Load-Associated Crack Movement Mechanisms in Roads

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The increasing use of modified binders to inhibit reflection cracking, and the fact that these materials are sometimes unsuccessful, highlights the need to investigate the mechanisms of load-associated crack movement and crack reflection. The Crack-activity Meter (CAM), developed to measure load-associated crack movement, is discussed in this paper. Heavy Vehicle Simulator (HVS) tests, incorporating crack-movement measurements are discussed, as well as various types of crack-movement behavior. Four typical mechanisms of crack and joint movement are identified and discussed. This work has led to an improved understanding of the mechanisms of crack movement and crack reflection and to a procedure, based on the measurement of crack movement, that can be used to aid rehabilitation design.

The reflection of primary cracks through overlays and seals on roads is recognized as a serious problem. The ingress of rainwater through such surface cracks can cause pumping, leading to forms of distress such as pot-holing and/or deformation. This can, in turn, lead to the premature failure of an otherwise sound pavement.

Asphaltic overlays are often used to rehabilitate both flexible and rigid pavements. However, such efforts can be invalidated by the reflection of cracks through overlays and seals. Special or innovative materials such as bitumen-rubber, geofabrics and low-viscosity asphalt have been used in attempts to solve this problem with varying degrees of success (*1*). This emphasizes the fact that the mechanisms of crack movement and crack reflection are not yet fully understood.

Cracks in a pavement can reflect due to thermal effects, as well as wheel load effects. Extensive investigation has been done regarding crack reflection due to thermal effects on concrete pavements. In South Africa there are relatively few concrete pavements, and the thermal changes are not as severe as in some countries. Furthermore, many pavements contain cemented bases where thermal movements are relatively low and, therefore, wheel load-associated crack reflection is of more importance.

In order to investigate and measure load-associated crack movement in the field a new instrument, the Crack-activity Meter (CAM), was developed (2). The CAM has been used extensively with the Heavy Vehicle Simulator (HVS) during the accelerated testing of various types of pavements. The measurement of crack movement and changes in crack movement with pavement deterioration has led to the identification of four typical mechanisms of crack and joint movement. Crack-movement measurements and the analysis of crack-movement mechanisms has led to better understanding of how and why cracks move under heavy wheel loads. This improved understanding has laid the foundation for more meaningful research into the problems of and possible solutions to crack reflection.

THE CRACK-ACTIVITY METER (CAM)

The Crack-activity Meter (CAM) can measure both relative vertical and horizontal crack movement simultaneously. Figure 1 shows a schematic diagram of the CAM. Data are recorded continuously as a wheel approaches the point of measurement and passes over it. A plot of crack movement versus the distance of the wheel from the measuring point is, therefore, the influence line of crack movement.

The CAM was specifically designed to measure the relative crack movements directly and with reasonable accuracy. The CAM has the following features:

- Its reference point is as close as possible to the point of measurement. This minimizes the risk of errors resulting from calculating crack movement from two deflection measurements (*1*).
- It is small enough to fit between the dual wheels of the HVS or a truck. Measurements can therefore be taken between the tires of a dual wheel where the maximum crack movement and surface deflection occur.
- The contact area between the CAM and the road surface is as small as possible; this minimizes errors caused by the possible tilting of its frame.
- The effect of the curvature of the road surface on the accuracy of measurements is minimal. The ratio between the distance above the road surface where crack movement is measured (10 mm) and the radius of curvature (say 100 m) is so small that its influence can be ignored.
- The data are recorded on a microcomputer, thus simplifying data validation and processing, and allowing the recording of total influence lines of data rather than only peak values.

The CAM can be used to measure crack movements on a pavement at different stages during its structural life. Typical influence lines of crack movement recorded on a cemented base pavement are shown in figure 2; the structure of this pavement is shown in figure 3. These influence lines show that, on this pavement, a crack goes through an opening-closing-opening cycle for one pass of a wheel. It is interesting

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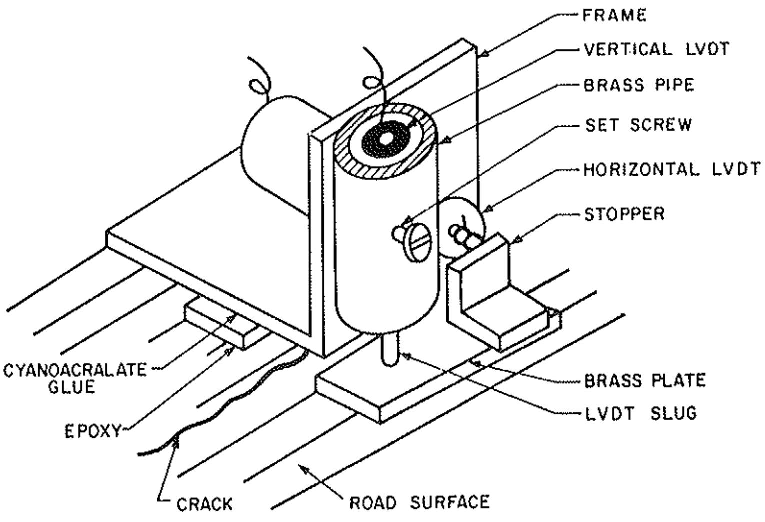


FIGURE 1 **The crack-activity meter (CAM).**

to note that, on this pavement, the horizontal load-associated crack movement was much larger than the vertical crack movement. This contradicts previous assumptions that horizontal crack movement is mainly due to thermal effects and that wheel loads cause only vertical movement.

Naturally, the crack movements can change if the factors influencing them change. Changes in crack movement are brought about artificially during HVS testing when accelerated trafficking causes changes in parameters such as the shape of the deflection basin or the size of the blocks defined by the cracks. The peak crack movements recorded at various stages of an HVS test can be plotted against trafficking to produce a crack movement behavior curve (see figure 4). The CAM can thus be used in conjunction with the HVS to determine how the crack movement will change as a pavement deteriorates.

CRACK MOVEMENT BEHAVIOR

The CAM has been used extensively to measure crack movements on various types of pavements as part of HVS test programs to investigate typical mechanisms of crack movement and the crack movement behavior of various types of pavements. These included a flexible pavement, a cracked Jointed Concrete Pavement (JCP) and rigid pavements (uncracked JCPs and Continuously Reinforced Concrete pavements). On the uncracked JCPs the movement of the joints was monitored to establish their mechanisms of failure. The crack movement behavior and their controlling mechanisms on these pavements are discussed below.

Crack Movement Behavior on a Flexible Pavement

The MR27 is a cemented base pavement near Cape Town; the structure of this pavement is shown in figure 3. At certain locations the pavement displayed severe signs of distress; this took the form of cracking (block sizes two to three meters), rutting and pumping from the cemented base.

In order to aid the rehabilitation design for this pavement an HVS test was conducted on a section in the fast lane of the pavement where the pavement structure was still in a reasonable state. Crack movements were measured at two points on the test section. Figure 4 shows the crack movement behavior recorded during the HVS test. The crack movement reached a maximum of 200 μm and then decreased again. Figure 5 shows the recorded surface deflections. The crack

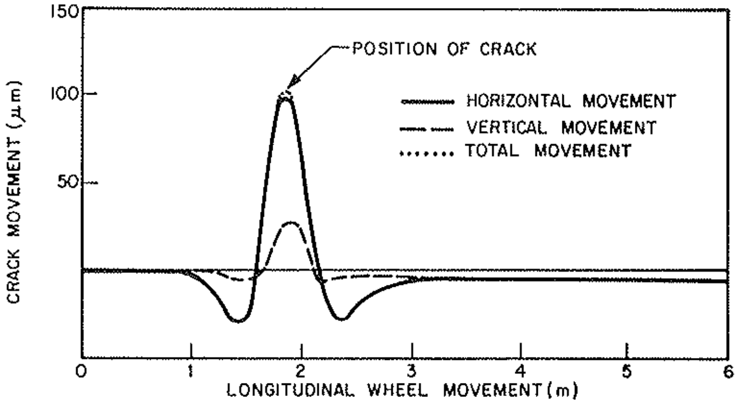
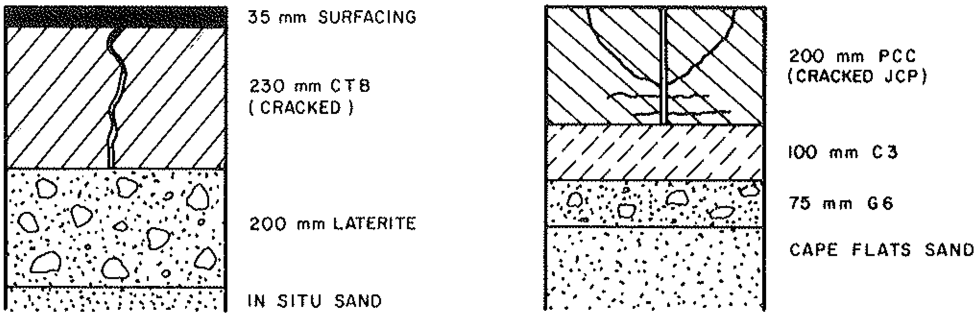
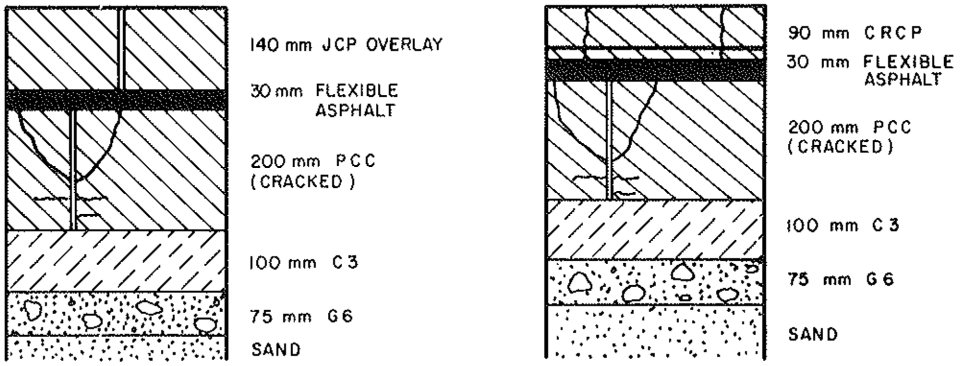


FIGURE 2 **Typical influence lines of crack movement obtained on the MR27.**



MR 27 - FLEXIBLE PAVEMENT

N2/1 - SEMI-RIGID PAVEMENT



N2/1 WITH JCP OVERLAY

N2/1 WITH CRCP OVERLAY

FIGURE 3 Structures of pavements on which crack movement behavior was determined.

movement as well as the surface deflection increased initially due to the ingress of rainwater. After the pavement dried the surface deflection decreased, as did the crack movement. A test pit opened on completion of the HVS test revealed that the blocks had not broken down further under HVS traffic. The crack movement behavior on this pavement section was therefore influenced by and correlated reasonably well with surface deflection.

Crack Movement Behavior on a Semi-Rigid Pavement

The N2 between Cape Town and Somerset West is a jointed concrete pavement (JCP); it shows unusual distress in the vicinity of the joints. Alkali-aggregate reaction in this pavement initiated cracking which, under the action of traffic loading, cyclic temperature, and moisture changes, led to structural distress such as progressive spalling. The size of the blocks defined by the cracks ranged from 350 mm to 450 mm in the vicinity of the joints. The frequency of the cracking was such that, for the purpose of analyzing crack movements, the pavement could no longer be regarded as a rigid pavement but rather as a semi-rigid pavement. The HVS was used to test several experimental overlays placed on this pavement. These included the use of bitumen-rubber modified asphalts, geofabric interlayers, a bitumen-rubber interlayer with a gap-graded asphalt overlay, granular layers, and concrete overlays. Viljoen et al. (*3*) discussed the behavior of a number of these overlays under HVS traffic.

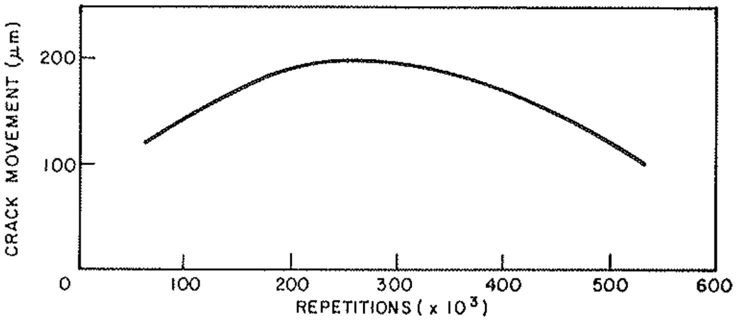


FIGURE 4 Crack movement behavior on the MR27 at measuring point 6.

As part of the above work, crack movements were measured in order to investigate the ability of the bitumen-rubber modified asphalt overlay to retard reflection cracking on cracks with a known activity. These measurements were taken on cracks in the vicinity of two joints in the pavement (joint 131 and joint 132). Joint condition ratings determined before the pavement was overlaid (*4*) indicated that joint 131 was in a more deteriorated state than joint 132. Figure 6 shows the crack movement behavior. At joint 132 the crack movement increased markedly to a maximum of approximately 600 μm as the test progressed and the blocks between the cracks broke down to a critical block size. Further block breakdown led to

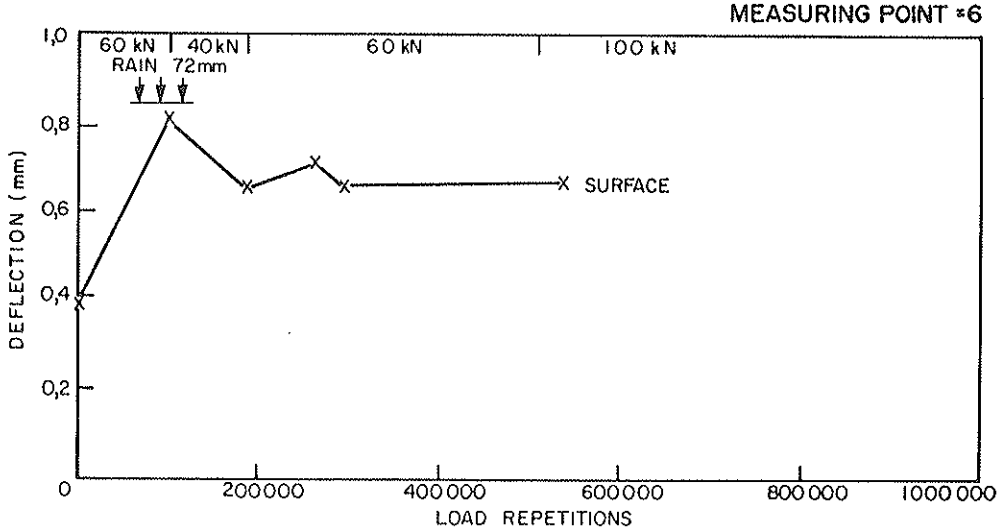


FIGURE 5 Average surface deflection on the MR27 at measuring point 6 under a 40-kN wheel load.

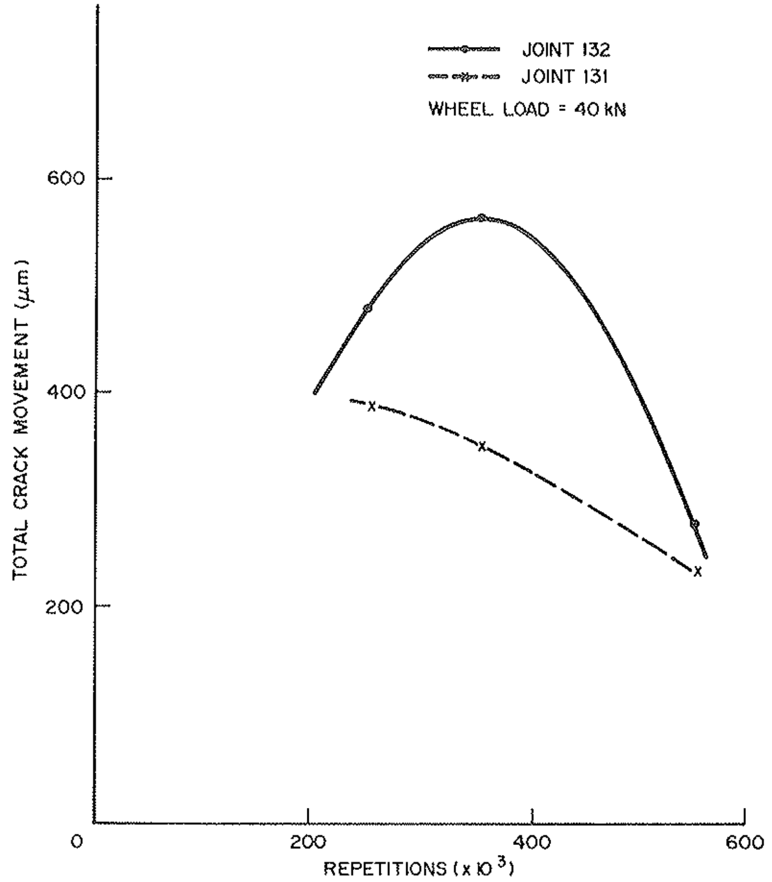


FIGURE 6 Crack movement behavior of cracks in the vicinity of two joints in the cracked JCP—Section 1.

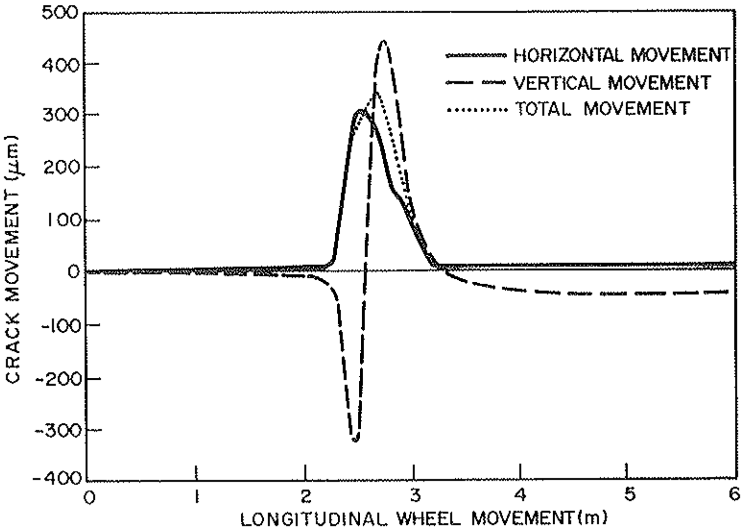


FIGURE 7 Typical influence lines of joint movement recorded on the thin JCP overlay—N2/1.

a decrease in crack movement. In the case of joint 131 the crack movement decreased from the beginning of the test. The difference in crack movement behavior between the two joints confirms their different states before commencement of the test.

A test pit opened at joint 132 after completion of the test showed signs of granulation of the top part of the concrete layer confirming that block breakdown had indeed taken place. Cracks that developed in the concrete after deterioration of the blocks did not reflect through the rubberized overlay, thus confirming that the crack movement had decreased after the blocks deteriorated.

Crack movement can be caused by the tilting or rocking of the blocks under a wheel load. High-crack movements were therefore still present in the case of this relatively stiff pavement with low deflections. The crack movement increased with block breakdown until the critical block size was reached. Further block breakdown led to a decrease in crack movement as the blocks became too small to tilt under the wheel. For this pavement, therefore, there was a clear correlation between block size and crack movement. Block size can therefore be very important if tilting is the major mechanism of crack movement.

Crack Movement Behavior on Rigid Pavements

The CAM was also used to measure the joint movement of rigid pavements to investigate their mechanisms of failure. This was especially successful on experimental JCP and continuously reinforced concrete pavement (CRCP) overlays placed on the cracked JCP discussed above. The crack movement behavior of these two pavement types, monitored during HVS testing, is discussed below.

A thin and a thick unbonded JCP overlay (115 mm and 145 mm respectively) were placed on the cracked JCP with an asphaltic bond-breaking layer separating them. Figure 3 shows the pavement structure after the placing of the new JCP. The thin JCP carried approximately 12 million equivalent axle loads (E80s) in the dry state before cracking. In the case of the thick JCP the pavement lasted approximately 30 million E80s before it started cracking. Crescent-shaped cracking appeared at distances of 600 mm to 700 mm away from the joint in the new JCP. Secondary cracking developed with further trafficking of the pavement. In the wet state the thin JCP (115 mm) started cracking after only 3 million E80s, and the thick JCP (145 mm) after only 7 million E80s. It is evident that the ingress of water into the pavement considerably shortened its life.

CAM measurements were taken on the joints of the new JCP during testing of the thin as well as the thick overlay. Figure 7 shows typical influence lines of joint movement. The high vertical movement (greater than the horizontal movement) is typical of an uncracked JCP—the slabs between the joints are too large to rock under the wheel load.

Figure 8 shows the joint movement behavior recorded during HVS testing of the thin JCP in the dry state. The vertical joint movement was, at first, relatively low but increased quickly to a level of approximately 200 μm after approximately 80,000 repetitions of a 100-kN dual wheel load. The crack movement remained constant at 200 μm up to approximately 320,000 repetitions. At this stage the JCP developed D-cracking about 600 mm away from the joint. Shortly after commencement of the test, a small void developed directly underneath the JCP in the vicinity of the joint; this explains the initial increase in joint movement. The high vertical movement caused tensile strains to develop at the surface of the slab. The joint movement then remained constant for a number of repetitions, while the slab was bending in a cantilever motion because of the loss of support. The concrete eventually fatigued and D-cracking developed at the position where the maximum bending moment (and tensile strain) occurred in the slab. After cracking, the joint movement increased markedly as the blocks between the cracks tilted or rocked under the wheel.

In the case of the wet test, the high vertical movement and the presence of water created an aggressive pumping action, which caused erosion of the asphaltic bond-breaking layer, leading to a larger void and a correspondingly higher vertical movement. The concrete was therefore subjected to much

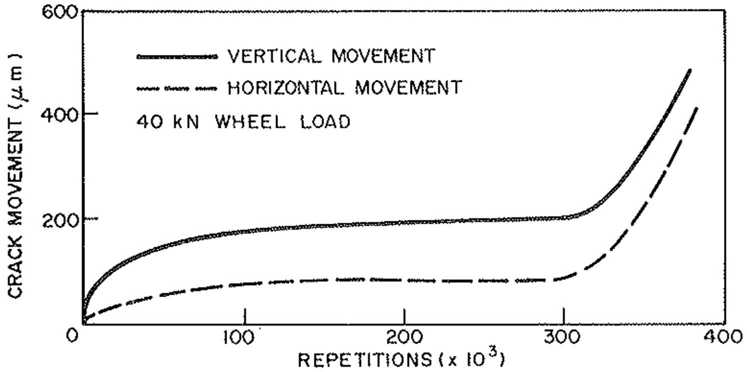


FIGURE 8 Joint movement behavior recorded during HVS testing of the thin JCP overlay in the dry state—N2/1.

higher levels of strain and lasted fewer repetitions. The thicker JCP (145 mm) lasted longer because of its greater strength when subjected to bending or cantilever action.

The CRCP experimental overlays on the cracked JCP consisted of 90 mm and 125 mm continuously reinforced concrete with 0.67 percent longitudinal reinforcement and a flexible asphalt levelling layer. The thin CRCP was tested both in the slow lane and on the shoulder. In the wheel path, the CRCP was well supported by the levelling layer and the cracked JCP. On the shoulder, the support consisted of a thin asphalt surfacing on top of a granular layer and Cape Flats sand. During HVS testing of both sections under dry as well as wet conditions the structure performed extremely well. In the wheel path, approximately 40 million equivalent standard axles (E80s) were applied with no apparent distress becoming visible. Figure 9 shows the crack movement behavior during HVS testing. The mechanism of crack movement on a CRCP is mainly that of a hinging action of the blocks (defined by the shrinkage cracks) on the reinforcement steel. This results in very low vertical and horizontal crack movements (generally below 30 μm). The aggressive pumping action, found under the JCP overlays, did not therefore develop in this case. The result is that the thin CRCP lasted much longer than even the thick JCP. Figure 10 shows a summary of the crack movement behavior curves obtained during HVS testing.

The load-associated joint movements on JCPs are also influenced by thermal change. Under a 40-kN wheel load the vertical joint movement of a JCP has decreased by 30 percent and increased by 47 percent during a 24-hr cycle of HVS testing.

CRACK MOVEMENT MECHANISMS

The crack movement measurements in conjunction with HVS testing indicate that cracks or joints on a pavement will move due to various mechanisms. Furthermore, there are various reasons for changes in crack movement. In particular, the following were noted:

- The cracks on a flexible pavement can move due to their position in the deflection basin.
- Crack movement on a flexible pavement can change due to a change in either the shape of the deflection basin or the block size.
- The cracks in a semi-rigid pavement can move due to the tilting of the blocks under a wheel load; this crack movement can change with the size of the blocks.
- On a rigid pavement (such as a JCP) the joints may move

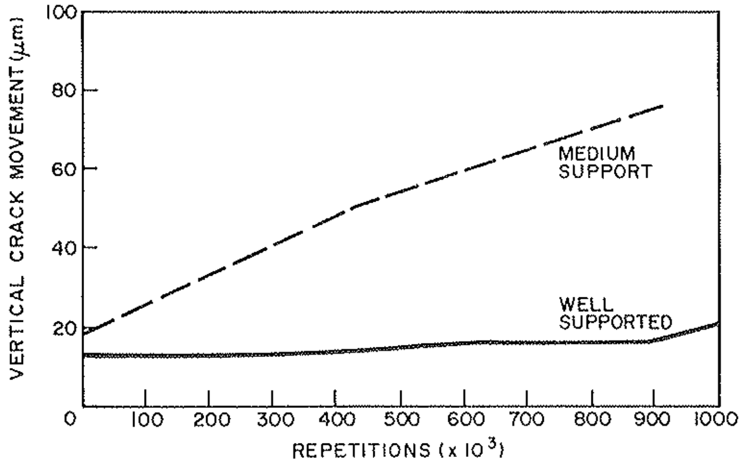


FIGURE 9 Crack movement behavior recorded on the thin CRCP overlay on the N2/1.

vertically due to a cantilever action of the slabs if a void is present under the slab.

- On a CRCP the cracks can move due to the hinging of the blocks on the reinforcement steel.

Four mechanisms of crack movement and changes in crack movement will be discussed below. The understanding of these mechanisms has been instrumental in the explanation of crack movement behavior on flexible pavements, as well as in the explanation of the mechanisms of failure on rigid pavements.

Crack Movement Resulting from the Shape of the Deflection Basin

The deflection basin of a flexible pavement under a heavy wheel load will normally be as shown in figure 11. The middle portion of the deflection basin will be concave and toward the end of the basin its shape at the surface will tend to be convex. A typical deflection basin on a flexible pavement will therefore have one concave portion and two convex portions. The magnitude of the peak deflection is indicative of the support conditions of the pavement, and the degree of curvature in the deflection basin is indicative of the state of the layers closer to the surface. Horak (*5*) has indicated that analysis of the deflection basin can be used to assess the state of the structural layers in a pavement. The above indicates that the shape of the deflection basin can change with the support conditions or with the state of the structural layers.

Figure 11 also shows that cracks on the surface of a pavement will be open or closed, depending on their position in the deflection basin. A particular crack will go through a cycle of opening-closing-opening for every wheel that passes over it. The magnitude of the peak crack movement will depend on the degree of curvature of the deflection basin as well as on the size of the blocks defined by the cracks. Figure 12

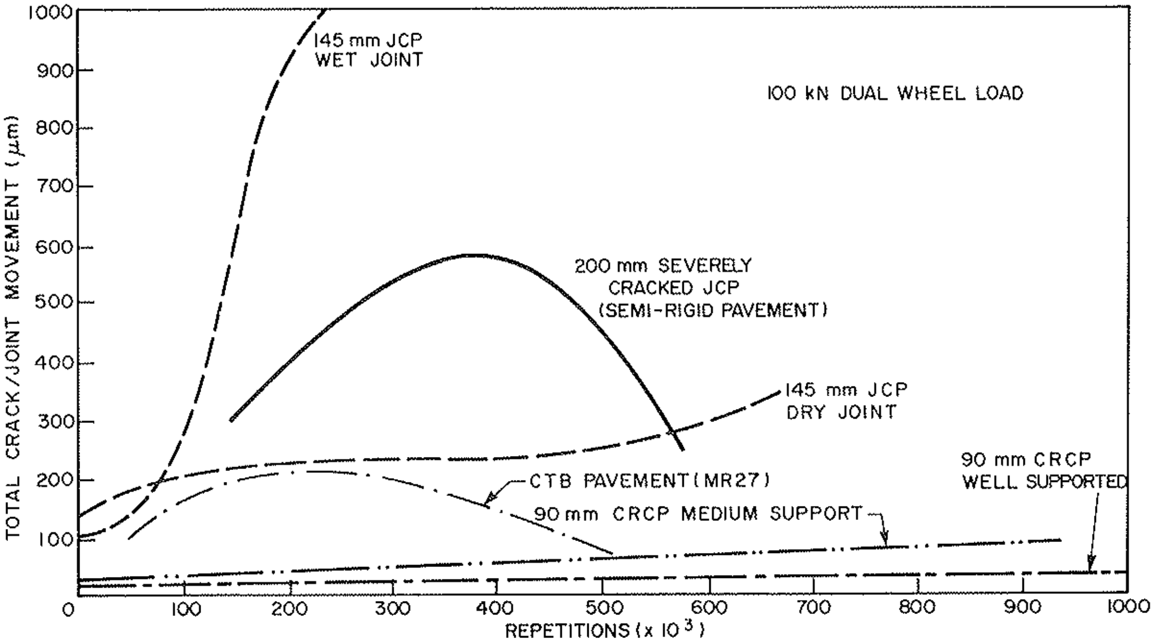


FIGURE 10 Crack movement behavior curves obtained during HVS testing.

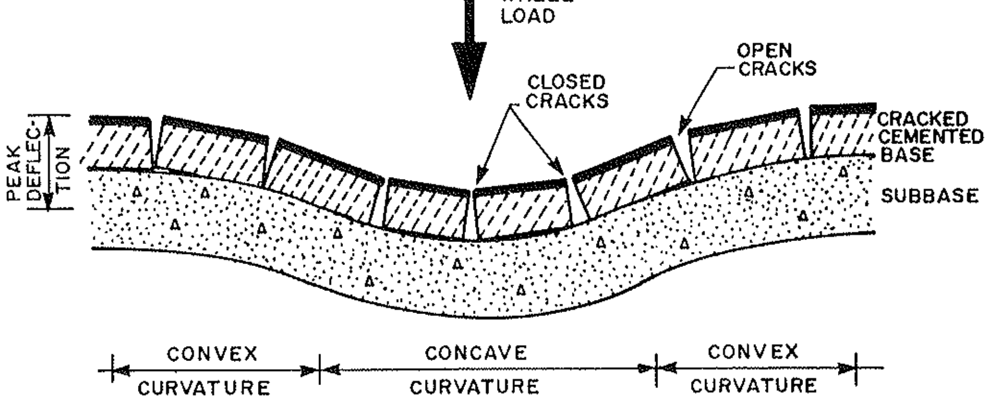


FIGURE 11 Typical deflection basin of a flexible pavement.

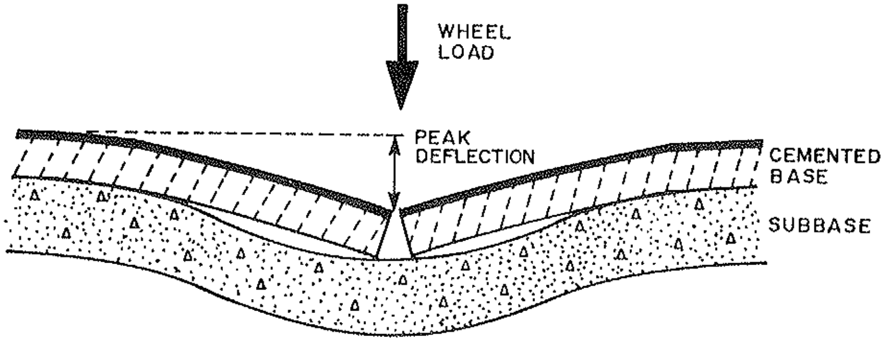


FIGURE 12 Large blocks in a typical deflection basin—crack movement due to downward deflection.

shows a large block in a typical deflection basin. If the blocks are very large, the crack movement will result from the cantilever action of these blocks under the wheel load. This implies that in the case of large blocks the magnitude of the peak crack movement will relate to the peak deflection. This fact was illustrated during the HVS test on the MR27 discussed above.

If the block sizes are in the order of 0.5 m to 1.0 m the cantilever action will be a minimum as the blocks are more rigid. In this case the shape of the deflection basin as well as the block size will influence the magnitude of crack movement. On the other hand, if the blocks are very small the crack movement will be very low (see figure 13). The above implies that the crack movement can change during flexible pavement life with changes in the deflection basin or the block size.

Crack Movement Resulting from the Tilting of the Blocks

The HVS test on the semi-rigid pavement discussed above showed that the crack movement can be significantly high even if the peak deflection recorded is relatively low. This fact indicates that crack movement can be caused by tilting or rocking of the blocks defined by the cracks under a heavy wheel load. Figure 14 illustrates this phenomenon. In this case the peak deflection and the shape of the deflection basin will have only a minor influence on the crack movement. If the blocks are very large they will not be tilted by the wheel load, and the cantilever action will cause only small crack movements. If the blocks are very small the wheel load will also not be able to tilt them. In the case of semi-rigid pavements, the crack movement will be mainly due to the tilting of the blocks and can change with the block size. However, the deflection basin, being relatively shallow, will have little influence on the crack movement.

The HVS test on the semi-rigid pavement illustrated the above. On this pavement the crack movement was initially in the order of 300 μm and the block size in the order of 300 mm to 400 mm. The breaking up of the blocks led to an increase in the crack movement to a maximum of approximately 600 μm with eventual decrease as the blocks became to small to be tilted under the wheel load.

Joint Movement due to Cantilever Action on Rigid Pavements

The CAM can also be used to measure the movement of the joints in JCPs. HVS testing of these pavements has shown that the vertical movement of the joint was generally larger than the horizontal movement. This is unusual and was caused by the existence of a small void under the slab in the vicinity of the joints. This void led to very high vertical movements generated by a cantilever action of the concrete slab. Figure 15 shows the cantilever action due to the loss of support under the slab.

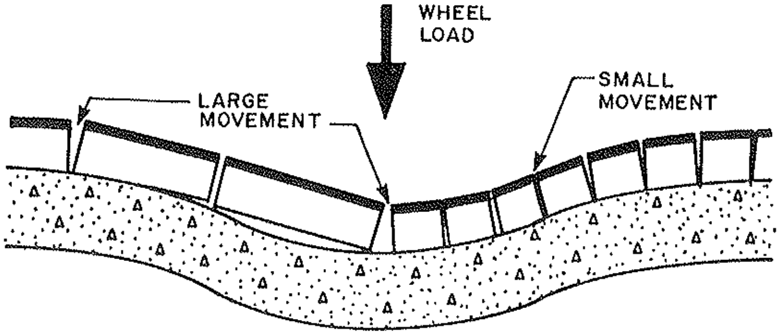


FIGURE 13 Crack movement related to the size of the blocks.

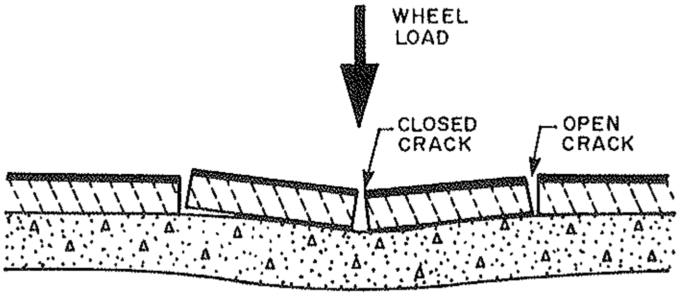


FIGURE 14 Crack movement due to the tilting of the blocks.

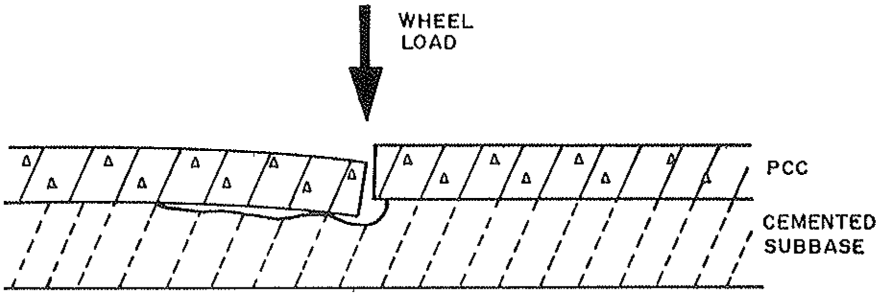


FIGURE 15 Movement of a joint in a JCP due to a void under the slab—cantilever action.

Crack Movement due to Hinging Action

On CRCPs the crack movement mechanism is mainly one of hinging of the blocks on the reinforcement. The reinforcement steel in the concrete prevents excessive vertical crack movement. The crack movements are therefore very low and the aggressive pumping action is absent. This mechanism is shown in figure 16.

CONCLUSIONS

The phenomenon of the reflection of primary cracks through overlays and seals is partly due to repetitive thermal and/or load-associated crack movement. The development of the Crack-activity Meter (CAM) provides a means of measuring load-associated crack movements accurately and effectively. The CAM has been used extensively in conjunction with Heavy Vehicle Simulator (HVS) testing.

The measuring and analysis of crack movements has led to a better understanding of the mechanisms of crack reflection. Four typical mechanisms of crack movement have been defined:

- Crack movement caused by the shape of the deflection basin,
- Crack movement caused by the tilting of blocks under a heavy wheel load,
- Joint movement on uncracked JCPs caused by the cantilever action of the slabs, and
- Crack movement on CRCPs caused by the hinging of the blocks on the reinforcement steel.

In the case of the deflection basin mechanism the crack movement during pavement life can change should the shape of the deflection basin or the block size change. In the case of the block-tilting mechanism the deflection basin has a minor influence on the magnitude of the crack movement. This mechanism is, however, influenced by a change in the block

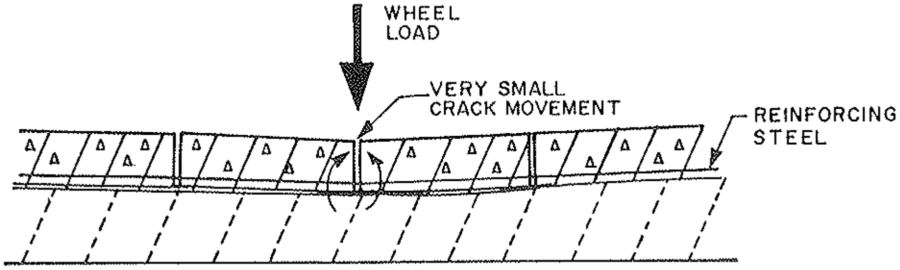


FIGURE 16 Crack movement on a CRCP—hinging of blocks on reinforcement steel.

size. On JCPs it was found that the vertical movement of joints can be very high due to cantilever action if a void is present directly under the slab. In the presence of water, this cantilever action can lead to a very aggressive pumping action, which aggravates the joint movement and leads to very rapid failure. On CRCPs the crack movements are generally low and therefore no pumping takes place.

The analysis of the mechanisms of crack movement has also led to an improved understanding of how and why cracks on pavements move. This work has not only led to an improved understanding of the mechanisms of load-associated crack and joint movement but has also laid the foundation for research which has led to a procedure, based on the measurement of crack movement, that can be used to aid the rehabilitation design of cracked pavements.

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