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Impact of Aggregate Type on Performance of Transverse Cracks in Jointed Concrete Pavements-A Field Study

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Jointed concrete pavements (JCP) develop transverse cracks as the drying and temperature-related volume changes of the PCC slab are resisted by the friction with the foundation layers. These transverse cracks degrade over time because of traffic and loss of shear capacity. This rapid deterioration triggers unscheduled maintenance and reduced performance lives. This paper synthesizes the impact of aggregate type on the load transfer potential of transverse cracks in JCPs. The ongoing work involves the collection and analysis of deflection data from 49 field sites. Based on the field investigation it can be concluded that jointed concrete slabs constructed using the natural aggregate products provided better crack deterioration performance than did concrete slabs constructed using the manufactured aggregate when all other variables were held constant.

BACKGROUND

In general, most JCPs rely on aggregate-to-aggregate interlock to achieve the required load transfer capacity across cracks. Degradation of these cracks is strongly related to the loss of transfer efficiency. Therefore, the succeeding paragraphs summarize the mechanisms and models of aggregate interlock.

Aggregate Interlock Mechanism(s)

Aggregate interlock is the primary mode of load transfer across transverse cracks in JCPs. For the purposes of this study, aggregate interlock will be considered to be the only mechanism contributing to load transfer across such cracks. This shear transfer mechanism is effective in providing load transfer as long as the crack faces are kept close to one another (*Paulay and Loeber, 1974*). This finding was clearly affirmed by Benkelman in 1933 when he declared, "...when roughened edges of two slabs are held firmly together, the aggregate interlock may be expected to function perfectly and permanently as a loadtransfer medium" (*Benkelman, 1933*). When a crack develops in a JCP, the two crack faces are usually rough and irregular (*Paulay and Loeber, 1974*). Such roughness is due to aggregate protrusions from the crack face and the irregular texture of the cement matrix. As a wheel approaches a crack, differential vertical displacement of the two slab fragments takes place, causing the particles of one face of the crack to come in contact with the matrix of the other face (*Raja and Snyder, 1991*). A combination of bearing and friction between the

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aggregate particles of the two crack faces inhibits further differential movement between the slab fragments (*Paulay and Loeber, 1974*). Aggregate interlock is the name given to this mechanism which allows a portion of the wheel load to be transferred from one side of a crack to the other through shear, as it involves an interlocking of aggregate particles across a crack plane. There are several models that have been developed to describe this mechanism.

Aggregate Interlock Model(s)

Laible et al. proposed one model, which divides the crack face roughness into "local" and "global" components. Local roughness causes interlocking of the fine aggregates through a crushing or bearing action. Global roughness involves the interlocking of coarse aggregate particles through a sliding and overriding action. Local roughness is presumed to dominate the aggregate interlock mechanism at small crack widths (less than 0.25 mm), whereas global roughness controls the mechanism for wider cracks. (*Laible et al., 1977*)

Walraven proposed a model of aggregate interlock that considers concrete to be a two-phase material consisting of aggregate and a cement matrix. Concrete is modeled as a distribution of rigid spheres of a range of sizes embedded to varying depths within a deformable rigid-plastic matrix. Shear forces are resisted through a combination of sliding and crushing of the aggregates (rigid spheres) into and over the plastic cement matrix. Initially, a sliding of the opposite crack faces occurs, where the aggregates on one side slide against the cement matrix on the other side. High contact stresses develop as the contact area is reduced and crushing of the aggregates into the matrix occurs. Eventually, equilibrium of the forces is reached and further plastic deformation ceases. This model does not consider contact between aggregates from opposing sides of the crack surface. (*Walraven, 1981*)

Millard and Johnson performed a laboratory investigation to test the validity of the above models. Test results did not support the local and global roughness model or the frictional sliding model. However, the two-phase aggregate interlock model did seem to provide consistent agreement with their test results. (*Millard and Johnson, 1984*)

Quantification of Load Transfer and Shear Transfer

Load transfer across discontinuities in JCPs is commonly quantified by a term called load transfer efficiency (LTE). Expressed as a percentage, LTE gives an indication of the effectiveness of a crack in transferring load, as illustrated in Fig. 1. Computation of load transfer efficiency based on deflections near the crack under an applied load is a very useful method of determining the LTE. The load transfer efficiency computed using this approach is termed the deflection load transfer efficiency (LTE_δ) (*Ioannides and Korovesis, 1990*). Use of LTE_δ assumes that the amount of load transfer across a crack is directly proportional to the relative deflections of the unloaded to loaded sides of the crack (*Benkelman, 1933*). LTE_δ was used in this study to characterize the ability of cracks and joints to transfer load. Deflection load transfer efficiency was computed in this study by using Equation 1 (*Ioannides and Korovesis, 1990*):

$$\mathrm{LTE}_\delta = \frac{\delta_\mathrm{U}}{\delta_\mathrm{L}} \times 100\% \qquad (1)$$

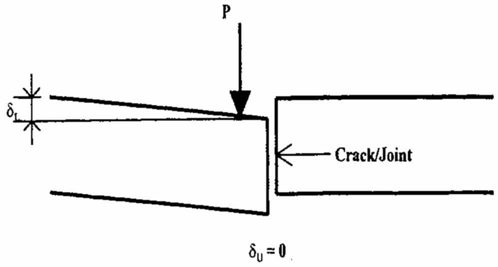
where:

LTE_δ = deflection load transfer efficiency, %

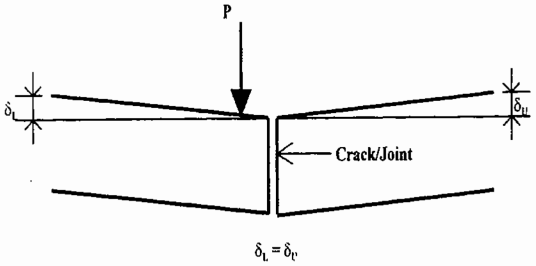
δ_U = deflection on the unloaded side of a crack or joint, μm

δ_L = deflection on the loaded side of a crack or joint, μm.

This definition of load transfer efficiency was adopted for this study for two reasons. First, it is relatively simple in concept and thus easily interpreted. Secondly, and more importantly, it was used because LTE_δ can be easily computed using field data from a falling weight deflectometer (FWD), which was used in this study. A FWD is a device that applies an impulse load, using a 300-mm diameter circular load plate (this allowed for the dependence of LTE on a/l), to a pavement and measures the resulting pavement deflections through a series of sensors. Deflection



Depiction of 0% deflection load transfer efficiency



Depiction of 100% deflection load transfer efficiency

FIGURE 1 Definition of load transfer efficiency

data for computing LTE_δ is thus readily available when this device is used.

Various researchers have adopted several other formulae for the computation of load transfer efficiency; the alternative definitions used are as follows:

$$\begin{aligned} LTE_\delta &= \frac{\delta_u}{(\delta_u + \delta_L)} \times 100 \\ LTE_\delta &= \frac{2\delta_u}{(\delta_u + \delta_L)} \times 100 \end{aligned} \qquad (2)$$

The definitions for the terms used in Equation 2 have been defined earlier. Load transfer efficiency can also be computed on the basis of stress using formulae similar to those described in Equations 1 and 2.

$$E = \frac{(f_f - f_j)}{(f_f - f_i)} \times 100 \qquad (3)$$

where:

E = joint efficiency,

f_f = stress for a given load applied at a free edge,

f_j = stress for a given load applied at the crack or joint edge, and

f_i = stress for a given load applied at the slab interior.

DESCRIPTION OF TEST PROGRAM

Field Test Sites

The study included test sites from in-service pavements in Michigan. The variables considered in site selection criteria were as follows:

- Presence of transverse cracks in the jointed concrete pavement.
- Coarse aggregate type (limestone, natural gravel, recycled concrete, and slag).
- Joint spacing (4.9, 8.2, 12.5, and 21.6 m).
- Shoulder types (asphalt and tied concrete shoulders).
- Traffic levels.
- Pavements not scheduled for rehabilitation in the near future.

In particular, it was desired to have a sufficient number of sites representing each of four concrete coarse aggregate types – carbonate (17 sites), natural gravel (8), recycled concrete (14), and slag (10). An intensive review of the construction records was performed to collect and compile inventory data for field-test sites. The summary of the inventory data can be found in Table I. On average the test sections were 25 to 65 m long (2–8 slabs in length). The outermost traffic lane was used for all test sites. Sites were chosen as far as possible from entry/exit ramps to prevent traffic flow problems during field data collection. In all, the database consisted of a total of 49 test sites. All PCC mixture designs (standard DOT paving mixtures) were targeted to achieve 23 MPa compressive strength in 28 days. Review of the concrete test data revealed that all pavement mixtures met the strength criteria.

TABLE I Inventory data

Attribute	*Description*
Pavement age, years	3–29
PCC thickness, mm.	178–305
Base thickness, mm.	102–178
Subbase thickness, mm.	203–356
Joint spacing, m.	4.9–21.6
Traffic (80 kN-ESALs)	2.3×10^6-4.5×10^7

Six cycles of field data were collected over a period of 30 months. The test cycles corresponded to different seasons of the year. The types of data collected during these six cycles are summarized below:

- Joint spacing
- Type of shoulder
- Different distresses within the test section
- Number of cracks
- Length and widths of cracks
- Deflection across full-depth cracks by means of a falling weight deflectometer to determine deflection load transfer efficiency
- Mid slab deflection to compute concrete modulus
- Corner deflection to determine void potential
- PCC cores to verify pavement thickness and study path of cracking. Several of these cores (only once) were then used to analyze the texture of the cracked face.

In addition to the above list, data collection also involved performing visual distress surveys, which were made to note the existence of faulting, spalling, and other distresses within the test sites. Core specimens were taken at cracks to be used in an analysis procedure to determine surface texture at crack faces. This allowed for the study of the effects of aggregate type and mode of fracture on surface texture, which can be related to pavement performance.

RESULTS AND DISCUSSION

Effect of Concrete Coarse Aggregate Type on Number of Cracks per Slab

This study examined the effect of coarse aggregate type on the average number of transverse cracks per slab for JCPs with a 12.5-m joint spacing. Figure 1 shows that recycled concrete and slag pavements tended to have approximately twice the number of transverse cracks as pavements with natural gravel or carbonate aggregates. This is possibly due to the greater susceptibility of slag and recycled concrete pavements to shrinkage cracking, when proper curing considerations are not made. Table II summarizes similar crack information for other joint spacings considered in this study.

Slag aggregates have the potential to absorb a substantial amount of water from the concrete mixture due to their high porosity. If such absorption occurs, the resulting loss of water from the paste can lead to shrinkage cracking. Likewise, recycled aggregates commonly demonstrate a non-uniform, sometimes high moisture absorption capacity (*Raja and Snyder, 1991*). It is expected that the variability (standard deviation of 1.8 and # of cracks range from 1–10) in the absorption capacity of these aggregates is linked to the variability in the amount of old mortar which exists on the aggregate particles. In areas where a large amount of old mortar covers the aggregate particles, a greater tendency for moisture absorption will exist, and the excess mortar also results in a poor aggregate-cement paste bond. This is at least partially due to the presence of un-hydrated cement particles within the old mortar. Hydration of these particles may occur as they come in contact with the mix water. Such hydration results in a loss of mix water and can contribute to shrinkage cracking. In addition to the old mortar content, the porosity of the aggregate particles also affects the absorption capacity of recycled concrete aggregates, and thus the potential for shrinkage cracking in these pavements. Natural gravel and carbonate pavements are much less likely to experience significant shrinkage cracking caused by aggregate absorption of mix water. These aggregates have low absorption capacities compared to recycled concrete and slag aggregates.

TABLE II Effect of aggregate type on number of cracks/slab

Aggregate	*Avg. # of cracks/slab*				*Avg. pavement age, years*			
Type	*4.9 m*	*8.2 m*	*12.5 m*	*21.6 m*	*4.9 m*	*8.2 m*	*12.5 m*	*21.6 m*
Carbonates		1.3	2.4			7.7	15	
Gravels			1.9	4			18	28
Recycled			4.2				13	
Slag	1.4	1.6	4.4		4.5	7.1	11	

Volumetric Surface Texture (VST) Analysis

Core specimens taken at cracks were sent to the University of Minnesota to be tested for surface texture using a new analysis procedure, which was developed there – the VST test. A detailed explanation of this procedure is given in (*Wade, 1997*). The VST test procedure involves testing a given area of a crack face (cracked core face in this case) for surface texture. This test area is divided into many smaller individual areas (A_i) in a grid pattern. For each of these individual areas, distances (d_i) are measured from an arbitrary datum plane to the fractured surface within that area. The average distance from the datum plane (d_{ave}) is then calculated, and the differences, $r_i = d_i - d_{ave}$, are computed for each of the individual areas. These differences, r_i, are then multiplied by their respective areas, A_i. The product of r_i and A_i is V_i, the volume of material above or void space below the plane defined by d_{ave} for the individual area. The absolute values of all V_i's are then summed, and the resulting quantity is divided by the total test area to produce the microtexture volumetric surface texture ratio (VSTR). The VSTR indicates the volume of texture per surface area of the specimen. A high VSTR indicates a rough surface texture, while a low value indicates a smooth texture.

It should be noted that both a microtexture and macrotexture VSTR could be computed. Microtexture VSTR quantifies the surface texture within a fracture plane due to aggregate protrusions or roughness in the paste texture, whereas macrotexture VSTR accounts for both the surface texture of the fracture surface and texture due to multiple fracture planes (adjacent fracture planes oriented at angles to one another). Only microtexture VSTRs were considered in this analysis. Several cores for each of the four aforementioned aggregate types considered in this study were VST tested.

Results from this testing are summarized in Table III. For each specimen tested the microtexture VSTR is given as well as a visual assessment of the core's surface texture, which was made at the time of testing. The mode of fracture through the core (i.e., through or around the aggregates) is also included in this table.

TABLE III Volumetric surface texture test results

Specimen name	*Aggregate type*	*Microtexture VSTR (cm^3/cm^2)*	*Mode of Fracture Microtexture*	*(T)hrough/(A)round*
CARB-1	Carbonate	0.0678	Smooth	90%T
CARB-2	Carbonate	0.0767	Smooth	99%T
CARB-3	Carbonate	0.0958	Smooth	Poor Visability[a]
CARB-4	Carbonate	0.0691	Smooth	98%A
CARB-5	Carbonate	0.0429	Smooth-Moderate	99%T
NG-1	Natural Gravel	0.1624	Rough	95%A
NG-2	Natural Gravel	0.1238	Rough	60%A

Specimen name	*Aggregate type*	*Microtexture VSTR (cm^3/cm^2)*	*Mode of Fracture Microtexture*	*(T)hrough/(A)round*
NG-3	Natural Gravel	0.2498	Moderate	90%A
NG-4	Natural Gravel	0.1406	Moderate	80%A
NG-5	Natural Gravel	0.0550	Moderate	98%A
RCY-1	Recycled Concrete	0.1426	Rough	80%T
RCY-2	Recycled Concrete	0.0419	Smooth	99%T
RCY-3	Recycled Concrete	0.1699	Moderate	85%T
RCY-4	Recycled Concrete	0.0878	Moderate	90%T
RCY-5	Recycled Concrete	0.0635	Smooth	95%T
SLAG-1	Slag	0.0663	Smooth	70%T
SLAG-2	Slag	0.0781	Smooth	99%T
SLAG-3	Slag	0.0659	Smooth-Moderate	95%A

a. Poor visability – was unable to tell whether the fractures went through or around the aggregate particles.

The visual assessments of surface texture are found to be mostly in agreement with the VSTR values. That is, higher VSTR values generally correspond to "rougher" texture assessments. Results also indicate a relationship between the mode of concrete fracture and surface texture. Cracks, which propagated through the aggregates, were generally found to have smoother surface texture (and lower VSTRs), whereas cracks propagating around the aggregates were associated with rougher texture (and higher VSTRs). This relationship can be easily explained, as cracks which propagate around the aggregates result in a greater amount of aggregate protrusions at the crack face and thus more surface texture.

The effect of concrete aggregate type on surface texture (Fig. 2) was also studied. It can be seen in Table III that carbonate and slag specimens were generally found to have smooth surface texture, while natural gravel specimens demonstrated rough texture. Recycled concrete specimens showed a range of surface texture.

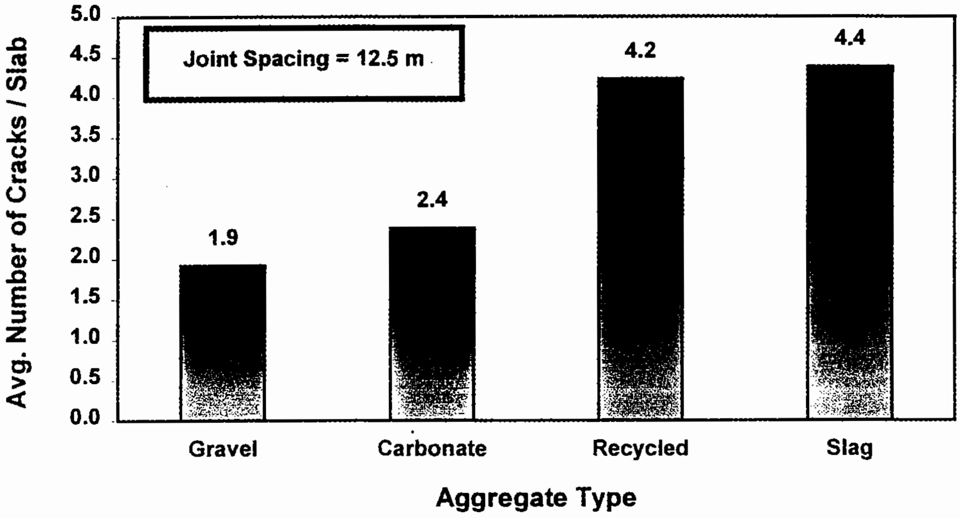


FIGURE 2 Effect of coarse aggregatse type on number of cracks per slab

The difference in texture between natural gravel and carbonate specimens can be explained in terms of the relative aggregate-paste bond strength and the aggregate strength of each specimen type. The natural gravel aggregates form a relatively weak bond with the paste due to their rounded shape. Cracks are thus more likely to propagate around rather than through these aggregates, which are relatively strong. Conversely, the angular shape of carbonate aggregates produces a strong aggregate-paste bond for such specimens, and cracks thus tend to propagate through rather than around these aggregates, which can be relatively weak. Noting the relation between mode of fracture and surface texture explained above, it is reasonable that natural gravel specimens have a rougher texture than carbonate specimens. (*Raja and Snyder, 1991*)

The smooth surface texture of slag specimens is likely due to the porosity and size of the slag aggregates. These aggregates are relatively weak due to their high porosity. Consequently, cracks can easily propagate through the aggregates, leading to a smooth texture at the crack face. Even if cracks propagate around slag aggregates, poor texture often results due to the typically small size of the aggregates, which leads to a reduced volume of protrusions from the crack face.

The variable surface texture found for the recycled concrete specimens can be primarily attributed to the composite nature of these aggregates. Recycled aggregates are composed of old aggregate particles partially covered with old mortar. At a given crack face, a higher old mortar content will translate to a lower amount of aggregate particles protruding from the face. Thus, recycled aggregates with high old mortar contents will result in a relatively smooth crack face. However, if the old mortar content is low, a rough surface texture could be obtained. (*Vandenbossche and Snyder, 1996*)

Vandenbossche and Snyder found that increasing the coarse aggregate size leads to a rougher volumetric surface texture. They also determined that stronger aggregates such as limestone result in a rougher volumetric surface texture than weaker aggregates such as slag. Regarding aggregate treatment, a rougher texture was found for virgin aggregate specimens than for specimens with recycled concrete aggregate. This was attributed to the reduced amount of aggregates at the crack face for recycled specimens, as they are composed of not only aggregates but also old mortar. Blending recycled aggregate with virgin aggregates did lead to improvements in the volumetric surface texture. It was also found in their study that rougher volumetric surface texture corresponds to higher load transfer efficiency. Thus, it may be inferred that increased aggregate size, stronger aggregates, and/or use of virgin or blended aggregates lead to improved load transfer efficiency.

Effect of Aggregate Type on Load Transfer Efficiency

In Fig. 3, the four aggregate types are compared in regard to average crack width and average LTE_δ's. It can be seen that lower average crack widths correspond to higher average LTE_δ's and vice versa, as would be expected due to the nature of the aggregate interlock mechanism. Slag pavements are found to own the highest average LTE_δ (and lowest average crack width), while recycled pavements (average age of recycled pavements is 13 years) have the lowest average LTE_δ (and highest average crack width). Average LTE_δ's and crack widths for natural gravel (average age of gravel pavements is 22 years) and carbonate pavements (average age of carbonate pavements is 16 years) fall in between these two extremes with natural gravel pavements having a higher average LTE_δ (and lower average crack width) than carbonate pavements.

With the exception of the slag pavements these results are expected. Recycled concrete pavements are comprised of the relatively weakest aggregate type, i.e., crushed, recycled concrete, and it is thus reasonable that they have the widest cracks and the lowest LTE_δ's. Likewise, carbonate pavements are comprised of relatively weak carbonate aggregates, and thus have wider crack widths and lower LTE_δ's than natural gravel pavements. These aggregates probably fall in between natural gravel and recycled concrete aggregates concerning strength and durability characteristics of the aggregate. The reason for natural gravel pavements

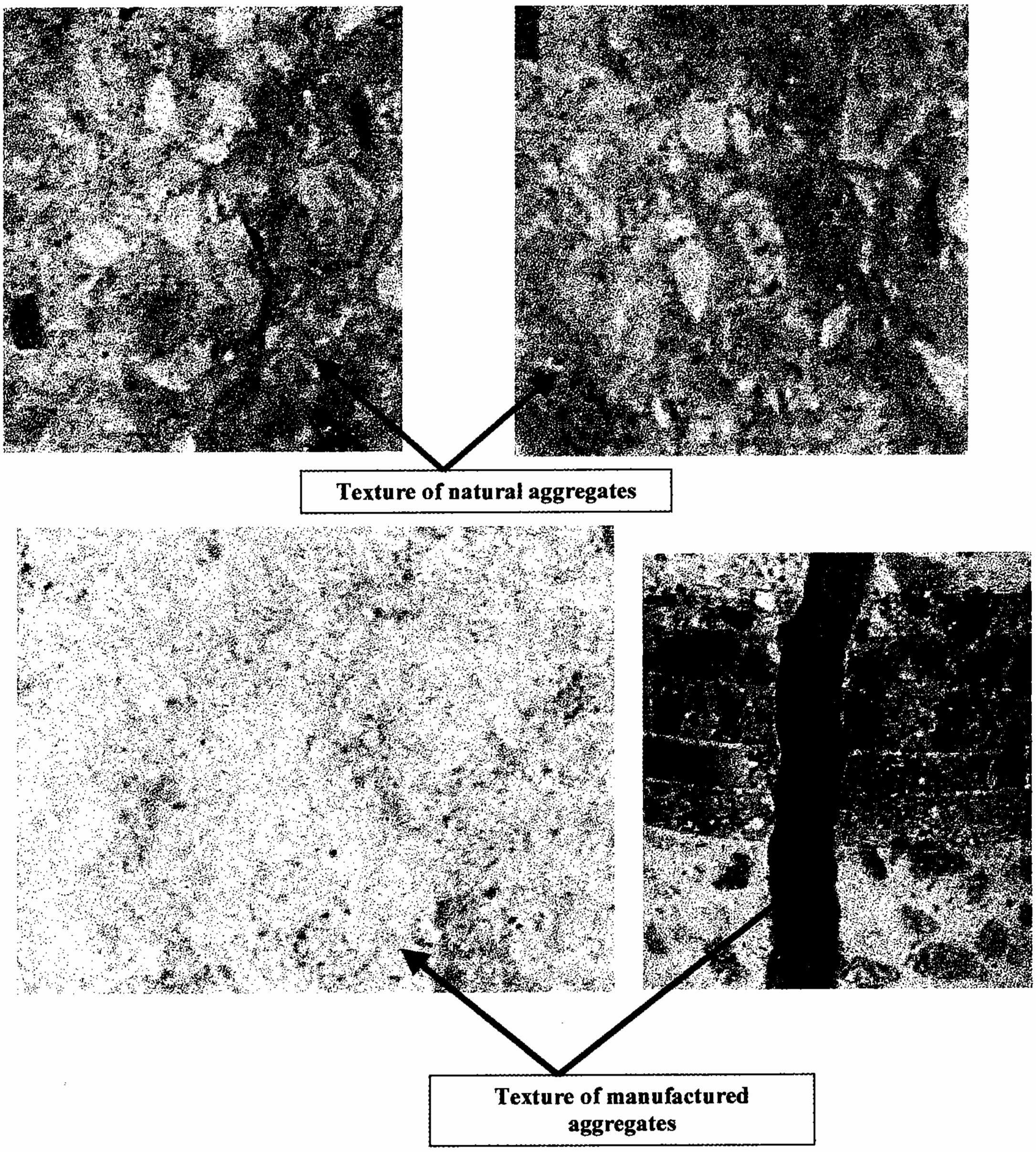


FIGURE 3 Comparison of surface textures

having higher LTE$_\delta$'s than carbonate aggregate pavements may also be due to the relative hardness of the rocks. Carbonate is a fairly soft rock, which means that cracks will likely propagate through the aggregate rather than around the aggregate due to load stresses. Natural gravel aggregates are harder rocks and thus cracks are more likely to propagate around these aggregates. The aggregate interlock mechanism depends on aggregates bearing against one another, among other factors, in order to transfer load across a discontinuity. Thus, carbonate pavements have less potential than natural gravel pavements to transfer load across cracks.

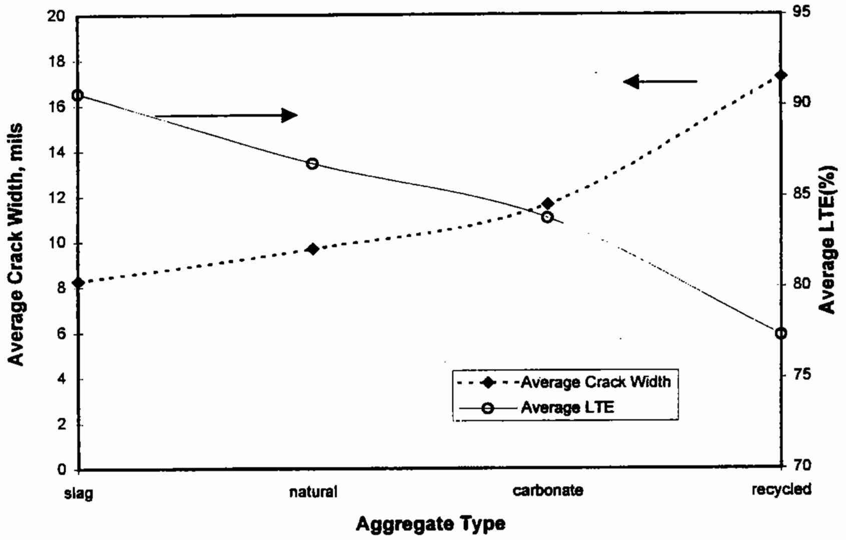


FIGURE 4 Effect of aggregate type on crack width and LTE

The fact that the slag pavements exhibited the highest LTE_δ's seems to be an anomaly since these aggregates are extremely porous and certainly a relatively weak aggregate type. What may be happening in this case is that the cracks found in these pavements may be shrinkage cracks with fairly tight crack widths. The slag pavements studied here are also significantly younger pavements (average age of the slag pavements is 6.7 years), in general, than the other pavement types. Thus, these cracks may not have been subjected to as much traffic and the crack widths have not yet been forced open. Since the crack widths are tight, the load transfer efficiency across these cracks is relatively high.

A similar field study was conducted by Wade et al. in which the investigators surveyed the performance of nine in-service concrete projects, representing a total of 16 pavement sections. The primary objective of this study was to document the performance of recycled aggregate pavements. Six out of the nine projects consisted of "control sections" that were constructed out of virgin aggregate materials and served as a basis for comparison. Some important conclusions from this study are summarized below:

- It is believed that recycled aggregate concrete is less resistant to abrasion than conventional concrete due to a reduction in the natural aggregate content. The Connecticut recycled concrete sections exhibited an average crack load transfer efficiency of 76% (range 29–100%). The average crack load transfer efficiency for the control section was 84% (range 65–94%). It was also concluded that the average load transfer efficiencies for any given crack severity level were higher for the control section than for the recycled section.
- In general, the Kansas recycled concrete pavement sections exhibited lower load transfer efficiencies and greater potential for loss of support than the control section. The VSTR tests of joint faces contained within cores found greater surface texture in the control section. Similar VSTR quantities were obtained from cores from the Wyoming test sections.
- The VSTRs across cracks for the Connecticut sections were slightly higher for the control section. This is consistent with higher load transfer efficiencies and will probably provide good aggregate interlock when the cracks are tight.

- In the Minnesota section MN4 88% (medium to high severity) of the recycled concrete panels exhibited transverse cracking whereas only 22% of the control section panels were cracked.

More detailed information can be found in Wade et al. (1997). It is clearly evident that the findings of this national study are in agreement with the author's findings.

CONCLUSIONS

Based on the data and analysis of the data the following conclusions can be made:

- Pavements containing slag or recycled concrete coarse aggregates demonstrated a larger number of transverse cracks per slab than those using natural gravel or carbonate aggregates. A greater susceptibility to shrinkage cracking for slag and recycled pavements, when proper curing considerations are neglected, was cited as a possible reason for this.
- Very reasonable results were obtained from the VST testing, as good agreement was found between visual assessments of surface texture and values for the surface texture indicator in this procedure. Results from this testing also agreed with the intuitively reasonable notion that cracks propagating around aggregates lead to a rougher surface texture than cracks propagating through aggregates.
- VST test results revealed a smooth crack face surface texture for carbonate and slag specimens, whereas natural gravel specimens had a rough texture. Recycled specimens demonstrated a range of textures. Greater surface texture corresponds to better aggregate interlock load transfer potential; these test results can be used to make inferences regarding the crack performance potential of pavements with the four noted aggregate types. Based on the test results, natural gravel pavements should show the best crack performance, while slag and carbonate pavements should demonstrate relatively poor crack performance.

References

Benkelman, A.C. (1933) Tests of aggregate interlock at joints and cracks. *Engineering News-Record*, 111 (8), Aug. 24, pp. 227–232.

Ioannides, A.M. and Korovesis G.T. (1990) Aggregate interlock: a pure-shear load transfer mechanism. *Transportation Research Record 1286*, TRB, National Research Council, Washington, D.C. pp. 14–24.

Laible, J.P., White, R.N. and Gergely, P. (1977) Experimental investigation of seismic shear transfer across cracks in concrete nuclear containment vessels. *Reinforced Concrete Structures in Seismic Zones.* ACI Special Publication SP 53–9. ACI. Detroit, MI, pp. 203–226.

Millard, S.G. and Johnson, R.P. (1984) Shear transfer across cracks in reinforced concrete due to aggregate interlock and to dowel action. *Magazine of Concrete Research*, 36 (126), Mar. pp. 9–21.

Paulay, T. and Loeber P.J. (1974) Shear transfer by aggregate interlock. *Shear in Reinforced Concrete*. ACI Special Publication SP 42–1, Vol. 1. American Concrete Institute (ACI), Detroit, MI, pp. 1–15.

Raja, Z.I. and Snyder, M.B. (1991) Factors affecting deterioration of transverse cracks in jointed reinforced concrete pavements. *Transportation Research Record 1307*, TRB, National Research Council, Washington, D.C., pp. 162–168.

Vandenbossche, J.M. and Snyder, M.B. (1996) Estimating potential aggregate interlock load transfer based upon measurements of volumetric surface texture of the fracture plane. *A paper prepared for the Open Paper Session of ACI Annual Meeting*, Denver, CO, March.

Wade, M.J., Cuttell, G.D., Vandenbossche, J.M., Yu, H.T., Smith, K.D. and Snyder, M.B. (1997) Wade, M.J., *Performance of Concrete Pavements Containing Recycled Concrete Aggregate*. Report FHWA-RD-96-164. FHWA, U.S. Department of Transportation.

Walraven, J.C. (1981) Fundamental analysis of aggregate interlock. *Journal of the Structural Division, ASCE*, 107 (1), Nov. pp. 2245–2270.