The maps shown in Figures 9 and 10 indicate the geographic impact of this rating system.

After all sources had been rated and the freeze-thaw specification established, a second round of testing was started. For crushed stones, agreement with the initial results has been excellent. However, for gravels, especially those with moderate to high expansion, differences between the initial and follow-up tests were quite pronounced. The problem has been attributed to the extreme variability within the gravel deposits themselves. Obtaining samples that are "representative" is extremely difficult, and pronouncing judgment on the basis of one freeze-thaw test has proved inadequate. Therefore, numerous samples will be taken from production throughout the next year, after which the additional freeze-thaw results will be analyzed and new ratings will be issued. The Iowa pore index, although no longer used as an acceptance test, has proved to be an effective screening test and is still used to determine when a crushed-stone deposit has changed, which makes it necessary to do additional freeze-thaw testing.

The current freeze-thaw specification should eliminate the use of D-cracking aggregates in construction. The freeze-thaw test, although expensive and time-consuming, has proved to be extremely versatile. Since it can be used to evaluate any type of aggregate, each source can be judged by its performance rather than its geologic origin or geographic location.

Although the test is now being used to evaluate routinely processed aggregates, it can also be used to evaluate aggregate improvement techniques. The effectiveness of reduced top size, heavy media, new crushing processes, or additives can be judged by comparing freeze-thaw plots before and after treatment.

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Recycling Portland Cement Concrete Pavement

ANDREW D. HALVERSON

Quality aggregates for highway construction are in short supply in many parts of Minnesota. Although the current total supply is adequate, the distribution of sources results in localized shortages. It is sometimes necessary to import high-quality aggregates from distant locations. Haul distances can increase aggregate prices substantially, add to the overall project cost, and require the expenditure of sizable amounts of energy. One available source of aggregate is existing portland cement concrete (PCC) pavement currently in need of reconstruction. Reusing this aggregate would result in cost savings in aggregate-short areas, conserve natural resources, and conserve energy in the form of fuel savings when aggregates must be acquired from distant sources. A research study is described that was undertaken to determine the feasibility of recycling PCC pavement, evaluate the new recycled pavement, determine the cost-effectiveness of recycling versus conventional paving, and determine the amount of energy consumed and natural resources conserved. Economic and engineering factors led to the selection of a 16-mile segment of US-59 from Worthington to Fulda in southwestern Minnesota for the study. The in-place roadway, which was constructed in 1955 and consisted of 9-, 7-, 9-in-thick, 24-ft-wide, nonreinforced, D-cracked concrete pavement with soil shoulders, was broken, salvaged, and crushed. Material passing the no. 4 sieve was used for base stabilization and shoulder aggregate, and material retained on the no. 4 sieve but passing the 0.75-in sieve was used as the coarse aggregate for concrete paving. The project results are evaluated based on pavement performance and energy and cost comparisons.

High-quality aggregates for use in highway construction are in short supply in many parts of the country, including portions of Minnesota. Although the total supply is adequate to meet the country's needs, the distribution of sources is such that many local areas experience shortages. In these areas, it is often necessary to import high-quality aggregates from distant locations. Depending on the length of haul, aggregate prices can increase substantially and add significantly to the total project costs. In addition, sizable quantities of energy are expended in the form of fuel for hauling vehicles.

One available source of high-quality aggregates in aggregate-short areas is the many pavements in need of reconstruction. Some of these pavements have exceeded their design life and have failed due to overuse, some have simply become geometrically outdated, and others are exhibiting some form of premature distress due to inadequate design, use of marginal materials, or poor construction practices.

Many of these roads still contain durable aggregates. Reusing these aggregates would not only conserve natural resources but, in aggregate-short areas, could also result in energy and construction cost savings.

In November 1980, the Minnesota Department of Transportation (DOT) completed a major recycling project. That project can be discussed in terms of three distinct activities: selection, experimental work, and project evaluation.

PROJECT SELECTION

In September 1976, during the initial search for a recycling project, candidate projects were selected on the basis of several criteria:

1. The roadway should have adequate vertical and horizontal alignment to preclude extensive regrading.
2. The existing right-of-way should be sufficient to allow reconstruction without further land acquisition. The existing roadway should be in such an advanced state of deterioration that the reconstruction is either programmed or imminent, and the project should be located in an area of aggregate scarcity.
3. If the existing pavement is rigid, it should be nonreinforced; if it is flexible, it should be thick enough to minimize new material requirements.

In 1977, a 16-mile segment of US-59 in southwestern Minnesota was selected for a recycling project. The existing roadway had been constructed in 1955, and was a 9-, 7-, 9-in-thick, 24-ft-wide, nonreinforced concrete pavement with soil shoulders. The pavement had been placed on a minimum of 3 in of gravel base, which in turn had been placed over an in-place bituminous surface. The roadway exhibited no frost heaves, but the pavement exhibited extensive D-cracking, a series of crescent-shaped cracks on the pavement surface that usually start at the intersection of pavement joints and progress to the center of the concrete panel. In Minnesota, this distress is physical in nature and is associated with poor-quality aggregates that absorb moisture and fail through freeze-thaw action. D-cracking exists in about 63 of Minnesota's 87 counties. Nearly 1700 miles, or 14 percent, of the 12 350 miles of Interstate and trunk highways appear to be affected.

In the case of US-59, the coarse aggregate in the concrete was from a local deposit of glacial gravel. The cause of the D-cracking was a limestone-dolomite material that constituted 55-60 percent of this aggregate. The maximum particle size was 2 in.

Early in 1978, a surface determination was made for reconstructing US-59. On the basis of this evaluation, an 8-in-thick, recycled, nonreinforced concrete pavement appeared to be the most economical alternative. In November 1979, the Minnesota DOT let a construction project to crush the distressed pavement, use the material passing the no. 4 sieve for base stabilization and shoulder aggregate, and use the material passing the 0.75-in sieve and retained on the no. 4 sieve as the coarse aggregate for reconstructing the concrete pavement. The winning bid of $5.1 million was submitted by Arcon Construction Company. This included $425 000 for two bridges that were replaced.

EXPERIMENTAL WORK

During the planning for the US-59 recycling project, the Minnesota DOT removed a 3-ft-wide section across the full width of the roadway. This material was crushed and examined for quality. The material was then used in trial mixes. Initially, five concrete mix designs, made up of various combinations of recycled and virgin materials, were identified.

One mix was designed to use recycled coarse and fine aggregates. One mix used recycled coarse aggregate and natural sand. One mix was designed to contain recycled coarse aggregate and natural sand and substitute fly ash for 10 percent of the cement. Another mix used recycled coarse aggregate and natural sand and 20 percent fly ash replacing 15 percent of the cement. The final mix was a control mix with a natural coarse aggregate and sand and 20 percent fly ash replacing 15 percent of the cement. It was found that the material passing the no. 4 sieve was very angular, and the trial mixes that used this material vastly increased the water demand to get workability. The result was that the cement requirement was very high. The decision to use the minus no. 4 material for base stabilization and to use natural sand in the concrete was made at this time.

The concrete mix design that used recycled coarse aggregate and natural sand and 20 percent fly ash substituting for 15 percent of the cement was selected for use on the US-59 recycling project. Its cement content was the lowest of the recycled concrete alternatives, and the amount of water required to produce concrete with 1-2 in of slump was also the lowest.

The gradation specified for the recycled coarse aggregate called for 95-100 percent passing the 0.75-in sieve and allowed up to 10 percent passing the no. 4 sieve.

Computations of the total coarse aggregate available on crushing assumed (a) 5 percent of the material wasted in salvage and crushing, (b) 1200 tons lost in yield, and (c) 500 tons of stockpile loss. This indicated that an adequate supply of recycled coarse aggregate would be available to make a design of 40 percent sand and 60 percent coarse aggregate feasible for the recycling options.

Another study of recycled concrete is currently under way. In the initial phase of this study, four concrete mixes were evaluated. Data existed on a mix that used virgin material from a source near US-59. One concrete mix was produced that had recycled coarse aggregate and natural sand, and another mix had recycled coarse aggregate and natural sand and fly ash substituting for 10 percent of the cement. These were compared with a previously tested mix that used an Ohio non-D-cracking aggregate.

Freeze-thaw testing was done on the recycled concretes to determine the potential for D-cracking activity. Freeze-thaw testing was done in a Weber cabinet with a large compressor. This unit is capable of 28 freeze-thaw cycles in a 24-h period, but it is operated at 12 cycles. Since the rate of freezing and thawing is not variable, and to ensure uniform conditioning, a timed delay is included at 0°F and a somewhat longer delay at 40°F. The beams of the four concrete designs were subjected to as many as 603 freeze-thaw cycles.

The recycled concretes showed some reduced D-cracking potential when compared with the natural aggregates, and the concrete in which fly ash substituted for 10 percent of the cement showed greatly reduced potential.

Initially, 3x4x16-in beams for freeze-thaw testing were cast one day, stripped and set in lime soak the next day, and soaked for 14 days. Once removed from the lime soak, beams were held in a freezer at 0°F until they could be freeze-thaw tested. Currently, beams are placed in lime soak for 28 days, allowed to air dry for one day, and moist cured for 30, 90, 150, and 210 days. They are then placed in the freezer at 0°F until they can be freeze-thaw tested.

Reconstruction of US-59 took place in 1980. Breaking and salvage of the in-place roadway began in May. Bituminous overlays originally placed by maintenance forces were removed with an elevating scraper. This was done in the afternoon when the overlay was warm. Smaller patches and joint filler were easily removed by using a small loader with a boom attached to the bucket and a tooth on the boom. The operator placed the tooth in the joint and, with the loader in reverse, dragged out the joint filler. Cleanup was done by hand and completed in June.

The in-place concrete was broken by using a shop-fabricated pavement breaker pulled by a crawler loader. The pavement breaker consisted of a two-wheel, rubber-tired trailer with a pile hammer attached. At the bottom of the pile hammer was a 14x18-in metal shoe that impacted and broke the pavement. The pile hammer was rated at 18 200 ft•lb and operated at 88-92 blows/min. Four passes were made per 12-ft lane. The speed at which the pavement breaker was pulled varied. The pavement broke more easily next to the edge or next to a previous pass of the machine. The breaker was pulled faster in those areas. The contractor attempted to break the concrete into 2-ft-square pieces. Breaking into smaller pieces made salvage more difficult. In order to avoid damage to in-place culverts, the contractor used a drop hammer to break the pavement in those locations.

The broken concrete was picked up by a power shovel with a wider-than-normal bucket. The contractor originally used two power shovels for salvage but, after a short trial, switched to one. Production was not affected, and eventually the salvage operation reached 0.5 mile/day.

Overbreakage and small pieces of concrete missed by the power shovel were gathered by a small dozer.

This was modified by adding teeth to the dozer blade. This allowed the operator to rake the material to the shovel without accumulating a significant amount of gravel base. The base was then shaped with a blade and compacted to protect it from the rain. Concrete salvage was completed in July.

Broken concrete was stockpiled at the crushing plant. A dozer worked the stockpile. A rubber-tired loader charged the 36x48-in single-toggle primary crusher. The contractor added a 1-in screen at the primary crusher to remove gravel base picked up with the pavement. The primary crusher reduced the material to less than 6 in in size. As this was moved by belt to the screening plant, reinforcing steel was removed by hand. Screened material was separated into stockpiles of minus no. 4 and no. 4 sieve to minus 0.75-in material. Of the minus 0.75-in material, the maximum natural aggregate particle size was on the order of 0.625 in, since all particles included some sand cement paste.

Oversized concrete from the screening plant was fed to a 54-in secondary cone crusher and then rescreened. Crushing began in May and was completed in July.

Concrete paving began in July 1980. Concrete was produced by a 9-yd^3, dual-drum central mix plant. The paving was preceded by an autograder that fine-graded the stabilized base. Concrete was supplied to a belt placer, which was followed by a conventional slip-form paver. Surface texture was applied with an astro-turf drag to enhance skid resistance. The final piece of equipment placed transverse tining and sprayed membrane curing compound.

The nonreinforced concrete pavement has random repeat spacing of skewed panels, 13, 16, 14, and 19 ft in length. Effective spacing is 15.5 ft. Joints are skewed 2 ft in 12 ft.

Paving of the northbound and southbound lanes was completed on September 9, 1980, and turn lanes were completed on September 24. On September 18, the last of the recycled aggregate was used and the contractor switched to natural aggregate of the same maximum size. The concrete contained 22 259 yd^3 of recycled aggregate and 640 yd^3 of natural aggregate. The use of natural aggregate does not indicate a shortage of recycled material. Turn lanes were added to the project after the computation of available aggregate was made.

PROJECT EVALUATION

The US-59 project can be evaluated in terms of pavement performance, cost comparison, and energy comparison.

As expected, paving with the recycled concrete was no problem. The recycled concrete finished well, but this has been the experience with all concrete mixes containing fly ash. Minnesota DOT specifications for surface finish allow a 1/8-in variation on a 10-ft straight edge and a 3/16-in edge slump. The pavement satisfactorily met these specifications.

A roughometer test was run on both lanes of US-59 after construction of the shoulders. The roughometer indicates riding quality by recording inches of roughness per mile. A riding quality of $\leq$85 in/mile of roughness is acceptable.

The average roughness for US-59 was 71 in/mile. The construction contract provided a bonus of 50¢/yd^2/lane mile of pavement when the riding quality indicated less than 69 in/mile of roughness. The bonus was awarded on 13 lane miles or 41 percent of the total lane miles of the project. The contractor received about a $41 000 bonus.

The quality of the transverse tining applied to the US-59 project reflects, in part, the condition of the skewed joints in the new pavement. These joints are cut with a saw when the concrete is still not fully cured. The sawing of a skewed joint across transverse tining often results in breaking or raveling of the surface concrete at the edge of the saw cut. The raveling, in turn, produces a rough surface. On this project, the contractor marked the joints and placed a metal strip approximately 6 in wide over the mark for the future saw cut. When the tining was applied, the tines passed over the metal strip, leaving the concrete surface at the joint untined. Since the pavement surface was smooth at the location of the joint, the concrete did not ravel when the cut was made. This is not expected to affect skid number.

A comparison of costs for recycling PCC as opposed to conventional concrete paving was originally assembled by personnel in the Minnesota DOT Estimating Unit and later updated from project records. Table 1 gives the updated project costs that are applicable. The first two items in the table are a direct comparison of the representative cost to remove and dispose of concrete pavement in the area of the state where the project is located and the contract price to remove, crush, and stockpile the old concrete pavement.

As mentioned earlier, recycled stabilizing aggregate was included in this project. The cost indicated is the additional cost for natural material from local sources to replace the recycled material.

Several shoulder designs were used on US-59. All of these used 2 in of bituminous over variable depths of class 5 and class 3 shouldering material. The contract provided for the use of the minus no. 4 material from the crushed concrete pavement and the crushed material from the bituminous overlays as a substitute for virgin material. The incremental cost difference for virgin material is included in the column for conventional concrete paving.

The final items relating to structural concrete reflect the contract amounts for the project as opposed to local costs for conventional concrete. The table also reflects the standard structural concrete used when recycled aggregate was no longer available.

The cost savings resulting from the recycling project were approximately $726 000. This amounts to 14 percent of the total project cost or nearly 16 percent of the grading and paving costs.

Part of the project evaluation compared the energy consumed in recycling with the energy required to construct a conventional pavement. Due to the difficulty in determining energy consumption for

Table 1. Cost saving from recycling concrete on US-59 project.

Item	Quantity	Cost ($) Recycle	Cost ($) Conventional
Remove concrete pavement	229 170 yd^2		401 047
Salvage concrete pavement, crush, and stockpile	229 170 yd^2	595 842	
Stabilizing aggregate	24 238 tons		60 595[a]
Shouldering[b]			
Class 3	23 114 tons		57 785[a]
Class 5	21 238 tons		53 095[a]
Recycled concrete	52 651 yd^3	1 289 950	
Recycled concrete with high early strength	936 yd^3	28 890	
Standard concrete	1308/53 959 yd^3[c]	51 954	2 077 422
Standard concrete with high early strength	31/994 yd^3[c]	1 395	43 736
Total		1 968 031	2 693 680

[a]Differential cost between recycled material and natural aggregate.
[b]Portion of class for which recycled material was available.
[c]Virgin aggregate/total concrete used on project.

specific pieces of equipment, average energy consumption figures were used. Values published by the Asphalt Institute were the primary source.

The construction operations considered were materials removal, production, and transportation. It was assumed that, once the material reached the plant site, the mixing and placing operations balanced each other and only production of the component materials, such as crushing and screening, was significant.

The contractor would have used the same methods to break and remove the D-cracked pavement if it was to have been salvaged or disposed of. There was a net requirement of 130 additional equivalent gallons of gasoline for the concrete recycling option. This was the energy consumed in removal of bituminous pavement.

Overall, materials production for recycled concrete would require more energy than materials production for conventional concrete. This amounts to about 24 500 gal of gasoline.

To complete the evaluation of energy consumed, it was necessary to determine the energy requirements for transporting the construction materials. This determination assumed a constant source whenever possible, and the source was the actual supplier for the project.

The energy requirement for transportation of construction materials was less for the recycling option than for conventional paving. This amounts to a savings of 65 300 gal of gasoline.

A summary of the energy requirements in equivalent gallons of gasoline for recycling versus conventional paving is given in the table. There was an indicated savings of 40 610 gal of gasoline of an estimated 915 860 gal for conventional concrete paving. This would operate 51 automobiles, averaging 15 miles/gal, and traveling the normal 12 000 miles/year for a full year. This, in itself, is not an overwhelming savings, but it should be noted that conventional paving would require disposal of the broken D-cracked pavement. It is possible that the material may have been disposed of at the borrow pit where the contractor's plant was located. If another disposal site were required, additional truck haul would be necessary. The energy requirement would have increased further for conventional construction.

SUMMARY

In summary, the project selection process indicated the desirability of entering into a concrete recycling project on the basis of economic and engineering factors. Experimental work with trial mixes provided the concrete design most desirable for field application, and field application resulted in a project with a surface that has good riding quality. The US-59 recycling project is considered to be a success. The scarcity of quality aggregates in this area of Minnesota is partly responsible for that. In other areas, cost and energy savings may not be realized.

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Relation Between Pavement D-Cracking and Coarse-Aggregate Pore Structure

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Previous research has developed a relation between the pore structure of a coarse aggregate and the freeze-thaw durability, measured in the laboratory, of concrete made with that aggregate. This has permitted the calculation of an expected durability factor from a knowledge of an aggregate's median pore diameter and total pore volume. This work has been extended to a consideration of in-service pavements, some of which showed D-cracking distress and some of which appeared to be durable. Forty-seven pavement sections were cored, and coarse-aggregate samples were removed and separated lithologically. Their pore-size distributions were determined by mercury intrusion. Criteria involving the expected durability factor and relative amounts of good and bad aggregate fractions in the pavement were correlated with the extent of observed D-cracking. These correlations were distinctly superior to absorption measurements in identifying bad aggregates. It is suggested that the established criteria might be used to predict the performance to be expected from aggregate sources and might be a valuable acceptance standard.

D-cracking is an important durability problem in portland cement concrete (PCC) that is exposed to freezing conditions. It is particularly prevalent in pavements. It occurs when water in the coarse-aggregate pores freezes and causes sufficient expansion to crack the concrete. When D-cracking occurs in a pavement slab, it continues until the entire slab is destroyed. There exists no practical way to stop its progress. The only measure effective against it is the exclusion from the concrete mixture of those aggregates susceptible to the problem. Many agencies that have control over the materials used in paving perform regular tests on the coarse aggregate in an effort to screen out material that will cause D-cracking. Nevertheless, this form of distress still occurs in pavements made from materials that have passed current testing procedures. It is obvious that a more diagnostic test method is required.

In earlier work (1), the relation between the pore structure of an aggregate and its susceptibility to D-cracking was examined. The pore structures of a variety of crushed-stone coarse aggre-