Using Initiators In Portland Cement Concrete Pavements To Propagate Transverse Joint Cracking

Malcolm Lim[1], David Gress[2] and Peter Foster[3]

Abstract

Past research on dowel bar placement has evaluated dowel bar misalignment relative to the saw cut at the top of the pavement. Determining misalignment measurements relative to the saw cut at the top of the pavement assumes that the crack propagates vertically downward immediately below the saw cut joint. This assumption is flawed although it is current practiced by the industry. Present detection methods cannot accurately determine the point at which the crack crosses the dowel bar. This study recognizes that there is not a technique to determine the path of the crack to measure the true misalignment but offers an alternative by dictating the crack path with cracking initiators attached to the dowel bars. Previous research has indicated that cracking initiators secured to the base of the pavement are ineffective or have little benefit due to the stress profile in the pavement slab. This study presents the results of work performed in dictating the path of a crack by attaching the crack initiator to the dowel bars. The results include utilizing different shape and size initiators. The work performed to date on crack initiation and the benefits attributed to utilization of crack initiator, including the ability to determine the true amount of misalignment are presented.

Research significance

It is often assumed that when the pavement joint develops, creating the transverse joint, the cracks forms vertically plumb from the bottom of the saw cuts to the sub base of the pavement, thereby cracking across the dowel bar immediately below the saw cut. Dowel bar alignment evaluations that have been performed determine the misalignment relative to the saw cut joint at the top surface of the pavement without regard to the orientation of the crack. Since the concrete pavement cracks when the concrete is relatively young in age, this early age cracking typically develop around the aggregate rather than through the aggregate, because of the weak concrete paste/aggregate bond present, thus making a vertically plumb crack virtually impossible. In addition, axial restraint stresses, due to the friction between the slab bottom and the subbase in combination with bending restraint stresses results in uneven stress development over the depth of the pavement. The development of stresses is not uniform throughout the depth of a pavement making it unlikely for a crack at the transverse joint to propagate vertically straight dowel from the top of the pavement to the subbase. Dowel bar alignment evaluations do not account for non-vertical crack propagation and typically assume vertical cracking, which is flawed.

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[1]Malcolm Lim, PE. Consultant, 109 Bernard Drive, Buffalo Grove, IL 60089, malcolm.lim.314@gmail.com

[2]Dr. David Gress, PhD, PE, University of New Hampshire, Department of Civil Engineering, Durham NH 03824, david.gress@unh.edu

[3]Peter Foster, Research Consultant, 1811-E W. Winnemac Ave., Chicago, IL 60640, pbfoster79@gmail.com

Many states have adopted either the early entry saw cutting technique or the conventional D/3 or D/4 saw cutting technique. In a recent study by the National Concrete Pavement Technology Center (Wang, et al 2009), it was noted that a large variation in joint cracking time for the early entry saw cut and a smaller variation in joint cracking time for the conventional saw cut. Currently, under certain unfavorable environmental conditions or a given mix placed on certain base materials, it is possible that not every joint cut instantly cracks or cracks at the same time. Joint cracking times can vary significantly depending on the saw cutting technique and the material and environmental conditions. When all joints do not crack at the same time, the cracks that do develop are unusually wide, similar to what can occur when skip sawing is used to control fast cracking pavements. These conditions result in joints being venerable to sealant distress.

Electromagnetic tomography, a nondestructive testing technique, is the preferred means of evaluating in-placed dowel basket alignment. The process consists of scanning a pavement, from the top, with specialized equipment called MIT Scan-2, referred to here as MIT. MIT has been shown to be very reliable and highly accurate on dowels inserted with dowel baskets (with cut tie wires) or Dowel Bar Inserters (Yu and Khazanovich, 2005). Federal Highway Administration’s Concrete Pavement Technology Program (CPTP) now promotes a loan program encouraging the use of the MIT to evaluate dowel bar misalignment.

The primary focus of this research was to control the crack path without compromising the performance of the pavement and develop a means of stress relief within the slab. In this study, the influence of introducing an initiator within the concrete pavement attached to the dowel bars and the effects of dictating the crack path within the pavement was investigated. Researchers in West Germany attached crack initiators to the bottom of the pavement with cement treated bases works. (Okamoto, et al, 1994) The results of the work have been in question and suggest that the bottom crack inducer will result in stray cracking at the joint and not at the desired location (at the bottom of the saw cut). This research unlike the West Germany study proposes to attach the initiators to the dowel bar, as oppose to attaching the initiator to the base of the pavement.

Introduction

Dowel baskets: Dowel bars are placed at regular intervals at approximately 12 inches (300 mm) on center and positioned in the pavement during construction process in two ways; attached to a cage or with an automatic dowel bar inserter. In each instance, the underlying goal is to position the dowel bars at mid-depth of the pavement slab. The primary purpose of positioning these dowel bars at mid-depth is to ensure that the bending stresses associated with traffic loading are minimized by locating the dowel bars at the neutral axis of the cross-section. Secondary goals of mid-depth positioning include maximizing the concrete above and below the element to minimize the risk of shear failure. More importantly, it is essential to ensure that the dowel bars are correctly positioned, perpendicular to the centerline and parallel to each other, in order to prevent locking of the pavement slab leading to cracking, loss of load transfer and occasionally faulting.

The outcome of the dowel bar basket installation depends on several key items including utilizing solid mechanical fastenings to secure the basket to the sub base material. A solid fastening ensures that, when the concrete is placed, the basket will not translate or become skewed with respect to the intended position. When utilizing a dowel bar inserter, proper calibration of placement depth is important. When the automatic inserter is out-of-calibration, the bar placement will be misaligned relative to its intended position. Over the length of a typical roadway project, this can amount to a large quantity of misplaced dowel bars. With either placement method, if the placement mechanism results in the dowel bar being skewed (horizontal skew or vertical tilt), pavement distress will occur.

Saw depth: The FHWA (Okamoto, et al, 1994) study noted that the saw cut (forming) depth (D) to the slab thickness (T) is an important factor to control transverse joint cracking, but not the most critical factor. Other factors such as timing of sawing, design, curing conditions and joint sawing/forming technique play a more important role in the formation of the transverse crack. Load and temperature stresses are a large contributor in the formation of uncontrolled transverse slab cracking.

After placement, it is typical practice to make a saw cut at the intended crack location approximately 6 to 12 hours after placement. The depth of the saw cut reduces the cross-sectional area thereby reducing the tensile capacity at the location of the saw cut. This creates a weakened plane through the cross-section that passes through the dowel bars. The ideal result is a vertical crack that passes through the center of the dowel bar leaving two equal embedded portions of the dowel bar in each section of the pavement slab. This is the desired result, but in reality, this does not typically happen.

Recommended saw cut depths range between 1 inch (25 mm) to 1-$^{1}/_{2}$ inches (38 mm) deep for early age saw cutting and approximately $^{1}/_{3}$D to $^{1}/_{4}$D for conventional saw cutting (American Concrete Pavement Association 1991). The saw cut depth in early age saw cutting greatly increases the quantity of cross-sectional area, (the area bounded by the bottom of the saw cut to the sub base) required to crack vertically in order for the crack path to extend through the middle of the dowel bar. With conventional saw cutting methods, the effects of a non-vertical crack path are lessened, given that a deeper saw cut will reduce the overall cross section of the pavement slab. In both cases, the cracking characteristics of the pavement and the depth of the saw cut will determine the point at which the crack passes across the dowel bar.

Allowable misalignment: Every state has set tolerances on the allowable dowel bar misalignment and the relative position of the dowel bar to the position of the saw cut. TABLE 1 provides relative tolerances on the various dowel bar positions. Limits on longitudinal translation specified ranges from 0.25 inches (6 mm) (Montana/New York) to 3.0 inches (76 mm) (South Carolina) per 18 in. (456 mm) of dowel bar. These allowances are referenced back to the saw cut at the top of the slab and not at the point where the crack crosses the dowel bar. Although the tolerances are set by each State, there is no reliable method to determine the true about of misalignment.

TABLE 1: Summary of Tolerable Limits Outlined by States (Rao et al. 2008)

Dowel Bar Error	Allowable Tolerance
Vertical Translation	0.25 in. to 1.0 in. (6 mm to 25mm)
Horizontal Translation	0.25 in. to 3.0 in. (6 mm to 76 mm)
Vertical Skew	0.25 in. to 0.75 in. (6 mm to 19 mm)
Horizontal Skew	0.19 in. to 0.75 in. (5 mm to 19 mm)

Paste/aggregate interface: The crack propagation of the pavement is based upon mix properties, type of sub base, weather, size of large aggregate, etc. Typically, when the pavement cracks at the joint, the cracking occurs when the paste/aggregate bond in the pavement is weak. This paste/aggregate bond is not fully understood, but the bond is thought to be influenced by the aggregate and the hydrated cement paste and the roughness of the aggregate particle. The hydration of the portland cement at an early age results in weakened areas around the aggregate. The development of a crack during this period will form around the aggregate and not through the aggregate. This occurs due to a poorly developed area at the aggregate-paste interface, the weakest link of the paste matrix. The relatively weak cementitious bond around the aggregate and the spatial orientation of the coarse aggregate in the vicinity of the saw cut will dictate the path of the crack. This is shown is Figure 1. Given the tolerances set by each state, specifically for those states with small tolerances, the path of the crack propagation itself may exceed the allowable tolerances, despite the fact that the relative position of the saw cut and the dowel bar are positioned correctly.

Crack formation: The critical component of dowel bar misalignment is the point at which the crack passes through the dowel bar. Alignment measurements should be made relative to where the crack passes through the dowel bar (A), and not determined as a function of the relative position of the saw cut (B) as shown in Figure 1.

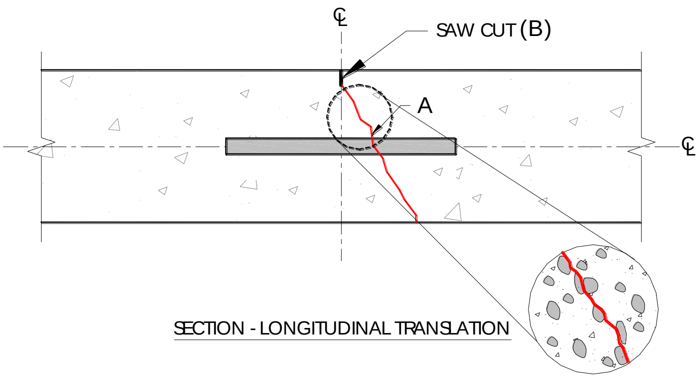

Figure 1: Misalignment measurements are typically obtained relative to the position of the saw cut (B) as oppose to the location where the crack crosses the dowel bar (A).

By assuming that the crack extends vertically plumb from the bottom of the saw cut to the sub base/base, and determining the amount of misalignment present based upon the saw cut position, the effects of the misalignment can be minimized or maximized depending on the route of crack propagation. This is true for horizontal, vertical, and longitudinal translation as well as vertical tilt. The effect, for example, of a longitudinal translation, as shown in Figure 2, is magnified when the crack propagates toward the 'shorter' end of the dowel bar (Crack B in Figure 2), resulting in an increase in bearing stresses compared to a correctly positioned dowel and will likely result in localized premature failure of the pavement slab. If the longitudinal translation is significant, the result could be an undowelled section where the formed crack bypasses the installed dowel bars. Conversely if the misaligned saw cut results in a crack that propagates toward the "longer" end of the dowel bar (Crack A in

Figure 2), the misalignment may not result in an increase in the bearing stresses on the bar. This may be one reason for the widespread performance variation seen in previous studies. A study (Khazanovich, et al, 2009) noted that an embedment length of 6 in. or more had little effect on the load transfer efficiency (LTE) of the joint. However, the misalignment measurement was determined based upon the relative position of the saw cut at the top of the pavement and not at the point in which the crack passes over the dowel bar. Given that the crack can vary as much as 2.5 in.from plumb at mid height of the pavement, the orientation of the crack as it passes over the dowel bar can affect the overall pavement performance.

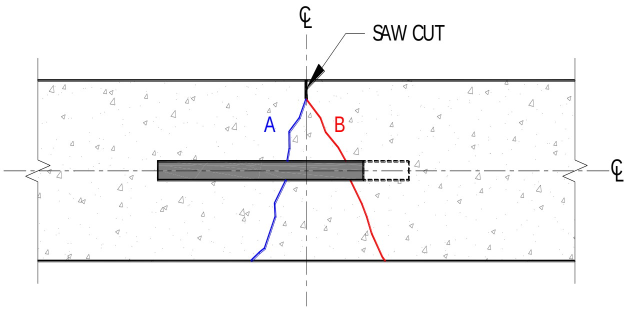

Figure 2a: Crack propagation through a longitudinally translated dowel (Field)

Figure 2b Random crack propagation on the edge of the pavement

Cracking Initiator Research

The goal of the research was to be able to dictate the crack path in a concrete pavement joint. The initiators were attached at mid depth of the test pavement slab, thus creating two smaller cross sections of pavements (top and bottom) at the same time influencing the crack to cross at the desired location. Besides being able to dictate the crack path, manufacturing and installation cost was also accounted for. The research looked at different shape factors, overall surface area, the location of the initiator and the critical slab surface area. The goals of the research were as follows:

- Increase the predictable behavior of the cracking path
- Reduce the depth of the conventional saw cut
- Allow for limited saw cut location offset

The test substrate, which represents a typical section of a pavement slab, was 24 inches in width and 120 inches in length. The typical thickness of the test substrate ranged from 9 inches to 16 inches. The test substrate had four (4) threaded bars installed to serve as the embedded reinforcing steel. Given that the intent of these bars was to act as typical doweling bars used in concrete pavement slabs, which are used to force cracks to occur at specific location to alleviate temperature and shrinkage stresses as well as maintain alignment in the pavement slab, the bars were continuous in length and extended beyond the boundaries of the test substrate. This allowed for the application of external stresses to the test media thereby simulating the aforementioned stress states at the location of the cracks. The embedded reinforcing steel represented a reinforcement ratio of approximately 0.6%.

To mimic the insitu behavior of typical dowel bars used in concrete pavement slabs, the embedded steel elements were debonded, via a plastic sleeve, over a length of 12 inches. The crack initiator (see Figures 4a, 4b and 5) was simulated by reducing the cross-sectional area of concrete at the location of the embedded steel element. In field applications, the crack initiator would be attached to the dowel bars and the basket positioned prior to the placement of concrete. This would facilitate proper transverse alignment of the dowel bar within the pavement slab. The gross cross-sectional area of the test substrate was 216 in^2 and at the location of the crack location, the cross-sectional area was reduced to 153 in^2, approximately 30%. (simulated 20% reduction is achieved via the crack initiator alone while the saw cut reduces the cross-section by a further 10%). The test substrate was not sawed at the location of the crack, as the goal was to simulate the ability of the crack initiator to form a crack at the prescribed location. Furthermore, the proposed crack initiator and the simulated initiator embedded in the test substrate divide the gross cross-section into two sections located above and below the initiator. This allows for a shorter crack path for the critical upper section, where the crack intersects the exposed surface of the concrete pavement slab. With traditional methods, this division is not available which lengthens the crack path and allows for significant deviation from the expected path. Once the crack extends below the dowel bar, the lower section of the pavement with the initiator, the orientation of the crack becomes less critical.

A number of representative sections of test substrate were prepared and tested. A graphic shown below in Figure 3 identifies the three (3) representative load vs. displacement characteristics at the location of the installed crack initiators. As noted in the figure, a linear relationship is noted until cracking occurs. Given that the externally applied force is applied to the reinforcing steel, this is reasonable. At the location of the crack and considering strain equilibrium, a measureable strain is imparted on the concrete at the location of the crack. The embedded reinforcing bars are debonded at this location and elongate due to the applied forces and given that the concrete is bonded to the reinforcing bars outside of the regions of the crack, a considerable and increasing strain is imparted on the concrete until the tensile capacity of the concrete is surpassed. At this point, the strain energy is released, the crack is formed. The crack width can be controlled by the level of stress applied to the reinforcing steel. The level of strain in the embedded reinforcing bars shown in the referenced figure ranges from approximately 825 to 1100, which is well within the elastic range of the reinforcing steel.

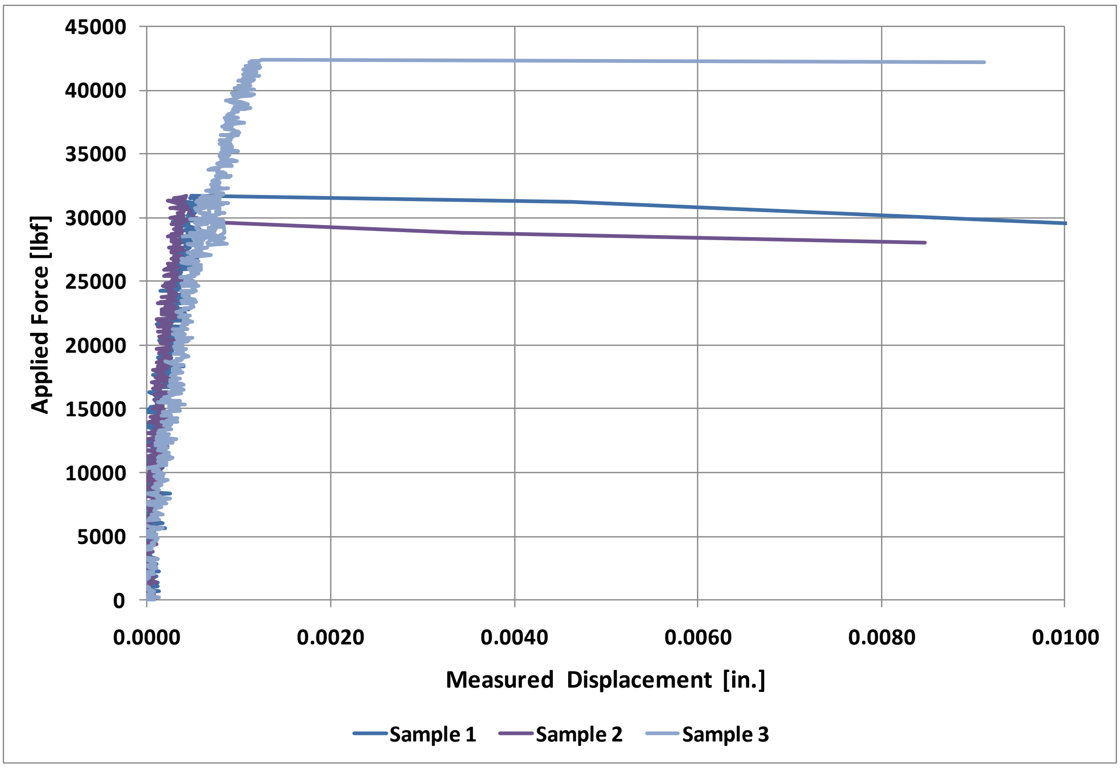

Figure 3: Load vs. deflection characteristics of the pavement with the crack initiator

Research Results and Discussion

Several hours after the concrete has been placed, the internal temperature reaches its maximum and then starts to cool resulting in thermal stresses developing as it approaches ambient temperature. Assuming that the saw cut was made correctly, a crack initiates and relieves the accumulated stress caused by thermal shrinkage. Pavement stresses can also be affected by warping due to vertical temperature gradients; however these stresses, in the absence of traffic, do not result in mid panel cracking providing the joints crack has developed. These stresses typically increase later in the life of the pavement when they are open to traffic. The pavement slabs in this research simulates thermal shrinkage and therefore early age cracking in the pavement slab.

The research considered various different shapes in an effort to optimize the size and shape of the initiator. The shapes included "V", square, circular and rectangular shaped initiators. The research also evaluated varying the overall size of the initiator to determine the optimum performance without compromising the initial intent of the initiator. Initiators with different thicknesses were also investigated in order to determine the influence of the spatial orientation of the coarse aggregate above the initiator. The research results are presented in TABLE 2.

The research determined the "V" shaped initiators required the largest overall area of all the different shapes tested that would consistently result in predictable cracking. The critical surface area is defined as the area between two dowel bars, was a high of 60 percent for the "V" shaped initiator. The vertical leg of the "V" shaped initiator was attached to the dowel bar extending below the mid height of the test slab, and shaped similar to the letter "V". The circular and square shaped initiators required approximately 30 to 40 percent of the critical surface area in size to result in predictable cracking patterns. The rectangular shaped initiators had the greatest influence in cracking propagation with the smallest amount of critical surface area requirement, approximately 15 to 20 percent of surface area.

The shape of the initiator was also examined with respect to concrete consolidation around the initiator. Optimizing the rectangular shape, the data showed that the rectangular shape with rounded edges was the most effective and predictable in developing a crack at the desired location and ensure proper consolidation of the concrete around the initiator and bar. The rounded edges allow for proper consolidation as the concrete flowed around the initiator.

The research also investigated the relationship between the thickness of the initiator and its influence on the cracking patterns resulting from the coarse aggregate distribution above the initiator. Different initiator thicknesses were utilized ranging from 0.25 inches (6 mm) to 1.5 inches (38 mm) thick. The results of the research noted that the thickness of the initiator in combination with the aggregate distribution above the initiator had a significant influence on the final location of the crack, which side of the initiator the crack propagates. It was found that that the precise crack location was varied with increasing initiator thickness. The research, however, noted that the thickness of the initiator had no influence on whether the slab cracked or not. It was concluded that 0.25 inch (6 mm) thickness was the optimum thickness that resulted in predictable crack propagation.

TABLE 2: Summary of Utilizing Different Shaped Initiators and Resulting Crack Propagation (Visual)

Shape of Initiator	***Number of Slabs Tested***	***Results***	***Comments***
"V" Shape – covering approx 60% of surface area – ¼ in. (6 mm) to 1.5 in. (38 mm) thickness	60 Slabs	Crack at initiator, 0.001 in. (0.025 mm) on surface	Cracking very predictable, requires largest critical surface area
Square/circular shaped initiator – covering approx. 30 - 40% of surface area, ¼ in. (6 mm) to 1.5 in. (38 mm) thickness	60 Slabs	Crack at initiator – 0.001 (0.025 mm) to 0.01 in. (0.25 mm) cracking at surface	Cracking controlled. $^{3}/_{8}$ in. (9 mm) thickness yield predictable results
Rectangular shaped with rounded edges initiator – covering 15 - 20% of surface area, ¼ in. (6 mm) to 1.5 in. (38 mm) thickness	200+ Slabs	Crack at initiator – 0.001 (0.025 mm) to 0.01 in. (0.25 mm) cracking at surface	Cracking controlled ¼ in. (6 mm) to $^{3}/_{8}$ in. (9 mm) thickness yield highly predictable results

Location of Initiator

The research shows that in order to predetermine the crack path propagation the greatest benefit is to attach the cracking initiators to the dowel basket assembly. Being able to predetermine the location of the crack results in the crack traveling along the desired path, through the middle of the dowel bar, as shown on Figure 4.

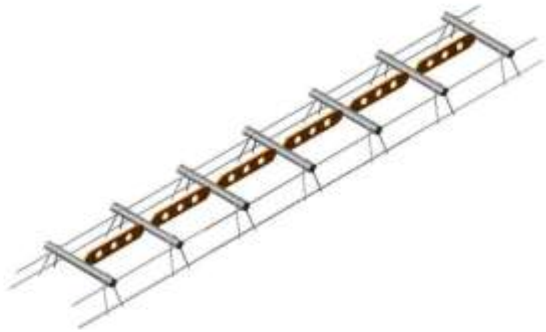

Figure 4a: Crack initiators attached to dowel on a dowel basket

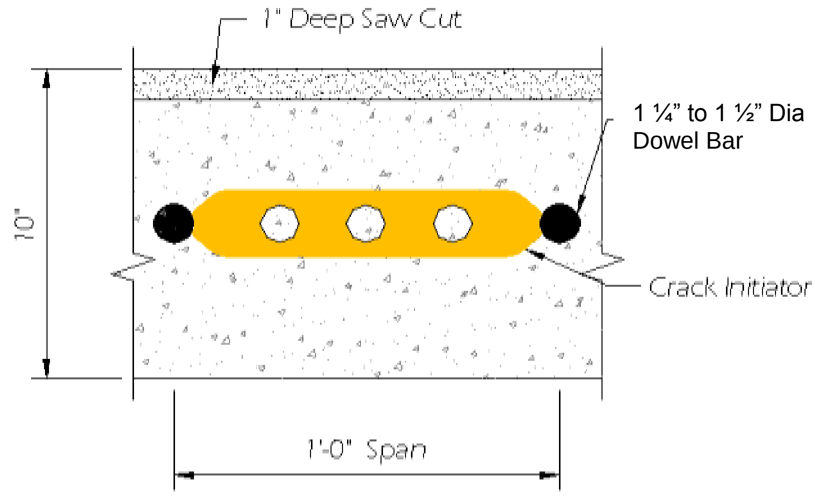

Figure 4b: Cross sectional view of pavement slab showing a crack initiator attached between two dowel bars

The research looked at previous work that noted stresses on the dowel bar are highest at the top and bottom of the dowel bar when the load is applied to the top of the slab (Porter et al. 2001). The past research concluded that the sides of the dowel bar does not aid in the shear stress distribution from the concrete and that smaller diameter bars result in higher stress concentration on the top and bottom of the dowel bar. Since the sides of the dowel bar do not contribute to the load transfer during loading, the sides of the dowel bar would be the ideal location to connect the initiator, as shown by Figure 5. Attaching the initiator to the sides of the dowel bar via a weld would result in the optimum functional approach.

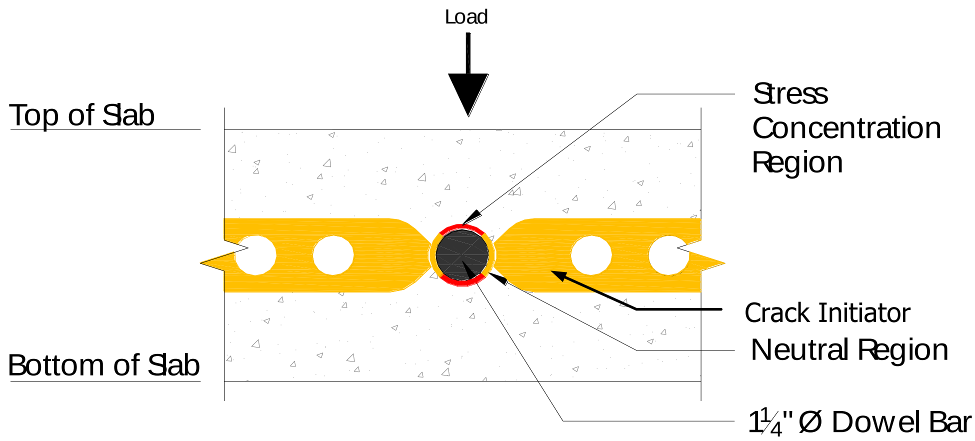

Figure 5: Schematic of stress concentrations on a dowel bar during loading and the region where the crack initiator attaches to the dowel bar

This research concluded that having a crack initiator in place within the slab has the benefit of having a weakened plane within the concrete pavement. The presence of the initiator divides the overall pavement depth into two equal sections, one above the initiator and one below the initiator. This weakened plane, created by the presence of the initiator, forces the crack to propagate through the middle of the dowel bar, and thereby ensuring that the desired crack path is achieved. Once the slab begins to contract after placement and with a saw cut in place, the crack follows the weakest path which is defined by the area immediately below the saw cut and above the initiator.

Current industry practice of utilizing a conventional saw cut or a early saw cut saw to create a weaken plane within the pavement, reduces the overall cross sectional area by 10 percent to 25 percent for a 10 in. slab. As discussed above, this practice is dependent on other external factors to ensure that the slab cracks at the desired location and does not control the crack path.

With the initiator attached to the dowel bar, the factors that influence the slab to crack are still present. The cracking initiator reduces the overall cross sectional area of the pavement, similar in function as saw cutting, but is inherent within the pavement slab. The initiator reduces the cross sectional areas of the pavement slab by approximately 50 percent, with the critical surface area being the area between the bottom of the saw cut to the top of the initiator (top section). This now becomes the critical component in the pavement where the orientation of the crack needs to be controlled, thereby ensuring that the crack passes through the middle of the dowel bar.

With the crack initiator attached to the middle of the dowel bar, it is relatively easy to determine nondestructively the center of the dowel bar, and thus determining where the crack propagates. This allows for an accurate determination of the true amount of misalignment present in the pavement if it is necessary to evaluate the pavement. The crack initiator also provides a weakened cross section within the slab that is currently not achieved by utilizing current saw cutting techniques. With the initiator attached to the dowel bar, a separation is made at the top of the pavement (saw cut) and in the middle of the pavement slab, as opposed to just the top of the pavement slab. The initiator divides the pavement cross section into small sections which are more susceptible to cracking, which is not achievable with saw cutting the top of the pavement alone.

If the saw cut is offset less than ±5 percent of the overall thickness of the slab, and the resulting outcome does not significantly increase this critical distance, the crack will propagate from the bottom of the saw cut, along the crack initiator and down to the sub base/base. With the minor offsets in saw cutting, which is typical in the field, the distance between the bottom of the saw cut and the top of the crack initiator is the governing area of influence. Larger offsets in the saw cut will result in a uniform surface crack although the path leading from the bottom of the saw cut to the top of the crack initiator will show variance and will be a function of the deviation or offset. .

The influence of the concrete mix design will have little impact on the performance of the crack initiators. The shape and smooth surface of the cracking initiator provide the required break within the pavement and will not impact current consolidation operations during placement of the concrete. Current placement techniques should be sufficient to ensure that the concrete fully consolidates around the dowel basket and cracking initiator.

Aside from the benefit of directing the cracking through the predetermined place within the pavement slab, using a crack initiator allows a shallow 1 in. (25 mm) saw cut, as opposed to the more expensive and time consuming conventional $^{1}/_{3}$ D or ¼ D required for conventional joints without initiators. Similarly with early age saw cuts, the 1 in. (25 mm) depth is sufficient to create the weakened plane in the concrete pavement. Saw cutting is still required in order to maintain a visually pleasing joint appearance and also minimize spalling of the pavement joint. The timing of when to saw cut should still be observed.

Current practices rely on stress buildup from shrinkage or thermal effects to crack the joint. All pavement joints do not crack at the same time. The joint will only crack if the stress buildup in the pavement exceeds the strength gain of the concrete. The cracking initiator creates an inherent separation within the pavement slab. The crack initiator in conjunction with the saw cut can assist in providing the necessary reduction in overall section of the pavement slab required to reduce stress buildup within the slab, thus narrowing the joint cracking duration window. This in turn will reduce potential joint sealant distress currently noted.

Conclusions

This research has shown that the use of crack initiators has advantages over current practices. The ¼ inch (6 mm) thick rectangular initiator, with rounded sides was determined to be the optimum size and shape to control cracking characteristics of the pavement while maintaining proper concrete consolidation around the initiator. The use of crack initiators that are attached to the dowel bars ensures the pavement joint crack propagates through the middle of the dowel bar, minimizing potential problems, such as longitudinal translation due to misplaced markings or dowel baskets within the pavement slab, assuring desired pavement performance. The crack initiator provides a separation within the pavement slab that is not achieved by current conventional saw cutting techniques. The research has shown that the crack propagation can be controlled even though the saw cut may be misaligned and cost savings are achieved through reduced depth of saw cutting with the use of crack initiators. A shallow saw cut of 1 inch (25 mm) works well for both early and conventional saw cutting. With the crack initiator attached to the dowel bar, the true amount of misalignment can be determined nondestructively, if needed.

The cracking initiator reduces the overall cross sectional area of the pavement slab, thus eliminating any potential stress buildup within the slab due to shrinkage or thermal changes. The reduction in stress buildup within the slab will result in a narrowing of the time window for cracking, which in turn will result in the crack width of each joint being more uniform and thereby reducing potential sealant distress in the joint.

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