

# Research Record

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## Cracking Up: Rapid Deterioration of Transverse Cracks in Recycled Concrete Aggregate Pavements

In the early 1980's, the Michigan Department of Transportation reconstructed several Interstate highway projects using recycled concrete aggregate (RCA). The reason for using RCA was twofold. First, although virgin aggregate is often considered a superior product and is not substantially higher in cost than recycled concrete aggregate, it was not always readily available, sometimes needing to be hauled considerable distances. Second, if not recycled, the old pavement would end up in a landfill—a wasteful prospect.

The sections that were replaced had experienced problems with D-cracking—poor resistance to the freeze-thaw cycle. To reduce the recycled concrete aggregate's susceptibility to that problem, the old pavement sections were crushed to a smaller top size. Although that decision was based on sound engineering principles, the smaller top size combined with other factors to set off a chain reaction of unintended consequences.

### *Shrinkage leads to cracks.*

Transverse cracks sometimes develop as the pavement shrinks. Because RCA contains old mortar from the recycled material plus the mortar in the new pavement, RCA has a higher coefficient of shrinkage. As a result, recycled concrete pavements can develop wider transverse cracks. While most of these newly recycled concrete aggregate pavements performed acceptably, MDOT was concerned that some of these recycled pavements deteriorated more rapidly than they should have.

### **Diagnosing the Problem—Aggregate Interlock**

One of the symptoms that researchers observed was straight vertical crack faces showing very little

roughness or meander. They speculated that the smaller top size of the recycled concrete aggregate, which was supposed to reduce the problem with D-cracking, may have adversely affected the aggregate's interlock load transfer capacity. Aggregate, or grain, interlock is important because most jointed reinforced concrete pavements (JRCP) rely on aggregate interlock to transfer shear loads across these cracks. In effect, the strategy for solving the D-cracking problem may have inadvertently contributed to another.

The final impact of this chain reaction was an accelerated maintenance schedule and ultimately a shortened pavement service life. MDOT needed hard answers as to what caused these pavement failures and solutions to prevent their reoccurrence.

### **Testing for Load Transfer**

Dr. Mark Snyder, currently of the University of Minnesota, served as Principal Investigator for the research study conducted at Michigan State University. Because several factors could have affected the deterioration of the transverse cracks in the JRCP, it was essential to determine which ones played the lead roles. The initial research study included six slabs, but because the initial data raised numerous questions, second and third phases were developed to acquire additional data. In all, thirty-five slabs were tested.

The test slabs included specimens made primarily from 6A and 4A virgin gravels and limestone as well as 6A recycled concrete aggregate and slag. These slabs were configured with differing combinations of reinforcement type and quantity and differing slab tensions.

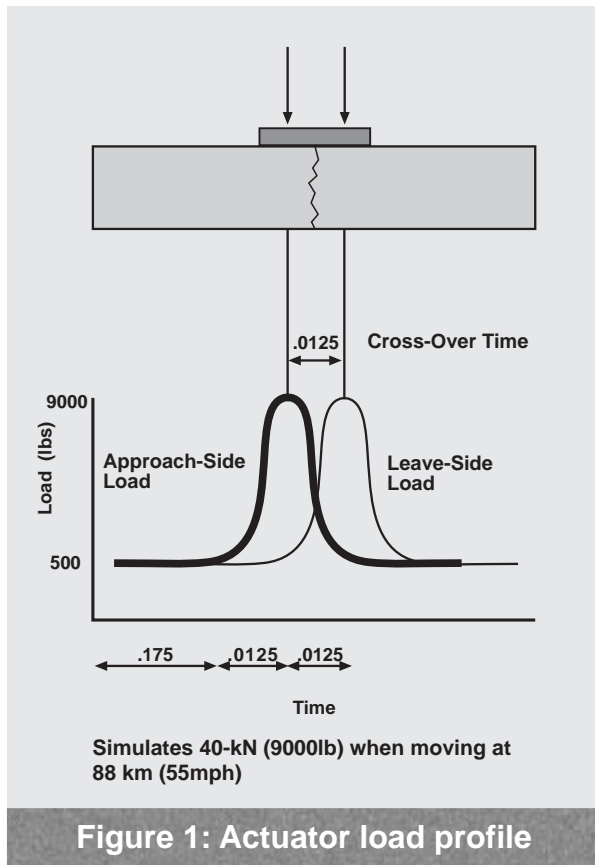


Figure 1: Actuator load profile

Each concrete slab was cast according to a schedule that allowed testing after 28 days of curing. A transverse crack was induced midslab after 18 hours of curing. After placing and centering the slab on a test stand developed to simulate heavy vehicle loading (see figure 1), the casting form was removed, and the cyclic load program was begun. Load, deflection, and crack width data were collected generally until the reinforcing steel in the slab ruptured, indicated by rapid increases in crack width and the inability to apply adequate tension to the slab.

### The Low-down on Load Transfer

#### Defining failure.

The study analyzed the impact of load transfer on the rate of crack deterioration for the various pavement materials and design features. A load transfer history was compiled and plotted for each slab to determine the number of load cycles to failure and the load transfer efficiency (LTE) at failure. LTE is defined as the number of cycles corresponding to the point on the load transfer history curve where a 45-degree line could be constructed tangent to the curve. The average load transfer efficiency at failure was approximately 76%.

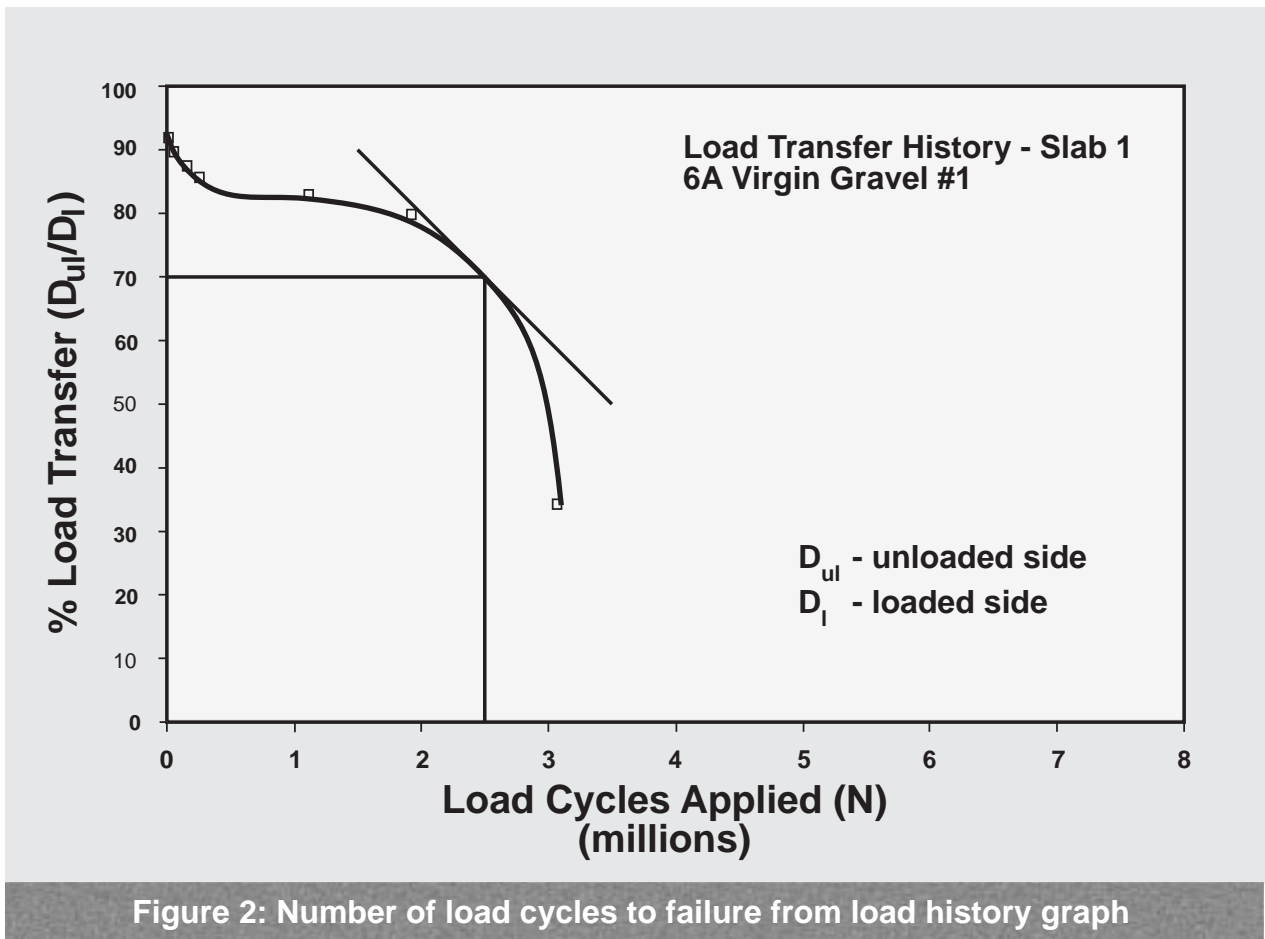
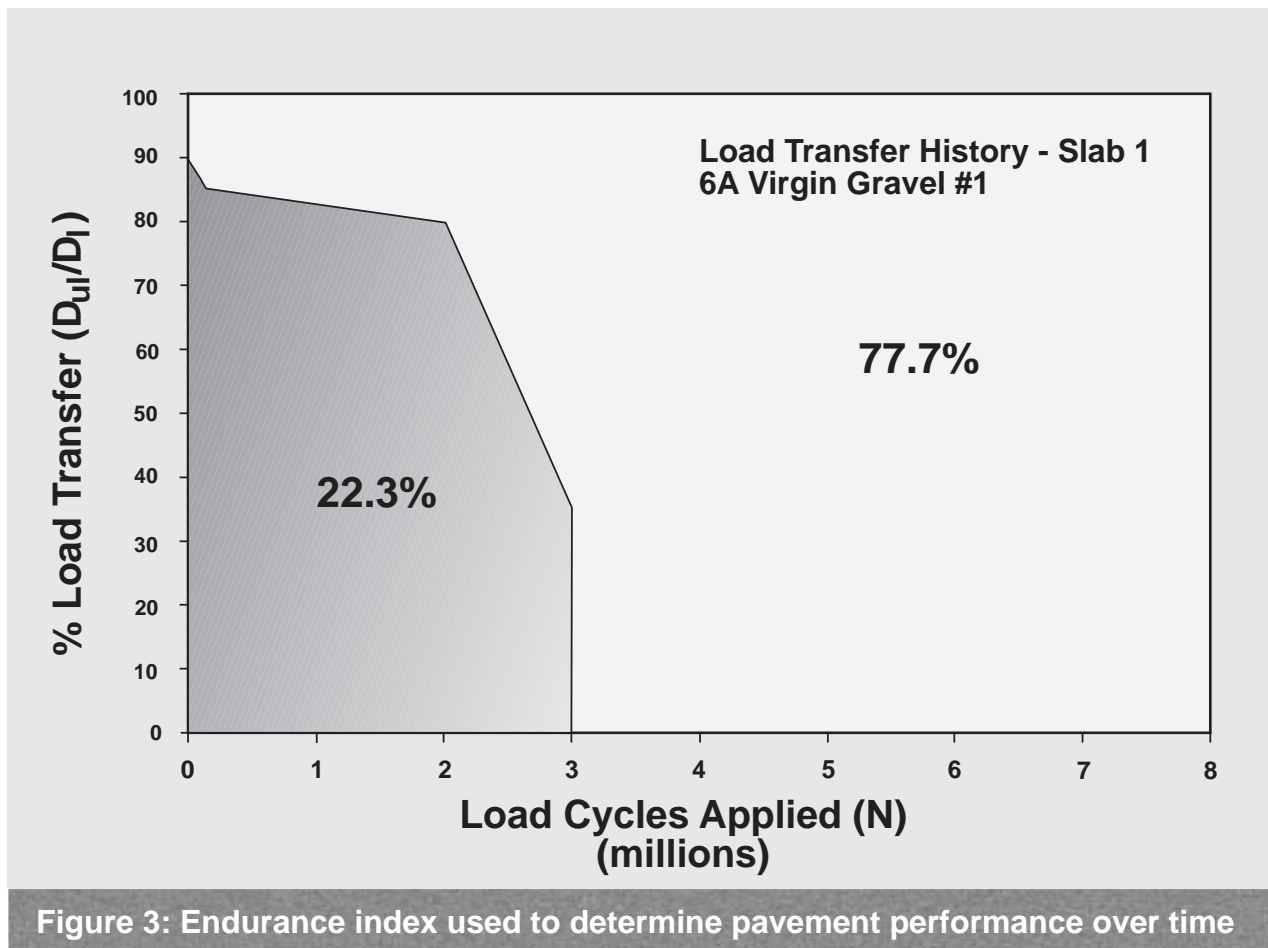


Figure 2: Number of load cycles to failure from load history graph



The load transfer history for slab 1 shows that failure occurred at about 2.5 million load cycles with a load transfer efficiency of about 70% (see figure 2).

#### **Endurance Index**

To analyze the load transfer performance of a crack not only at failure but over a period of time, an endurance index was developed to represent the cumulative load transfer performance of a crack over the number of load applications that had been applied.

The method found to best express the cumulative load transfer was to determine the area under the load transfer curve as a percentage of the area contained within load transfer limits of 0 to 100% and load cycle limits of 0 to 10,000,000 (with log scale limits of 0 to 8). The percentage under the load transfer curve becomes the endurance index. For slab one, the endurance index is 22.3% (see figure 3).

Differential deflections were used to determine the LTE. Evaluation of the LTE alone, however, was insufficient to predict differences in performance of different slabs. Any number of combinations of  $D_{u1}/D_l$  (the deflection of the unloaded side divided by deflection of the loaded side) can result in the same load transfer effi-

ciency, so both differential deflection and peak deflection are essential for complete analysis of slab performance. Peak deflections serve to indicate the degree of load transfer provided by grain interlock and shear in the reinforcing steel. Differential deflection helps predict crack deterioration due to fatigue of the reinforcing steel and abrasion of the crack face.

#### **Different Designs for Different Aggregates**

The broadest conclusion reached was that natural aggregates (that is, gravels and limestones) generally outperformed manufactured aggregates (recycled concrete and slag) in the test study when all other factors were held the same. Because different aggregates produce concretes with widely varying physical and mechanical properties, no single standard design can be expected to produce pavements with comparable performance.

Despite the disparity in performance between virgin and manufactured aggregates, several of the factors studied showed that designs can be modified to enhance the performance of recycled concrete aggregates. The most promising modifications either use a concrete mixture design that strengthens concrete made with recycled con-

crete aggregates or slag, or they use structural designs that reduce pavement stresses. These modifications help compensate for the reduced grain interlock of recycled aggregates.

In terms of mix design, gradation was an important factor in the performance of recycled concrete aggregate. Including larger coarse aggregate particles seemed to improve grain interlock at the transverse joints and cracks as long as the grading did not adversely affect the concrete's strength. Recycled concrete aggregates blended with virgin aggregate particles of equal or greater size also performed better than recycled concrete aggregate alone.

### Prescriptions for Better Performance

Several structural designs showed potential for enhancing crack performance in recycled concrete aggregates by minimizing reliance on aggregate interlock.

**Increased Foundation Stiffness.** Better performance for both virgin and recycled aggregates was attributed to reduced peak and differential deflections, resulting in reduced crack face abrasion and loss of grain interlock and to increased load transfer to the foundation, resulting in reduced shear stresses.

**Reduced Slab Tension.** Better performance was attributed to reduced crack width and steel stresses, allowing good grain interlock load transfer with reduced crack face abrasion. Slab tension can be reduced either by using shorter panel lengths or by reducing friction between the slab and foundation.

**Additional Steel Reinforcement.** Increased quantities of steel held cracks tightly because strain was reduced regardless of the level of tension. Performance increased even with wider initial cracks.

**Use of Deformed Wire Mesh.** This type of reinforcement consistently limited crack width. By shortening the length of strain, the crack is held more tightly, thereby maintaining better grain interlock. Simply put, the less strain, the tighter the crack.

**Use of Hinged Joints.** The superb performance of hinged joints was attributed to the elimination of crack

openings and increased quantity and size of steel bars. Failure was never induced in the test slab.

### When One + One Is Greater than Two

Three combinations of design features resulted in performance significantly better than from either design feature alone.

**Foundation + Reinforcement.** Foundation stiffness and reinforcement design together provided exceptional performance for recycled concrete aggregate. Although virgin gravels also performed better, the improvement was not as dramatic as for RCA. Researchers hypothesized that because foundation stiffness plays a significant role in reducing deflections, crack face abrasion and steel stresses, which are more problematic for RCA than virgin gravels, foundation stiffness is of greater benefit to the recycled concrete aggregate.

**Foundation + Tension.** Foundation stiffness and reduced slab tension also appeared to produce better crack performance in combination than when used alone. This apparently holds true for both virgin and manufactured aggregates.

**Tension + Deformed Mesh.** The other combination of design factors that provided superior results was reduced slab tension and deformed wire mesh. This design strategy, like the others, reduces the reliance on grain interlock to transfer loads.

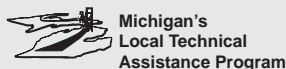
### One Size Does Not Fit All

Although the use of virgin aggregates may be preferable under certain conditions, it is not always feasible, so recycled concrete aggregates will likely be used with increasing frequency. Research indicates, however, that if standard structural and concrete mix designs established for virgin gravels are used with recycled concrete aggregates, the same performance results cannot be guaranteed. To compensate for its shortcomings, it will be increasingly important to establish structural and concrete mix designs for recycled concrete aggregates that will provide long lasting pavements. Despite the prior poor performance of some recycled concrete aggregates, Snyder is confident that the problems can be solved. "The technology *is* available," says Snyder. "It *can* be done."

For additional information, contact Dave Smiley, Supervising Engineer, Pavement Technology Unit, Michigan Department of Transportation, 517-322-1766.

Suggestions or questions concerning *M&T Research Record* should be directed to Jon Reincke, Engineer of Research; 517-322-1632, FAX 517-322-5664

*M&T Research Record*  
is produced by



Editor ..... Susan Sanders  
Research Assistant/Editor .... René Johnson

