Estimating Potential Aggregate Interlock Load Transfer Based on Measurements of Volumetric Surface Texture of Fracture Plane

JULIE M. VANDENBOSSCHE

The volumetric surface texture (VST) test was developed at the University of Minnesota to provide an estimate of the load transfer potential available through aggregate interlock across a concrete fracture plane. It can also provide an estimate of the abrasion that has taken place since fracture. A study was undertaken to validate the VST concept and test procedures. The factors investigated in this study include the effects of aggregate characteristics on measured surface texture and the effects of measured surface texture on crack and undoweled joint performance, as indicated by deflection-based load transfer efficiency. Deflection, load, and crack width data were collected for both field and laboratory slabs, and VST testing was performed with companion specimens for these slabs. This study has shown that the VST test provides a means of accurately measuring surface texture so that the selection of concrete aggregates can be performed with consideration of potential aggregate interlock at cracks and undoweled joints. Performance prediction equations were developed to provide an early indication of how cracks and undoweled joints will perform before a particular aggregate size, type, gradation, or blend is used in an actual pavement.

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VOLUMETRIC SURFACE TEXTURE TEST

The test apparatus consists of a spring-loaded probe with a digital readout that is mounted on a frame over a computer-controlled microscope stage of the type typically used to obtain linear traverse and other measurements of concrete air void systems (Figure 1). The probe measures the distance from an arbitrarily established datum to the fractured surface at any chosen point. These distances are recorded electronically for each point in a predetermined grid pattern to map the three-dimensional fractured surface. A 3.18-mm (0.125-in.) grid was established by determining how far apart readings could be measured while still maintaining a precision of ±0.0001 cm^3/cm^2 over a specified area, regardless of the positioning of the grid. The average measurement area in this study was about 161 cm^2 (25 $in.^2$) per specimen.

After the VST testing is completed, the surface texture is quantified in terms of a VST ratio (VSTR), which is defined as the ratio of the volume of texture per unit surface area (in cubic centimeters per square centimeter). To calculate VSTR, the distances d_i (such that i represents the individual square being measured from the predetermined grid) measured from the datum to the fractured surface are averaged (d_{ave}) (Figure 2). The difference between the average distance and each individual distance ($r_i = d_i - d_{\text{ave}}$) is calculated and is then multiplied by the area of the individual square (A). The resulting volume for each individual square ($V_i = r_i A$) represents the volume of solid material above (if the volume is positive) or the volume of the void below (if the volume is negative) the plane established by the average distance (d_{ave}). The sum of the absolute values of the volumes yields the total volume of solid material above the average distance plane plus the volume of voids below the plane (*vst*, where $vst = \Sigma\, \text{abs}[r_i A]$). This summation represents the total volume of surface texture. Dividing *vst* by the test area produces VSTR. This normalization allows comparisons to be made between *vst* values when the size of the total area tested varies between specimens.

Comparisons between potential aggregate interlock for various crack and undoweled joint faces can be made by multiplying VSTR by the "effective" pavement thickness. The effective pavement thickness refers to only that portion of the fractured slab face that contains crack texture. For instance, the effective pavement thickness is reduced at joints because the texture provided by the propagation of the crack starts at the bottom of the saw cut. The effective slab thickness is also reduced when the top or bottom of the slab, or both, is spalled. VSTR multiplied by the effective slab thickness is referred to as VST, and it represents the volume of surface texture per unit width of the cracked slab face.

VALIDATION OF VST TEST

A study was undertaken to validate the VSTR concept and test procedures. The factors investigated in this study include the effects of aggregate characteristics on measured surface texture and the effects of measured surface texture on crack and undoweled joint performance, as indicated by deflection-based load transfer efficiency.

Data Sources

VST testing has been performed on both field and laboratory specimens. The laboratory study included tests performed on the fractured surfaces of flexural beam specimens broken after 18 h, 7 days, and 28 days of curing. The beams were companion specimens cast in conjunction with full-scale concrete pavement test slabs. These slabs were cracked 18 h after casting and were then subjected to simulated vehicle loads after 28 days of curing. Deflection, load, and crack width data were collected for each slab (*1*).

Office of Materials and Road Research, Minnesota Department of Transportation, 1400 Gervais Avenue, Maplewood, MN 55109.

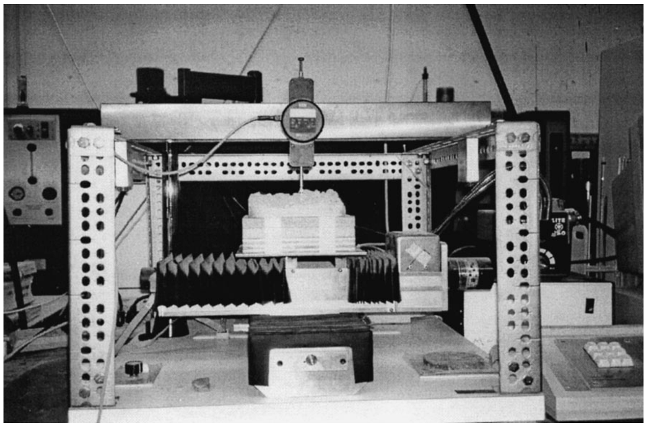


FIGURE 1 VST measuring device.

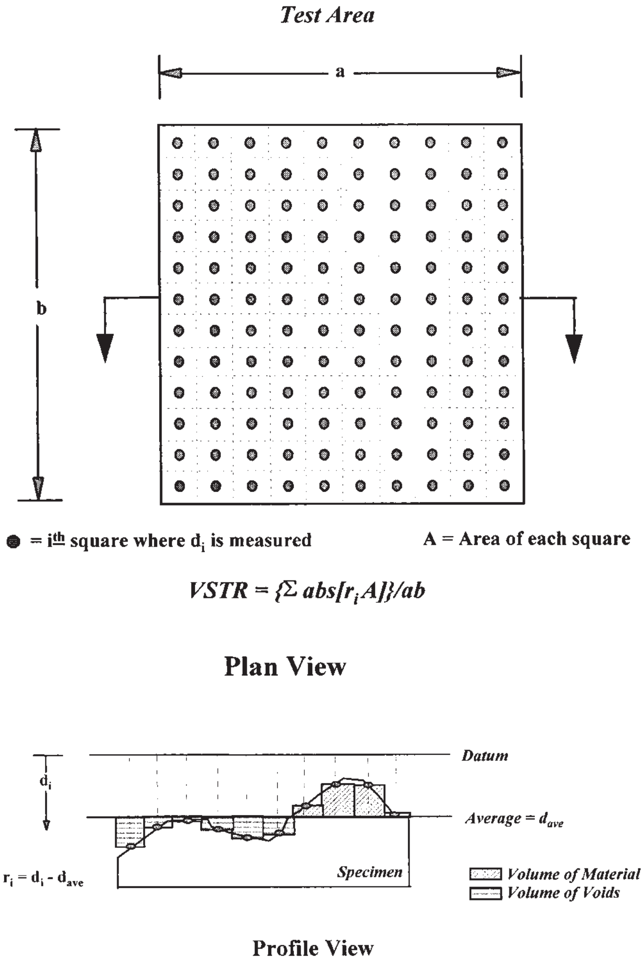


FIGURE 2 Pictorial representation of VSTR measurements and calculations.

VST testing was also performed with cores retrieved from the cracks and undoweled joints of several concrete pavements located in various parts of the nation. Joint and crack load transfer measurements were obtained for each pavement section by using a falling weight deflectometer at the time that the cores were retrieved. Thus, the VSTR results obtained represent the crack or joint surface texture present when the load transfer efficiency was measured. The VSTRs of the laboratory flexural test beams represent the surface textures that were present along the induced cracks before the slabs were loaded and any abrasion took place at the fractured plane (*2*).

Aggregate Characteristics

The first parameters examined were the effects of aggregate size, type, blend, and content on measured surface texture. As expected, both the laboratory and field data indicated a significant increase in VSTR when aggregate top size was increased. Figures 3 and 4 show increases in VSTR with increasing aggregate top size for angular aggregate.

Aggregate type also proved to have a significant effect on VSTR when other factors (e.g., top size) and mix proportions were held constant. Figure 5 shows that the stronger, more angular aggregates, such as a durable limestone, tended to produce higher VSTRs than weaker aggregates, such as slag. This is because the crack will tend to propagate through the weaker aggregate particles and around the stronger aggregate particles. The weaker aggregates also tend to abrade more easily under repeated joint and crack movements.

Concrete prepared with virgin aggregates consistently exhibited higher VSTRs than the recycled aggregate counterparts in both the field and laboratory studies, as shown in Figure 6. It is also worth noting that the angular recycled limestone aggregates typically exhibited higher VSTRs than the recycled round gravel aggregates. The lower VSTR for recycled aggregates can be attributed to the reduction of natural aggregate particles at the crack face, since the total volume of recycled concrete aggregate includes natural aggregate particles and reclaimed mortar. It was found that the characteristics of recycled aggregate concrete can be comparable to that of conventional concrete if the old mortar content of the recycled aggregate is low, thereby resulting in approximately equal virgin aggregate contents. This

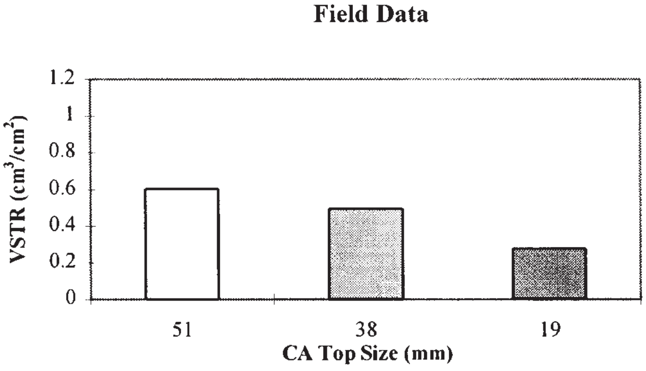


FIGURE 3 Effect of coarse aggregate (CA) top size on VSTR for cores retrieved from dowelled joints. The graph is based on VSTR measurements made with cores from 16 different dowelled joints.

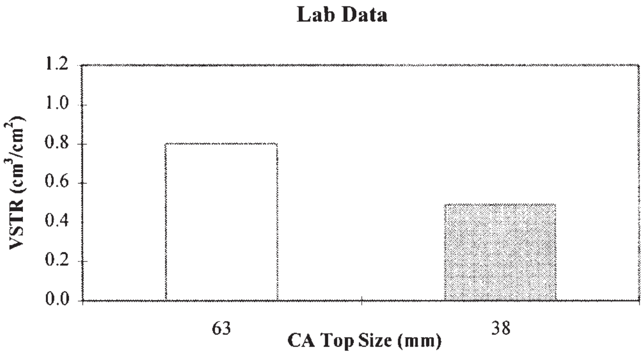


FIGURE 4 Effect of coarse aggregate (CA) top size on VSTR for laboratory specimens. The graph is based on six VSTR measurements (limestone aggregates only).

emphasizes the importance of choosing a crusher with care, because the quantity of old mortar clinging to the aggregate particles depends, in part, on the crushing process used.

Figure 7 shows the test results for one control section that contained 79 percent (by volume) more aggregate particles than its corresponding recycled concrete aggregate section. This resulted in a 40 percent reduction in the VSTR for the recycled section. Care should also be taken not to inadvertently reduce the particle size of the recycled aggregate because, as previously stated, VSTR decreases with decreasing particle size.

The laboratory study was expanded to determine whether the measured surface textures of slabs that contained recycled concrete aggregate could be increased by blending the recycled aggregate with virgin aggregates (Figure 8). The blending did prove to be beneficial as long as the number of virgin aggregate particles present at the crack surface was sufficiently increased. Blending with angular aggregates provided additional increases in surface texture.

The relationship between crack age and surface texture was also examined, as shown in Figure 9. As expected, crack face textures generally decreased with increasing crack age. The rate of deterioration was found to be higher for the sections containing recycled concrete aggregate because, presumably, they have higher mortar contents and the mortar abrades more quickly than rock under the action of passing wheel loads.

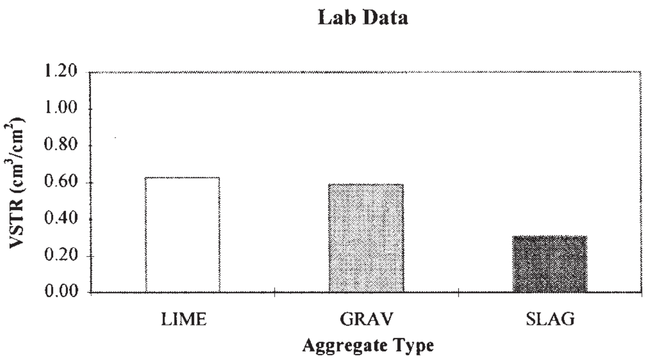


FIGURE 5 Effect of coarse aggregate type on VSTR for laboratory specimens. The graph is based on eight VSTR measurements.

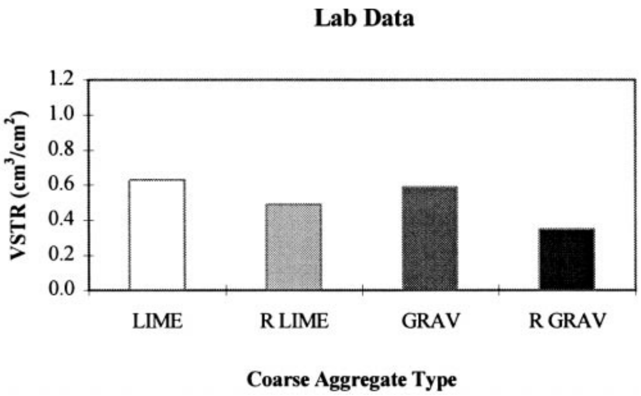


FIGURE 6 VSTR measurements for recycled and virgin coarse aggregate laboratory specimens. The graph is based on eight VSTR measurements (top size, 40 mm).

Performance

Once it was established that the volumetric surface texture method was a viable means of measuring and quantifying surface texture, both the field and laboratory data were used to correlate VST with performance, as measured by deflection-based load transfer efficiency. Load transfer efficiencies were calculated by the following equation.

$$\mathrm{LTE} = \frac{\delta_{\mathrm{unl}}}{\delta_l} \times 100\,\%$$

where

LTE = deflection load transfer efficiency (in percent),
δ_{unl} = deflection measured on unloaded side of joint or crack, and
δ_l = deflection measured on loaded side of joint or crack.

It was determined that VSTR measured for the 28-day flexural beam breaks is most effective in predicting crack performance. Load transfer efficiency is also highly dependent on crack width because increases in crack width decrease the effectiveness of surface texture. Therefore, VST was divided by its corresponding crack width for use as the independent variable in a least-squares regression analysis of load transfer efficiency [versus log-(VST/crack width)].

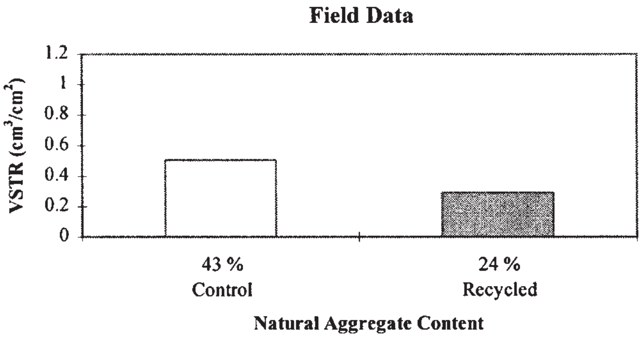
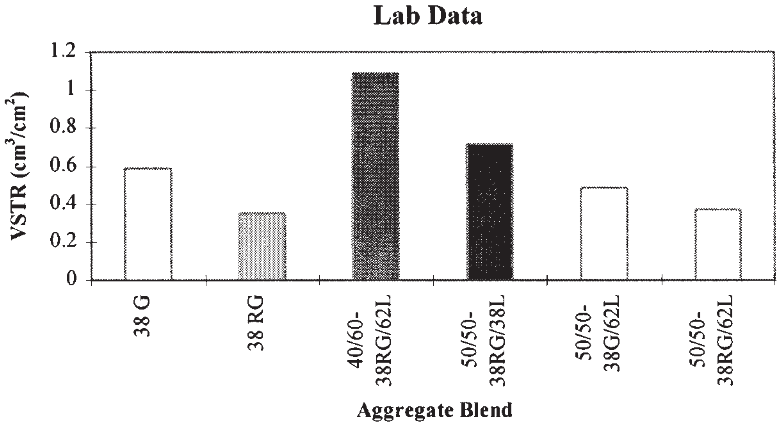


FIGURE 7 Effect of natural aggregate content on VSTR (doweled joints). The graph is based on four VSTR measurements.



38G: 100% Gravel with 38 mm top size.
38RG: 100% Recycled gravel with 38 mm top size.
40/60-38RG/62L: 40% Rec. gravel with 38 mm top size and 60% limestone with 62 mm top size.
50/50-38RG/38L: 50% Rec. gravel with 38 mm top size and 50 percent limestone with 38 mm top size.
50/50-38G/62L: 50% Gravel with 38 mm top size and 50% limestone with 62 mm top size.
50/50-38RG/62L: 50% Rec. gravel with 38 mm top size and 50% limestone with 62 mm top size.

FIGURE 8 VSTR measurements for various aggregate blends.

This analysis shows a high degree of correlation between the surface texture parameter and load transfer efficiency for the accelerated load testing data collected at "failure." Failure was assumed to have occurred when the transverse temperature steel ruptured. The data shown in Figure 10 represent only those for specimens tested when all parameters except aggregate type are constant (i.e., longitudinal steel content, subbase support, environmental conditions, etc.).

Therefore, the resulting performance prediction equation for the laboratory data is as follows:

$$\text{LTE}\,\% = 40\log\left(\frac{\text{VST}}{\text{cw}}\right) + 6$$

where

LTE% = deflection load transfer efficiency (in percent) from full-scale test,
VST = volumetric surface texture (in cm^3/cm^2), and
cw = crack width (in cm).

This equation can be used to predict load transfer efficiency on the basis of VSTR measurements made with flexural specimens broken after 28 days of curing, an estimated or calculated crack width, and the expected slab thickness. The equation could be used to select concrete aggregates on the basis of performance requirements.

The same type of analysis was performed with data obtained from field cores, deflection test results from the slabs before coring, and crack widths calculated on the basis of subgrade drag theory. The results of the least-squares regression analysis are shown in Figure 11. An acceptable coefficient of determination was obtained for the field data ($R^2 = 0.67$), although it is not as high as that obtained for the laboratory data ($R^2 = 0.95$). Part of the decrease in R^2 can be attributed to the fact that the VSTR measure for the field study represents the surface texture present when the load transfer efficiency was measured, whereas VSTRs values for laboratory study represent the surface texture before the specimens were loaded. In addition, the field data were collected from various pavements across the nation, so the effects of other factors that influence load transfer efficiency, such as subbase support, longitudinal reinforcement, and the assumptions made when calculating the crack width, are not considered. The same type of analysis was performed with data obtained

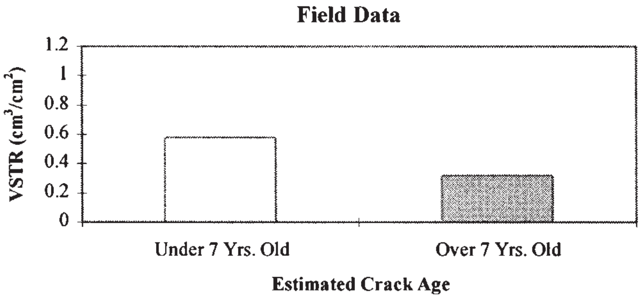


FIGURE 9 Effect of crack age (abrasion effects) on VSTR. The graph is based on five VSTR measurements made with cores retrieved from cracks in a recycled pavement.

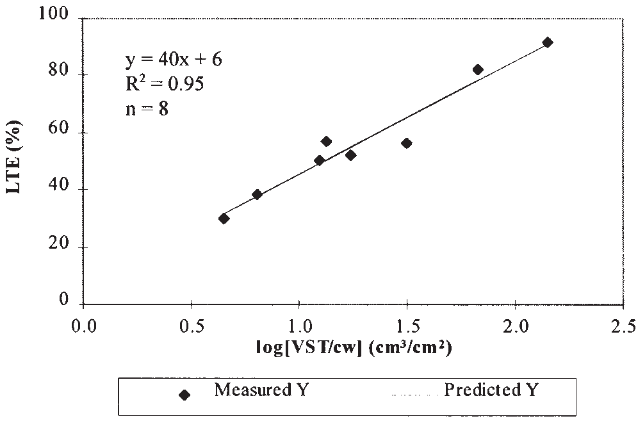


FIGURE 10 Least-squares regression model of load transfer efficiency based on laboratory data.

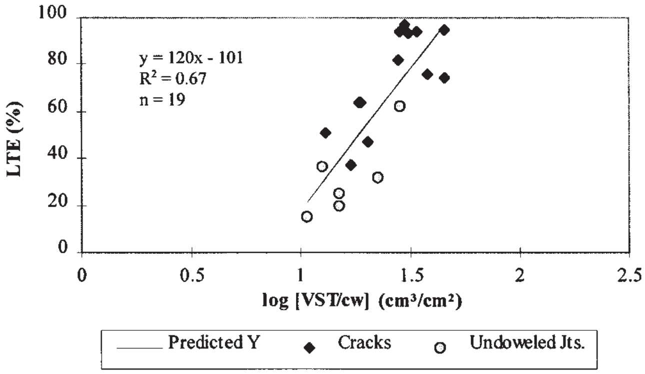


FIGURE 11 Least-squares regression model of load transfer efficiency based on field data.

from field cores, deflection test results from the cored panels, and crack widths calculated on the basis of subgrade drag theory.

The resulting performance prediction equation for the field data is as follows:

$$\text{LTE}\,\% = 120 \log\left(\frac{\text{VST}}{\text{cw}}\right) + 101$$

where

LTE% = deflection load transfer efficiency (in percent) from falling weight deflectometer testing,
VST = volumetric surface texture (in cm^3/cm^2), and
cw = crack width (in cm).

This equation can be used to predict the expected load transfer efficiency for a pavement on the basis of an estimated or measured VSTR, crack width, and slab thickness.

This technique is useful as a tool for estimating the potential load transfer efficiency performance of a specific aggregate type or mix. To do this, the design engineer would start with the lowest acceptable load transfer efficiency and use the above equation to determine the VST required to obtain that level of LTE for a crack or undoweled joint. This VST would then be used to establish the number of loads to failure for that particular aggregate blend by using a relationship between the loss of VST and the number of applied vehicle loads.

CONCLUSIONS

The importance of crack or joint face surface texture or grain interlock on crack and undoweled joint performance has been known for many years but has not been well quantified. This paper describes a method that can be used to measure surface texture and confirm past beliefs by using quantitative measurements. This method was used to show that aggregate top size significantly affects surface texture (an increase in aggregate top size from 38 to 63 mm increased the VSTR by 66 percent). The use of stronger aggregates also produces greater surface texture since cracks tend to propagate around (instead of through) the stronger aggregate particles. Stronger aggregates are also less likely to abrade under repeated joint and crack movements.

Recycled concrete aggregates typically produce lower VSTRs and abrade more quickly than their natural counterparts. The grain interlock associated with the use of recycled aggregates can be improved by reducing the amount of old mortar clinging to the aggregate particles so that the total mortar-to-aggregate ratio is not significantly increased and by ensuring that the top size of the aggregate is not inadvertently reduced. It was also shown that the blending of larger, stronger, more angular aggregate with other more poorly performing aggregate, such as recycled concrete or slag, can improve surface texture.

This study has demonstrated that the VST test provides a means of accurately measuring surface texture so that the selection of concrete aggregates can be performed with consideration of potential grain interlock at cracks and undoweled joints. The volumetric surface texture test also provides the engineer with an early indication of how cracks and undoweled joints will perform once a particular aggregate size, type, gradation, or blend has been used to construct a pavement.

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