises future strength.

Practitioners and researchers have tried different means to add this water to the concrete mix. Some suggest simply wetting the aggregate or adding a little more water to the concrete mix (11). A local concrete batching plant automatically measures the absorption of the recycled aggregate and batching software adjusts the amount of water added to the concrete mix in order to achieve the desired water-to-cement ratio. Although it is convenient for recycled aggregates delivered to the batching plant, this technology may not be available at a remote site where a portable crusher and batching plant uses old pavement from the construction site to generate coarse aggregate for the site's new rigid pavement. If the existing pavement slated for recycling was constructed from a mix that met known state department of transportation requirements, a sample of that pavement or a similar, already demolished pavement could be crushed by the same methods anticipated at the construction site and the aggregate absorption tested beforehand. This way, the concrete engineer would have an idea of how much more water is necessary to achieve the desired water-to-cement ratio (15). Ultimately, in such a remote situation or when automated testing and mix adjustment are not available for immediate response to the recycled aggregate absorption characteristics, sprinkling the RCA for 48 h before incorporating it into a concrete mix ensures that each aggregate batch is fully saturated without guessing or testing for its water requirements while the intended water-to-cement ratio of the mix design remains relevant (16).

### Slump

Although many tests have showed a small decrease in initial slump as the amount of recycled aggregate increases, it is so small that a

decisive analysis cannot be made about RCA's impact on initial slump. Instead, various mixing conditions such as the water-to-cement ratio, the amount of water-reducing admixture, and the grading and volume of recycled aggregates control the initial slump of RCA (13). In addition, the slump of the concrete is dependent on the moisture state of the recycled aggregate when it is added to the concrete. For instance, when oven dry recycled aggregate is used, a high initial slump is observed due to the high amount of water that must be incorporated into the mix to accommodate the higher water absorption of the recycled aggregate (17).

### RCA Fines

Unless stated otherwise, when researchers claim that 100% of existing concrete is used, the recycled fines (0/4 mm) are incorporated into the subbase or frost blanket, not into the concrete mix (18, 19). The reason for this process is that recycled concrete fines are generally unwelcome concrete mix constituents. Recycled concrete fines are primarily small particles of mortar, not durable aggregates. Their absorption levels alone (6% to 12%) cause unpredictability in the behavior of the wet concrete (19). Other research indicates that recycled fines decrease workability, demand more water, increase absorption, and decrease strength compared with mixes made with natural fines (12, 18, 20).

As an exception to the conventional wisdom about RCA fines, a project in Switzerland successfully incorporated 100% recycled fine and coarse aggregates into a concrete pavement. After 2 years, the high-volume road sections that were constructed with this 100% RCA were still performing well. Most notably, this pavement resisted infiltrations from winter applications of salt. This success was attributed to splitting the aggregate into four sizes ( $\frac{1}{4}$ ,  $\frac{1}{8}$ ,  $\frac{1}{16}$ , and  $\frac{1}{32}$ ) before incorporating it into the new concrete mix and to ensuring that the old concrete cement paste was 100% saturated before the RCA was incorporated into the concrete mix (16).

Others have found a balance by exploring the limit of natural fine replacement with recycled concrete fines. Shayan and Xu found a mix design including coarse RCA, silica fume, air-entraining agent, and high-range water-reducing admixture (HRWRA) that included 50% recycled fines and still achieved 53-MPa compressive, 6.9-MPa flexural, and 4.0-MPa splitting tensile strengths after 28 days (13). The initial slump (60 mm) was also acceptable. However, it is important to mention that other research indicated that a concrete mix including coarse RCA and 50% RCA fines did not adequately resist the attack of frost and deicing chemicals (19). This concrete mix contained plasticizer but not a supplementary cementitious material (SCM) such as fly ash or silica fume.

### ASR and D-Cracking

Previous concerns with RCA in pavement applications were often restricted to ASR and D-cracking. However, current efforts in research surrounding RCA no longer focus on these issues because of mitigating measures such as incorporation of fly ash, ground granulated blast-furnace slag, or silica fume into the mix design; use of a blended cement that was designed and tested to control ASR; or use of a low-alkali portland cement (21). If ASR and D-cracking are investigated, it is usually because the recycled aggregate originated from previously D-cracked or ASR concretes, a practice that is discouraged by the pavement community at large. Furthermore, the processes for incorporating RCA into new pavements originating

from D-cracked or ASR concretes have been well documented in the United States and will not be reproduced here.

### RCA in Base Material and Leaching

Although many states avoid using RCA as a coarse aggregate in PCC, RCA is commonly used in unbound pavement base layers or as backfill for pipe trenches. Water that passes through unbound RCA leaves with a high pH and possibly carries other nutrients such as calcium. Research on this topic is conflicting and neither fully supports nor strongly cautions against this practice (1, 9, 14). Other concerns are that metal culverts could be sensitive to the effluent's pH and formation of tufta on the ground surface in the form of a white mineral stain (8). There are two primary justifications for continued use of RCA in pavement base layers in the United States. The first is that the effluent is sufficiently diluted a short time after it leaves the contaminant source. The second is that the potential environmental degradation resulting from the effluent is outweighed by the problem of filling landfills (1).

### Strength Properties of PCC with RCA

Although the absorptive layer of existing mortar around the original aggregate makes RCA PCC pavement mix design more complicated, this feature of RCA facilitates good bonds between the old mortar and the new cement. In turn, the compression, tensile, and flexural strengths do not decrease on account of the interlock failure between the aggregates and new cement (19). However, others hypothesize that the microstructure of the weak surface layer of porous mortar surrounding the aggregate is the cause of low ultimate strength values. A researcher found that treating RCA with a sodium silicate solution in an attempt to consolidate and improve the surface features of the aggregate did not improve strength or durability. Instead, the addition of an SCM, specifically silica fume, and limiting the amount of recycled concrete fines (0/4 mm) to 50% of total fines were the important factors in achieving 50-MPa compressive strength in RCA concrete (12).

Laboratory tests of cores taken from RCA PCC pavement sections confirm that with the addition of an SCM such as silica fume or fly ash (11, 12, 14, 16), the compressive strength is equal to or slightly less than that of PCC pavements made with natural aggregates (6, 11, 15, 18–21). Although the compressive strengths of some PCC made with coarse RCA decreased slightly, most of these compressive strengths are still equal to or comfortably above 35 MPa (5,076 psi). This finding implies that even if the substitution of RCA for natural coarse aggregates decreases the compressive strength slightly, the pavement's compressive strength is still equal to or greater than the required minimum. This in turn places an emphasis on the flexural and tensile strengths of RCA PCC.

For flexural strength, a majority of laboratory and field reports indicated either a similar value or an increase in value resulting from the substitution of coarse RCA for coarse natural aggregate (11, 15, 18–20, 22, 23). A few studies reported a decrease in tensile strength due to the use of RCA, but a review of the concrete mix constituents used in these studies shows that an SCM was not included in either mix and only one of them included an HRWRA agent (13, 21, 24).

Although strength is not the only characteristic of a durable and long-lasting pavement, these discoveries—the addition of SCMs, air, water reducers, and plasticizing agents as well as the limitation of the addition of recycled concrete fines to the concrete mix design—

are the keys to high-strength RCA concrete with adequate workability and indicate a solution to perceived limitations to RCA use in structural PCC pavements. In a best-case scenario, absorption is compensated for by presaturation of RCA, and plasticizing agents reduce the total required water-to-cement ratio to maintain both strength and workability (21).

### Shrinkage, Creep, and Warping

It has been observed that RCA concrete offers less restraint to volumetric expansion in response to temperature and moisture fluctuation (humidity and infiltration), primarily because its modulus of elasticity, and therefore its stiffness, is consistently found to be less than that of conventional concrete (6, 14, 21, 24). Yang et al. observed that shrinkage was dependent on the amount of mortar left on the original concrete (14). Though both moisture and thermal gradients are responsible for volume changes in PCC, research indicates that the temperature gradient is the primary cause of shrinkage and swelling in PCC containing RCA. Both laboratory and fieldwork indicated that the hygral gradient in PCC RCA pavement is negligible compared with the temperature gradient (24). Another source of shrinkage—carbonation—was also found to cause negligible shrinkage in RCA concrete (13).

Initially, the shrinkage rate of conventional concrete exceeds that of RCA concrete, but after approximately 10 days, the shrinkage rate of conventional concrete slows at a quicker rate than that of RCA concrete (14). Besides decreasing the amount of mortar attached to the recycled aggregate, both a partial substitution of fly ash for cement and a decrease in the water-to-cement ratio reduced the drying shrinkage and creep of recycled aggregate concrete. Researchers attribute this to a greater long-term strength development due to the pozzolanic reaction of fly ash (25). A third factor in decreasing creep and shrinkage is time. The total porosity of concrete made with coarse RCA decreases over a period of 90 days because of the crystallization of products that reduce both the number and size of the pores (20).

The importance of limiting shrinkage, creep, and warping is more apparent when the structural elements of pavements are considered. Because of the large strains caused by thermal gradients, cracks and joints can contract more given the appropriate conditions. The result is decreased load transferability across the joint or crack leading to early degradation of the pavement (6). An example of this finding is portrayed by a case study from a stretch of RCA PCC pavement in Minnesota. An RCA pavement section and a natural aggregate control pavement section were placed at about the same time on US-52 near Zumbrota, Minnesota. A sample of the RCA pavement indicated an 83.6% mortar content and the conventional sample revealed a 51.5% mortar content. After only 10 years of service, the RCA section was 88% cracked versus 22% cracked for the control section. After 22 years, the RCA section was 92% cracked and the control section was 24% cracked. Even though the control section was significantly cracked, the performance of the RCA pavement may have been due, in part, to the high mortar content of the recycled aggregate.

## RECYCLING OF OLD PCC PAVEMENTS

### Percentage RCA Reclaimed for Coarse Aggregate

The percentage of the existing concrete pavement that can be recycled into coarse aggregate is not uniform across experiences. A Wisconsin recycling project was able to salvage 70% of the original material

for coarse aggregate. Of the remaining existing concrete, 20% was fines and 10% was lost to construction practices (4). Other projects reported lower salvage values of between 60% and 65% (11, 17). Austrian specifications require a minimum 65% reclamation (18).

The variability of salvageable coarse RCA from recycling suggests that the crushing procedure as well as the properties of the existing concrete are causes of this variability. Methods for recycling existing concrete pavement into aggregates are not governed by a single methodology, and certain methods allow workers to recapture more of the existing concrete into aggregate sizes above 4 mm than others. An account of one experience suggests that impact-type crushers operating at less than maximum output allow the maximum coarse aggregate particles to be reclaimed (18).

Size specifications for coarse RCA also affect the percentage of recycled material that is usable. A greater portion of the existing pavement can be recycled as the maximum recycled aggregate size increases. For example, a 25-mm maximum aggregate size corresponds to reclaiming 55% to 65% of the original concrete pavement for coarse aggregate use, whereas 80% of the existing pavement could be recovered if the maximum aggregate size of the new concrete pavement mix increased to 38 mm (6). Although increasing the maximum coarse aggregate size will result in more recyclable material, a larger aggregate size could, depending on the maximum original size of the aggregate and the nature of the old mortar, potentially compromise workability, durability, and strength.

### Condition of Existing Concrete

A majority of current and past research in RCA addresses issues related to the condition of concretes before they become RCA. Though this review will not speak to all of these issues, it will detail some that are more well known. Here it is important to emphasize that one of the primary differences between the European and American experience with RCA is that Europeans refuse to crush an existing pavement for RCA in a new structural pavement layer if it is distressed because of D-cracking or ASR. European researchers praise existing concrete pavements for their strength and durability and frequently indicate that the old concrete pavement being recycled into coarse aggregate must be in good condition (17, 18, 21, 26, 27).

#### *D-Cracked and ASR Pavement as New RCA*

Practitioners in the United States have, because of successful laboratory experiments, used D-cracked and ASR-damaged existing pavements as coarse aggregate for new concrete pavements. For example, in Minnesota, a 16-mi rehabilitation project on US-59 between Worthington and Fulda was the first known project to recycle concrete pavement that failed extensively from D-cracking (4). Laboratory research identified that the original virgin coarse aggregate had shown poor durability and subsequently the concrete pavements containing this aggregate were D-cracked. In response, the Minnesota Department of Transportation (Mn/DOT) limited the size of the recycled coarse aggregate to 19 mm ( $\frac{3}{4}$  in.) for dilation reduction (5). Research also showed that fly ash could be used to reduce the chances of D-cracking. In laboratory studies, concrete pavement mixes with fly ash substituted for cement as 0%, 10%, and 20% by weight of cement were tested by ASTM C666 Method B modified to observe freeze-thaw durability. The mixture with 20% fly ash replacement showed a greatly reduced potential for D-cracking (4).

A 1994 FHWA report and a 2006 follow-up study described pavement sections, two in Minnesota and one in Kansas, that were constructed with previously D-cracked pavement (1, 7). The Minnesota section (MN-2) that contained less than 10% recycled mortar content showed no signs of recurrent D-cracking after 22 years. The other Minnesota section (MN-3) showed no signs of recurrent D-cracking after 26 years. The MN-3 section ultimately failed because of joint faulting and was rehabilitated in 2004. The coarse RCA used for both Minnesota projects was limited to a maximum size of 19 mm. The Kansas section (KS-1), which, in addition to coarse RCA, incorporated 25% recycled fines into its mix and allowed a maximum coarse RCA size of 38 mm, had a different outcome. Whereas after 9 years no recurrent D-cracking was observed, by 2002 the section was rehabilitated with a bituminous overlay because of recurrent D-cracking.

The same report also details the recycling of an existing PCC pavement with ASR problems in Wyoming (WY-1) for new PCC pavement. In this project, the coarse RCA contained less than 10% mortar content and 25% of natural fines was replaced with recycled concrete fines. Also important in the mix design was the use of ASR mitigation techniques such as using low-alkali cement and Class F fly ash. The original 1994 study reported that uranyl acetate testing found a moderate amount of silica gel in the mortar around aggregate particles of the RCA section and minimal amounts of silica gel in the control section. By 2006 there was visual evidence of localized ASR surface cracking, indicating minor ASR after more than 20 years. The possible conclusions from this case study are that the ASR mitigation techniques prevented more severe recurrent ASR and that using 100% natural fines may have prevented or lessened the recurrence. Although it is only one example, it may also be safe to conclude—especially considering the European practices of only recycling good PCC pavement—that recycling PCC pavement with ASR problems is not an acceptable practice or, at best, one that should be undertaken with caution.

#### *Existing Pavement with Thin Bituminous Overlay*

Placing a thin bituminous overlay on top of concrete pavement is a common way to extend its service life. In the United States, bituminous overlays are typically scraped away before the concrete pavement is salvaged, even for its use in the unbound base layer. However, this practice is time-consuming, inefficient, and not in accordance with the ideal of sustainable, rapid renewal. By the early 1990s, an Austrian motorway in need of reconstruction had been in service for many years, and as a result, many kilometers had been repaired with a thin bituminous overlay. The reconstruction plan included in-place recycling of the existing pavement for use as recycled aggregate in the base layer of the new PCC/PCC composite pavement. Through field research, limits were established for bituminous fractions in coarse RCA that could be used in new rigid pavements (17, 18). Although asphalt contents of up to 20% did not significantly reduce the pavement's flexural strength and asphalt contents of up to 33% did not compromise shrinkage and swelling behavior, asphalt contents of more than 20% impaired the pavement's frost resistance (18). Ultimately, Austria limited to 10% the amount of 4/32-mm asphalt particles in the recycled aggregate used in PCC pavement mixes (18). As a comparison, the state of Minnesota currently allows up to 3% of the coarse RCA used as unbound base material to be asphalt (1). In the United States, a similar experiment to Austria's showed no serious detrimental effects when bituminous material was included

as a percentage of the recycled coarse aggregate, but significantly lower strengths were experienced with the addition of crushed asphalt fines (28).

## **FIELD PERFORMANCE OF RIGID PAVEMENTS CONTAINING RCA AS STRUCTURAL COMPONENT**

### **United States**

Although the approach in this review is not to replicate the information widely disseminated in the United States, the American case studies that are highlighted here are interwoven within the text to emphasize an RCA topic or design suggestion. For more information on placements of RCA PCC single-layer pavements, the reader can refer to the 1989 NCHRP study (4) and the 1997 FHWA study (6).

A few high-profile RCA PCC pavement failures in the early 1990s may have made state departments of transportation hesitant to continue using RCA in the structural layers of its PCC pavements. Experiences by the Michigan Department of Transportation (MDOT), Texas Department of Transportation (TxDOT), and Mn/DOT provide some insight into this hesitancy. After paving approximately 650 lane-miles with RCA rigid pavement, MDOT issued a moratorium on new PCC RCA pavements in 1988 and then again, permanently, in 1991. The moratorium was instated after rigid pavements containing RCA on I-94 and I-75 experienced premature transverse cracking, faulting, and spalling. The moratorium continued despite results from a University of Michigan study suggesting that these problems were the result of not only the RCA but also problems with base design, uniformity of the foundation layers, stiffness of the subgrade material, thickness of the pavement slab, and the temperature when the concrete was placed (3). Although TxDOT is currently researching the use of RCA in PCC structural pavement, it restricts RCA from PCC pavement structural layers because it has experienced creep and shrinkage problems when pavements use RCA (1, 29).

An FHWA report highlighted four RCA PCC pavement sections in Minnesota that were constructed during the 1980s. One of the four, labeled MN-1, was on a stretch of I-94 near Brandon and proved to be the most underperforming section of the four. After 6 years, this dowel-reinforced pavement showed virtually no cracking despite 8.2-m joint spacing and was generally performing better than conventional pavement constructed in the same region at the same time. Unlike most RCA sections that are compared with conventional sections, its coefficients of thermal expansion were equal. By 2006, however, the RCA MN-1 section was 31% cracked compared with 0% for the control section. The RCA section contained less than the recommended amount of cement plus cementitious materials recommended by FHWA for durability, but it displayed no visible freeze-thaw distress nor did petrographic evaluation reveal signs of poor freeze-thaw resistance. Two causes for the cracking could be the low cement content and the relatively high water-to-cement ratio (0.56) and ratio of water to cement to fly ash (0.47) compared with the water-to-cement ratios of other well-performing RCA pavements (5). As noted earlier, some of the Minnesota RCA pavements are either still performing well or have failed because of circumstances not related to RCA use such as joint faulting. Although Mn/DOT was a pioneer in replacing aging highways with RCA PCC, contractors have not adapted these practices in recent times. Perhaps this situation is in response to the cracking of the MN-1 section or to an Mn/DOT change to a 60-year design life for all high-volume freeways and a 35-year design life for other highways associated with warranties (1).

## Europe

In some European countries, most notably Austria, RCA is used as coarse aggregate for the bottom layer of composite concrete-on-concrete pavement. In 1989 Austria pioneered this practice by developing a system to recycle the existing concrete pavement along the A1 motorway between Vienna and Salzburg, where more than 50% of the pavement required replacement. Today, Austria requires the use of recycled concrete in the lower layer of its two-course PCC pavements (28). This system entails using the 4/32-mm crushed coarse aggregates for the new roadway and the 0/4-mm fines to stabilize the frost layer (17).

From the Austrian experience of repaving the A1 motorway, German engineers replaced a 6-km section of the A9 motorway near Dessau. RCA was used as coarse aggregate in the bottom lift of a two-lift PCC pavement. The specific experience that persuaded the Germans to experiment with RCA despite their not having standard specifications for its use was Austria's suggestion to eliminate recycled concrete fines from the mix for the lower lifts because of the fines' negative effect on workability (20).

Another Austrian-inspired RCA PCC project was constructed on the A27 motorway in Lower Saxony, Germany. Coarse RCA was used in the lower lift of a two-lift pavement in 6-km sections (11). Later in the 1990s, German researchers confirmed the resistance of RCA PCC pavement to deicing salt penetration through observation of the in-field performance of the pavement along the A93 motorway in Bavaria. A single-layer concrete pavement with 100% coarse RCA (no recycled fines) survived the particularly hard winter of 1995–1996 and showed no deterioration (21). In a final example from Germany, sections of the A9 motorway constructed with RCA PCC were observed to have a higher resistance to cracking than their conventional counterparts undergoing similar environmental conditions. Two hypotheses were proposed for this phenomenon: first, recycled aggregate's rough surface has the ability to create a better bond with the new mortar than natural aggregate, and second, there may be a local reduction in the water-to-cement ratio near the bond area because of the porosity of the recycled cement paste (21).

A case study from Switzerland determined that cracking failure in RCA PCC that was initially attributed to low strength (and indirectly to the use of RCA) was instead the result of premature aggregate demixing and the contractor's inability to accommodate RCA's increased demand for water. Although the RCA concrete stockpile indicated a desirable aggregate gradation at the storage site, en route to the mixing site, the aggregate supply became severely demixed. The ensuing difficulties were irregular consistency for placement and, ultimately, hardened cores that did not meet strength requirements (16).

## NEW OPPORTUNITIES FOR ADOPTION OF RCA PCC IN RIGID PAVEMENT

The development of this review is due in part to the 2006 FHWA scanning tour of European concrete pavements, which overviewed the uses of RCA in European pavements (27). In addition, the desire to better understand unconventional uses of RCA was inspired by the Strategic Highway Research Program (SHRP2) R21 project on composite pavements.

The Iowa State University Center for Transportation Research and Education, under FHWA sponsorship, conducted an investigation into two-lift PCC pavements (30). This study also provided recom-

mendations and guidelines for the adoption of these pavements into U.S. practice. One of the caveats of this review was the additional expense of the construction of two-layer PCC pavements in the United States given the need for equipment and expertise that are not familiar to American pavement engineers and contractors. One immediate cost-saving measure would be the use of RCA in the lower of the two PCC lifts.

The California, Minnesota, and Washington departments of transportation are currently involved in Transportation Pooled Fund Study TPF(5)-149, Design and Construction Guidelines for Thermally Insulated Concrete Pavements. This study, under the guidance of FHWA, investigates composite pavements that consist of a jointed or continuously reinforced concrete layer covered by an asphalt layer during or shortly after construction. This asphalt layer is considered to be a kind of thermal insulation for the concrete lower lift. Although the main objective of this study refers to new construction, it will also investigate the use of asphalt overlays as thermal insulators for existing concrete pavements. These existing pavements might include single-layer PCC pavements that have RCA as a structural component.

The recent SHRP2 R21 project on composite pavements is designed to foster rapid, nondisruptive highway renewal with composite pavements. In the case of SHRP2 R21, composite pavements are new PCC pavements surfaced with either a new, high-quality asphalt layer or a second, relatively thin PCC layer. Though two-layer composite pavements have received little attention in the United States, they are a widely accepted solution for pavements in Europe. A recent tour of European pavements for the SHRP2 R21 project found that in Europe RCA has been used in these lower PCC lifts in composite pavements with great success.

The use of RCA in the lower PCC lift of a composite pavement, as detailed in the foregoing projects, allows for a number of opportunities for the pavement system:

- Economy and sustainability of reusing reclaimed materials,
- Ability to take advantage of RCA's structural contributions without suffering the drawbacks (polishing, smoothness, etc.) of RCA as an aggregate in an equivalent single-layer pavement, and
- Ability to take advantage of environmental incentives for road construction.

## CONCLUSIONS

This reappraisal is intended to provide further evidence that using RCA in a sustainable manner can extend beyond simply using it as fill material for a pavement base layer. As opportunities arise and technologies become more readily available, rehabilitations of future pavements can include the on-site conversion of old PCC pavements into new pavements that use RCA as a structural component. Doing so will allow for the quick, economical renewal of roadways, and using RCA in this process in a manner that is advised by some of the research detailed herein will ensure that these efforts are successful.

## ACKNOWLEDGMENTS

This work was sponsored by FHWA in cooperation with the American Association of State Highway and Transportation Officials and was conducted under the Strategic Highway Research Program 2, which is administered by the Transportation Research Board of the National Academies. This work was also sponsored by the Pavement

Research Institute and the Department of Civil Engineering at the University of Minnesota.

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*The Concrete Materials and Placement Techniques Committee sponsored publication of this paper.*