FACTORS AFFECTING PERFORMANCE OF CONCRETE PAVEMENTS

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INTRODUCTION

There is a popular belief among many pavement engineers that concrete pavements which survive the first 3 years of service without distress will likely perform well throughout their design life. This notion has some merit, although it is not necessarily based on scientific data but rather on personal experiences. In Florida there are approximately 3200 kilometer (2000 lane miles) of jointed concrete pavements. Age of service for these concrete pavements range between 5 and 50 years. Their performance has been variable. Many pavements are in very good condition and, in some cases, have long exceeded their design life. Others have exhibited signs of distress at very early age, and are in need of major rehabilitation to extend their service life.

Most design procedures for concrete pavements are based on the concept of fatigue failure. This is a simple criterion that has allowed pavement engineers to design many successful pavements. But pavements rarely, if at all, fail in fatigue during their design life. In Florida, there are many examples of 30 to 60 year old pavements that are in very good structural condition. There are also examples of new pavements that developed cracks within a few months after construction, as in the case of sections of I-75 south of Tampa, Florida (1). It is inconceivable that fatigue damage can be the driving mechanism in the early deterioration of these pavements.

Many forms of functional or structural distress in new pavements are direct consequences of problems in design, concrete mix or construction. A survey on I-10 of 100 replacement slabs ranging in age between 1 to 3 years, showed that 35% of the slabs had developed cracks and spalls. In these slabs, fatigue damage is clearly ruled out as a cause of early cracking.

Pavement distress can be a result of a single or combination of factors. It is hypothesized that warping stresses, and microcracks are developed in pavement slabs as a result of shortcomings in pavement design, concrete mix or construction. Residual stresses can also develop as a result of movement restraint at slab boundaries from dowels/tie bars and rigid bases.

The first distress in a pavement slab is likely induced by critical conditions. These critical conditions can occur at any time during the design life of the pavement. They develop as a result of a combination of heavy traffic loads and weak conditions of along the slab joints and edges. Weak conditions are characterized by loss of support due to upward warping and curling of the slab, and by the presence of voids beneath the slab corners. At the critical conditions, stresses induced by traffic loads are increased to a level high enough to initiate first crack. Beyond this point, repeated traffic loads gradually increase the rate and magnitude of the crack. This process will eventually cause the failure of the pavement.

This paper discusses the impact of temperature displacements on performance of pavement slabs. Also presented is a chronology of events leading to water related distress. Aspects of pavement design, concrete mixture, and construction are discussed, and their contribution to pavement performance is evaluated.

At the outset it should be emphasized that much of the information presented here is derived from Florida experience. It is also acknowledged that experience may vary from one region to another, depending on the environment, traffic and materials.

TEMPERATURE DISPLACEMENTS

Displacements and deformations in pavement slabs play an important role in creating the critical conditions responsible for pavement distress. The following is a discussion of various displacements that occur in pavement slabs.

Initial Slab Warping

There is evidence that during construction, pavement slabs assume an upward warping position upon hardening of the concrete. The upward warping position assumed at construction becomes a permanent deformation in the slab. The curling of slabs during a 24-hour temperature cycle further affects the warping position of the slab. During daytime, the upward warping is offset by downward temperature curling. In contrast, during nighttime, the upward warping is further increased by the upward temperature-curling condition (2,3).

Figure 1 shows a combination of warping and curling positions at different temperature differentials (ΔT). This figure shows surface elevations across the width of a 228-millimeter (9-inch) slab at the Gainesville test pavement. The elevations were measured at various negative and positive temperature differentials. Between +3.6°C (+6.5°F) and +6.7°C (+12°F) ΔT, the slab shifts position from upward warping to downward warping. It was determined through interpolation that the slab assumes a flat (no-warping) position at +5°C (+9°F) ΔT. This contradicts the notion that the no-warping condition occurs at zero degree ΔT. It also adds strong support to the hypothesis that slabs assume an upward warping position during construction. It is reasonable to conclude that a downward displacement corresponding to +5°C (+9°F) temperature differential is required to overcome the permanent upward-warping position of the slab.

The upward warping can occur irrespective of base material type and stiffness. This permanent deformation of the slab is believed to be caused by differential shrinkage between the surface and bottom of newly placed slabs. Deformations can also result from wide variation in temperature between the center and edges of the slabs.

I-10 Test Section

Temperature variations in newly placed slabs were monitored as part of a study to evaluate effects of cement type, curing method and joint design on cracking of replacement slabs. A 42-slab test section was constructed on the outside lane of I-10. The test section was part of a major rehabilitation project on I-10. High early strength concrete was specified, with strength requirement of 16.6 MPa (2400 psi) at 24 hours. Fourteen combinations of joint design, cement type and curing method were included in the test section. Each combination was represented by 3 slabs. Cement types I and III were used. The slabs were cured using wet burlap, curing compound, and 75 mm (3 in) thick styrofoam curing blankets. Five slabs representing different cement/curing combinations were instrumented with temperature sensors. Temperatures were monitored at the outside edge, inside edge (adjacent to existing lane), corners and center positions. The base under one of the slabs (with type III cement and blanket curing) included displacement sensors installed at corner, edge and center positions.

Temperatures and displacements were monitored for 48 hours starting at time of concrete placement. Figure 2, shows temperature variation with time for the slab with type III cement/curing compound combination (3-R). The variation in temperature between the inside edge, center and outside edge is clear. Table 1 shows the extent of variation at maximum and minimum temperatures for the 5 slabs. The center has the highest temperature. The inside edge (adjacent to existing lane) seems to have the lowest temperature.

At slab 3-S (type III cement and blanket curing), the maximum temperature at the center was 14.4°C (26°F) higher than the inside edge and 8.9°C (16°F) higher than the outside edge. It should be noted that the styrofoam blanket covered the surface of the slab only. The maximum upward displacement at the edge of slab 3-S, measured during the same 48-hour period, was 1 mm (0.04 in) (4).

It is believed that the wide variation in temperature between the edge and center of freshly placed slabs can create upward warping of the slab. There is also strong possibility that differential shrinkage between the surface and bottom of the slab can also contribute to this warping. The initial warping in today's pavements is expected to be greater than pavements built 30 or 40 years ago. One possible reason is that in today's construction concrete mixes are designed with higher quantities of cement to develop high early strength. A second reason is that slabs undergo shorter curing periods with less emphasis on water curing. The result is more shrinkage and higher temperatures, which produce more warping in the slab. With higher traffic weights and volume, the upward warping will contribute to higher stresses in the slabs. Effects of temperature and shrinkage variation on slab warping can be minimized by controlling the cement content and shortening the slab length.

Slab Curling

During the first few hours after concrete placement, temperature of the slab is affected by a combination of the internal heat generated from the hydration of the cement, and ambient temperature. As the hydration slows down the slab temperature will become more sensitive to fluctuations in the ambient temperature. This is illustrated in figure 2. During the first 3.5 hours the slab temperatures were increasing at a rapid rate, while the ambient temperature was gradually decreasing. After 3.5 hours the slab reached maximum temperature. Beyond this point, the slab temperature started to drop rapidly and became more sensitive to the decrease in ambient temperature. After 12 hours the slab temperatures followed a pattern similar to that of ambient temperature.

Likewise, the temperature gradient at any position within the slab is affected by the internal heat and ambient temperatures. Figure 3 shows the temperature at the center of slab 3-R. The temperatures were measured at 6.4 (0.25), 114 (4.5), and 222 (8.75) mm (in) from the surface. During the initial 3.5 hours of hydration, the highest temperature is at mid-depth and the lowest is at the bottom of the slab. After 12 hours, the temperatures at top, middle and bottom of the slab begin to follow the same pattern as that of the ambient temperature. Their response to the change in ambient temperature becomes similar to that of an old slab.

The slab responds to daily variation in temperature gradient across the slab thickness by undergoing different curling positions. The response to the change in the overall temperature of the slab is in the form of expansion and contraction at joints.

Temperature variations and vertical displacements of a slab in the Gainesville test pavement were monitored for a period of 48 hours (2,3). The slab is one of 6 slabs in the test pavement which had been instrumented with temperature and displacement sensors. The slab was undoweled at one joint and doweled at the other. Figure 4 shows the variation of the temperature differential (ΔT) between the surface and bottom of the 228-millimeter (9-inch) pavement slab. Figure 5 shows the response of the same slab to the temperature variations in Figure 4. This response is in the form of vertical displacements at the center, edge, and corners of adjoining slabs 3 and 4 (undoweled joint). During nighttime, the temperature differential becomes increasingly negative. This condition causes the center to move downward, (upward trend in the displacement curve), and causes the corners and edges to curl upward (downward trend in the displacement curve). During daytime the temperature differential become increasingly positive, causing the reversal of direction in the displacements. The center gradually curls up, while the corners and edges curl down. During a 5-month monitoring period, the highest vertical displacements recorded at corner, edge and center locations were 2.45 (0.1), 0.76 (0.03), and 1.14 (.045) mm (in), respectively.

The overall temperature of the slab discussed above was also monitored for a period of 42 hours (3). The corresponding horizontal displacements at the doweled and undoweled joints were measured. Figure 6 shows a the variation with time of the overall temperature of the slab. Figure 7 shows the expansion and contraction at the doweled and undoweled joints. During nighttime, the joints tend to open (downward trend in the displacement curve) as the adjoining slabs contract in response to the decrease in slab temperature. The direction of joint displacements are reversed during the daytime. The adjacent slabs gradually warm up and expand to cause the reduction of the joint opening (shown by upward trend in the displacement curve). Figure 7 also shows that doweled joints allow less displacement than undoweled joints. During a 5-month period, the maximum joint opening for doweled and undoweled joints were 0.58 (0.023) and 1.14 (0.045) mm (in), respectively.

Vertical and horizontal slab displacements during nighttime reduce the stiffness along the joints and edges. Under these conditions the deflections and stresses from the heavy traffic can have damaging effects on the slabs. The long term performance of the pavement may strongly depend on the extent of daily displacements of the slabs. Therefore, in order to extend the performance of today's pavements, slab warping and curling should be considered in design details, mix selection and construction practices.

WATER RELATED DISTRESS

Water can be the source of major problems in concrete pavements. Good performing pavements seem to drain water, while poor performing pavements tend to retain water. Pavements are designed and constructed with the primary objective of keeping the water out of the system. The first line of defense against intrusion of surface water is the joint sealant. During construction, slab joints are securely sealed. However, this situation does not last for long. Water will eventually penetrate the sealed joints. In the absence of positive drainage, water beneath the slab will start to pump through the joints causing joint faulting, voids beneath the pavement, and eventually corner cracking.

Conditions Leading To Water Intrusion

To understand how water penetrates the newly sealed joints, one must examine the combined action of temperature induced displacements and load induced deflections in pavement slabs. As discussed before, during nighttime, pavement joints open wide and the slab corners reach maximum upward curling. This is the weakest daily condition at the corners and joints. What makes this period even more critical is the fact that it coincides with heaviest daily truck traffic. A sample of traffic count statistics for Interstate I-75 (5), show that traffic between midnight and 8:00 A.M. is almost 40% of the total daily vehicle count. But, what is more important is that 50% of all trucks that weigh between 33,300 kg (73,400 lb) and 36,360 kg (80,000 lb), and 62% of the trucks that weigh over 36,360 kg (80,000 lb) travel on the interstate during the same period. High wheel loads induce high deflections.

Nighttime temperatures produce upward curling at slab edges and widen the gap between the adjoining slabs. A combination of the nighttime weakness of the slab coupled with heavy wheel loads, produce very high deflections at the corner region, and very low transfer of loads between the adjoining slabs. Excessive corner deflections during nighttime generate shearing action which gradually degrades the bond between the sealant material and joint edges. This will ultimately provide the opportunity for surface water to penetrate the sealed joint, and reach the interface between the slab and base.

Water Pumping

One of the first consequences of trapped water beneath the slab is pumping. Lack of an effective drainage system will cause the water to remain trapped beneath the slab. Water that is trapped in the pavement system over an extended period of time is responsible for initiating the distress mechanism in the pavement slabs, irrespective of pavement age.

As discussed earlier, the daily slab displacements in both horizontal and vertical directions generate frictional forces at the slab-base interface. This action produces loose fine materials on the surface of the base layer. Heavy wheel loads exert significant pressure on the trapped water, and force it to travel with high velocity (4). Water moving beneath the slab will carry the loose fine materials from the base. The joint sealant will ultimately rupture under continuous pressure from the trapped water. The water will then start to pump through the joints, carrying the fines from the base and depositing them on the shoulder.

As the pumping action continues, voids will begin to form and expand beneath the slab corners. The voids create a cantilever beam action at the corners. Falling weight Deflectometer (FWD) tests on the Gainesville test pavement, have shown that voids beneath slab corners increase the deflecting by more than 100 percent (3). The combined effects of heavy wheel loads, upward warping/curling at the corner and presence of voids beneath the slab produce high tensile stresses capable of causing corner and diagonal cracking.

Joint Faulting

Faulting is another form of distress in the pavement induced by the action of trapped water. It occurs at joints and transverse cracks where the leave side of the joint or crack becomes elevated from the approach side. Faulting is gradually formed by the continuous deposition of fine materials by the movement of trapped water beneath the adjoining slabs. Faulting is considered a functional distress which gradually degrades the ride quality. However, with increase in faulting, the impact force of heavy wheels at the joints becomes sufficient to cause the cracking of the approach-slab corner.

Mitigating Water Related Problems

Water problems can be mitigated by rapid removal of water from the pavement system and/or by reducing deflections at the corners. Pavements with dense graded subgrades should be designed using edge drains. Also, the use of drainable bases such as open graded or pervious concrete should be considered. Reference 6 is very useful FHWA guide for design and construction of permeable bases and edge drain. Some states are designing a drainage system composed of open graded pervious concrete for the base layer and edge drain (7). Early indications are that this drainage system is performing well.

Joint deflections can be drastically reduced by controlling slab curling, improving load transfer at joints, and shifting the truck wheels inward away from the pavement edge. These aspects are discussed in the sections that follow.

PAVEMENT DESIGN

Pavement design has a major impact on pavement performance. Most states use national design guidelines such as the AASHTO design guide. However, design specifics and practices for a particular region should be derived from environmental conditions, material characteristics and local experience with pavements in that region. A specific design that has a proven performance record in one region of the country may not necessarily be successful in another region. Therefore, pavement engineers should adopt imported designs after careful review of the design components, and a thorough assessment of the applicability of such designs to local conditions.

Today's pavements are designed with emphasis on thicker slabs and stiffer bases. Bonded and unbonded rigid bases have been used, including permeable bases. The joints are normal or skewed. Tie bars are normally specified, and dowels have become standard features in jointed pavements. Slab lengths are either uniform or variable. There is also more tendency to design shorter slabs. Some pavements have widened lanes. Tied concrete shoulders are becoming increasingly popular design features. Also more consideration is given to water drainage.

The following segments present assessment of various design components and their impact on the overall performance of the pavement. The information is based on results of Falling Weight Defloctometer (FWD) tests, faulting measurements, and pavement condition surveys. The tests and surveys were conducted on the Interstate system, state roads and test pavements in Florida.

Doweled and Undoweled Joints

Doweled joints perform better than undoweled joints. A reduction of 20 % in deflection and lower stresses are expected in doweled joints (3). Lower deflections minimizes pumping, faulting and corner cracking. Extensive crack survey on Florida's I-10 showed that doweled pavement sections had 30% less faulting and fewer corner cracks compared to undoweled sections. However type of joint did not seem to affect the rate of transverse and longitudinal cracks.

However, the extent at which the dowels, contribute to the distribution of loads between adjoining slabs, and transversely is still not well understood. Another aspect not clear is the role, if any, of dowel misalignment in producing cracks in the vicinity of joints. A Survey of deteriorated sections of I-75 was conducted to establish the impact of dowel misalignment on rate of cracking (1). Results of the survey showed no correlation between misalignment of dowels and rate of cracking.

Normal and Skewed Joints

Joints are traditionally formed normal to the center line of the pavement. However, skewed joints have also been used based on the to cut down rhythmic noise from truck wheels. This claim has not been adequately verified. Performance of skewed joints has been poor in pavements with rigid bases. Sections of I-75 south of Tampa, Florida, were designed as unbonded 229 mm (9 in) concrete on 152 mm (6 in) econocrete base with skewed joints (3). Significant corner cracks were observed at slab corners forming obtuse angles with the skewed joint. Also, at many joints a mismatch had occurred between position and orientation of the dowels in reference to the joint.

On US 41 test road, the performance of skewed much better. Normal joints and skewed joints were constructed in consecutive test sections (8). The two pavement sections had identical designs, which included a 75-millimeter (3 in) layer of quality concrete bonded to a 229-millimeter (9-inch) layer of econocrete (very low strength concrete). Both sections were placed on stabilized base. Performance of the two sections has been very good. Specifically, there are no corner cracks in both sections. But, in view past construction problems, and since skewed joints have not provided superior performance, their use is not presently considered in design of Florida pavements.

Slab Geometry

Slab dimensions have significant impact on short and long term performance of jointed pavements. Shorter slabs are preferred over long slabs. Curling from shrinkage and temperature differential tends to be lower in shorter slabs. This will likely result in lower deflections, less curling and reduced stresses. In general, shorter slabs develop less corner and transverse cracks (1,8). For best results, it is recommended that slab lengths for future pavements be between 4.57 to 5.49 m (15 to 18 ft).

Joint Sealant

Joint sealant is an important barrier against water intrusion, especially when the base is impermeable. Silicon and preformed compression seals have been used with good results in Florida. However joint sealing should not be a substitute for good drainage. As mentioned before, joint sealants can delay water ingress into the pavement system, but only for a short period of time. Silicon sealants should be replaced every 8 to 10 years as part of a preventive maintenance program. The preformed compression sealants have lasted much longer than silicon. Age of their service is more than 17 years on US 41, and more than 30 years on I-95 in Miami (8,9).

Lane Widening

Width of Slabs is normally specified at 3.65 m (12 ft). However some sections of I-75 have a widened outside lane. Here the lane is extended to 4.26 m (14 ft). The lane is still marked at the 3.65 m (12 ft) point, while the remaining 0.61 m (2 ft) is considered part of the shoulder. This lane-layout tends to shift the wheels 0.61 m (2 ft) away from the pavement edge. Studies have shown that deflections of loads at 0.76 m (2.5 ft) from the edge are between 20 to 30 percent lower than deflections of loads at 0.15 m (0.5 ft) (3). Condition surveys of the widened-lane section of I-75 showed no signs of pumping, or corner cracking. Also, the section seems to be providing very good ride quality. Widened lane is an effective design feature and is recommended on pavements which carry heavy truck traffic.

Base Stiffness

Stiffness of the base layer influences stresses and deflections of the slab. The base layer should have adequate stiffness to support the slab. At the same time the base should be flexible enough to accommodate slab deflections under load and temperature. Figure 8 is a correlation between slab cracking and the subgrade stiffness. The correlation is between rate of cracking of pavement slabs on I-10 and effective base stiffness (K). The K values were determined from computer backcalculation using FWD deflections at the center of slabs (10). The percent cracked slabs is higher at K values less than 200 pci and higher than 600 pci. Sections with the least amount of cracking have K values between 200 and 400 pci.

In another study, a computer program called FEACONS was used to calculate stresses in pavement slabs with rigid econocrete bases (11). This analysis was performed to evaluate the effect of the rigid econocrete base on premature cracking of sections of I-75, south of Tampa, Florida. Result of the analysis showed that stresses in pavement slabs increased significantly at subgrade stiffness between 800 to 1100 pci. The analysis showed that stiffness of the econocrete base falls within this critical range. An investigation of the distress on I-75 showed that the econocrete base played a major role in the premature cracking of pavement slabs (1). Based on performance records and stress analysis, the optimum K design values should be between 200 and 400 pci.

CONCRETE MIXTURE

High Early Strength Concrete

Concrete mixes are presently designed to develop 17.25 to 20.7 MPa (2500 to 3000 psi) compressive strength at early age (1 to 3 days). This strength allows earlier use of the paved sections for moving construction equipment and speeding up construction. High early strength concrete often requires the use of high quantities of cement. Increasing the cement content in the concrete mixture tends to increase the heat development in the mixture.

It is hypothesized that very hot mixes will likely induce significant microcracks inside the slab. These microcracks severely weaken the structural integrity of the concrete slab. It may not be possible to accurately verify the microcracking hypothesis. However, field surveys show strong evidence of their detrimental effects. Frequent condition surveys of the 42-slab test section on Florida I-10 (described earlier) showed that mid-slab cracking occurred in 39 of the 42 slabs. It should be mentioned that some slabs developed temperatures in excess of 66°C (150 °F). The cracks developed at different times ranging from 24 hours to one year. The concrete slab obviously developed excessive heat and shrinkage from high cement content and temperatures. These conditions tend to produce high tensile stresses in the slab. A large network of microcracks could have formed to relieve the high tensile stresses. Severe microcracking drastically weakens the integrity of the concrete matrix. Initially, no visible cracks are observed. But with repeated application of traffic loads, the microcracks gradually extend through stress concentration. As theses cracks grow they gradually connect up with neighboring microcracks. With time, more macrocracks become visible. The transition period between the formation of microcracks to the development visible cracks depends on several factors. These factors include the extent of microcracking, degree of slab warping, and volume and magnitude of the traffic loads.

Every effort should be made to maintain the slab temperature below 32°C (90°F) during the first few hours after concrete placement. Steps to accomplish this include limiting the cement content; using pozzolanic materials such as fly ash; and casting concrete at night during the summer season. It is also suggested that temperature differential in the slab, and between the slab and the surroundings be kept at a minimum level. This will minimize the formation of microcracks from shrinkage and temperature stresses. Controlling early microcraking will improve long term performance of the pavement.

CONSTRUCTION

Pavement Curing

Curing methods have changed with time to be compatible with the fast pace of construction. A wide range of curing technique are used. they include wet burlap curing, water ponding, use of curing compound, and covering the slab with plastic sheets or curing blankets. Curing can also involve more than one technique, such as combining water curing and another curing compound.

The most widely used curing method in today's pavements is the curing compound. This curing method may prevent water loss from the concrete surface but is not effective in controlling heat and shrinkage development in the slab.

Curing blankets are used in cold climates to speed up the rate of strength development in concrete. They are effective in insulating the slab surface, controlling heat flow from the slab, and maintaining a uniform temperature differential across the slab thickness. Control of temperature differential was observed during temperature monitoring of the insulated slabs of the 42-slab test pavement on I-10. This was the result of the insulating action of the 75-millimeter (3-inch) styrofoam boards which limited heat flow from or into the slab.

With all its advantages, blanket curing can also create serious problems in newly constructed slabs. In the 42-slab test pavement, every newly placed slab cured with insulating styrofoam boards developed transverse cracks within the first 12 to 48 hours. It should be noted that this was a limited study where hot concrete mixes were used. No firm conclusions on advantages and shortcomings of blanket curing can be drawn at this point pending further evaluations.

Wet Curing has always been the most effective curing method for concrete in pavement slabs. Water curing provides the best results with respect to strength gain, durability and volume stability of concrete slabs. Curing water provides constant supply of moisture to the concrete and control the rise in concrete temperature. Water curing may also be used in conjunction with other curing techniques such as curing compounds, blankets and plastic sheets. Therefore, it is highly recommended that water curing be used for pavement construction, especially in warm and dry regions. Benefits from water curing will most likely outweigh any increase in construction cost.

Joint Forming

Proper timing of saw-cutting the joints is a factor often overlooked during in construction. The process simply does not keep up with the fast pace of the paving operation. Delay in saw-cutting of joints often results in uncontrolled cracking in freshly placed slabs.

Time for saw-cutting the joints should be shortened depending on ambient and concrete temperature. Timely cutting of joints becomes vital in preventing the formation of uncontrolled cracks at early hours, especially in mixes that are rich in cement and are placed in temperatures over 32°C (90°F). For best results, joints should be cut within 1.5 hours after finishing the slab surface. Also the option of shortening the joint spacings should be considered in case of hot weather paving and in accelerated paving techniques (fast track pavements).

SUMMARY AND CONCLUSIONS

Based on the condition evaluations and test data gathered on Florida pavements, the following conclusions are drawn:

1. The concept of fatigue failure has been a good criteria for pavement design. However, pavements rarely , if at all, fail in fatigue during their service life.

2. Pavement slabs assume an upward warping position during concrete hardening. This warping remains as a permanent deformation in the slab. The warping is increased or offset by daily temperature curling of the slab.

3. Premature cracking in pavement slabs is attributed to accumulation of stresses from traffic loads; early warping and temperature curling of the slab; voids beneath the slab; and restraining of slab movement at the edges and base.

4. The joint sealant can keep the water from penetrating the joint for only a short period of time. Heavy truck traffic during nighttime combines with high warping/curling conditions to produce excessive deflections at joints. This daily occurrence of high deflections will gradually degrade the bond between the sealant and the joint edges, leading to the intrusion of water.

5. To mitigate water related problems, corner deflections must be reduced and an effective drainage system provided.

6. Elements of design that contribute to better performing pavements include doweled joints, shorter slabs, widened outside lane, and subgrade stiffness values between 200 to 400 pci.

7. Cooler concrete mixes contribute to less shrinkage and thermal cracks.

8. Water curing is the most preferred method of curing for pavement slab.

9. All joints should be sawed within 1.5 hours after slab-finishing time. This period should be reduced in hot weather paving and in fast track pavements.

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CONVERSION FACTORS:

mm = 0.0394 in
m = 3.28 ft
km = 0.6 mi
kg = 2.2 lb
Mpa = 145 psi
°C = (°F - 32) X 5/9

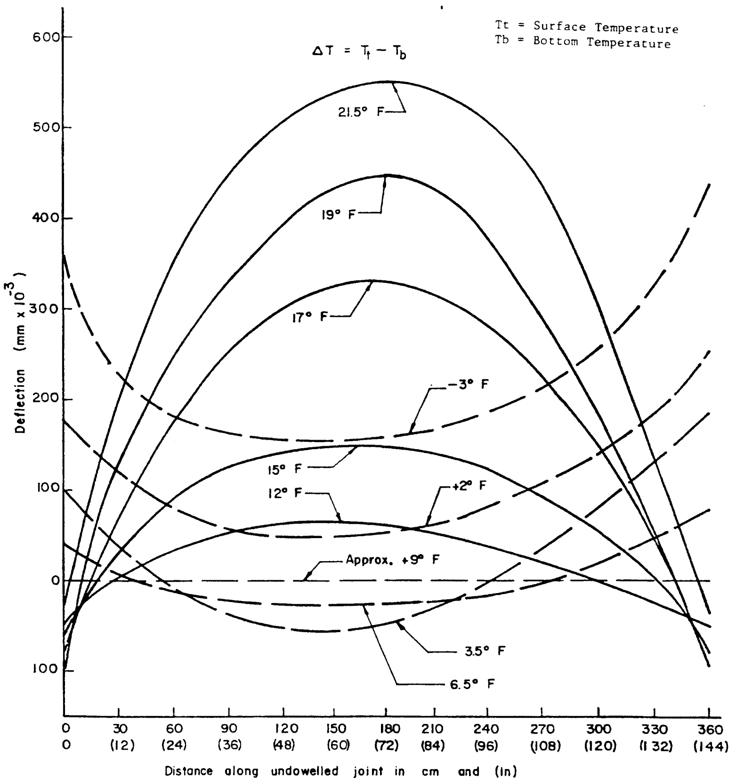

Figure 1 Slab Warping and Curling at Different Temperature Differentials

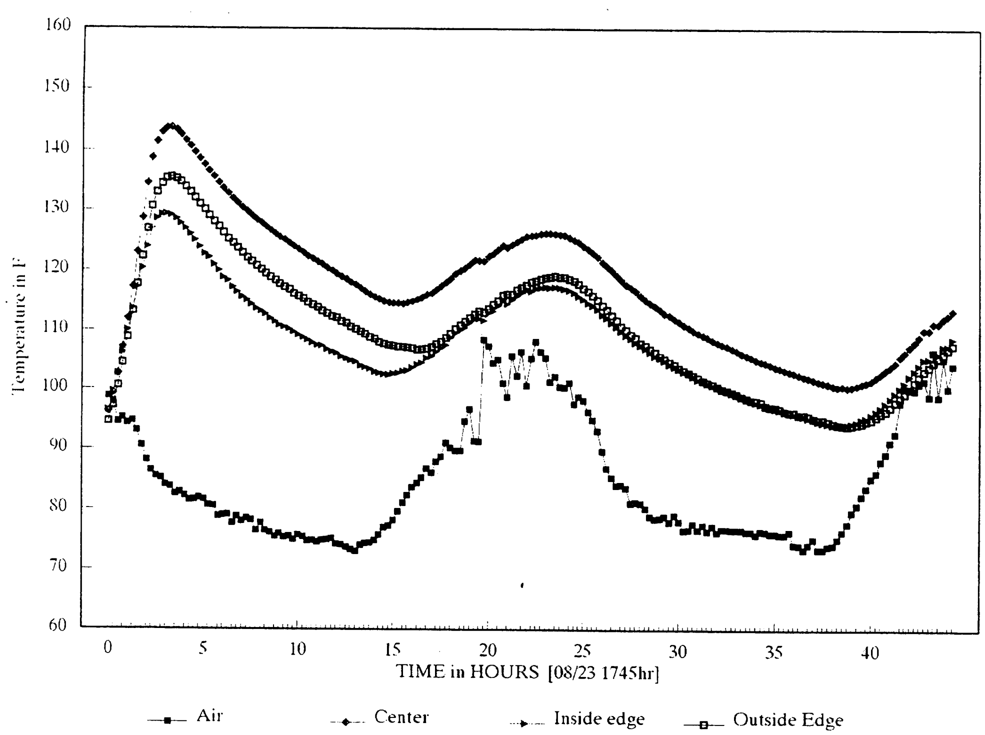

Figure 2 Temperature Variation in Freshly Placed Slab

Table 1 Temperature Records for Five Freshly Placed Test Slabs

Cement Type & Curing Method	Concrete Placement (F)		Air Temperature (F)			Maximum Slab Temperatures (F)					Minimum Slab Temperatures (F)				
	CR	Air	Min	Max	Ave	Air	OE	CR	IE	AS	Air	OE	CR	IE	AS
1-W	91	90	81	91	86	81	111	115	106	100	67	89	96	86	84
1-R	85	77	75	80	77	76	120	122	113	102	78	103	108	99	96
3-W	95	81	80	81	80	80	122	131	119	107	76	108	118	105	98
3-R	96	99	84	99	91	84	135	144	130	115	77	108	115	103	98
3-S	95	90	84	90	86	84	130	146	120	112	92	100	116	99	97

OE - Outside Edge CR - Slab Center IE - Inside edge next to adjacent slab

AS - Adjacent Slab

1 - Type I Cement 3 - Type III Cement W - Wet burlap curing R - Curing Compound

S - Blanket Curing

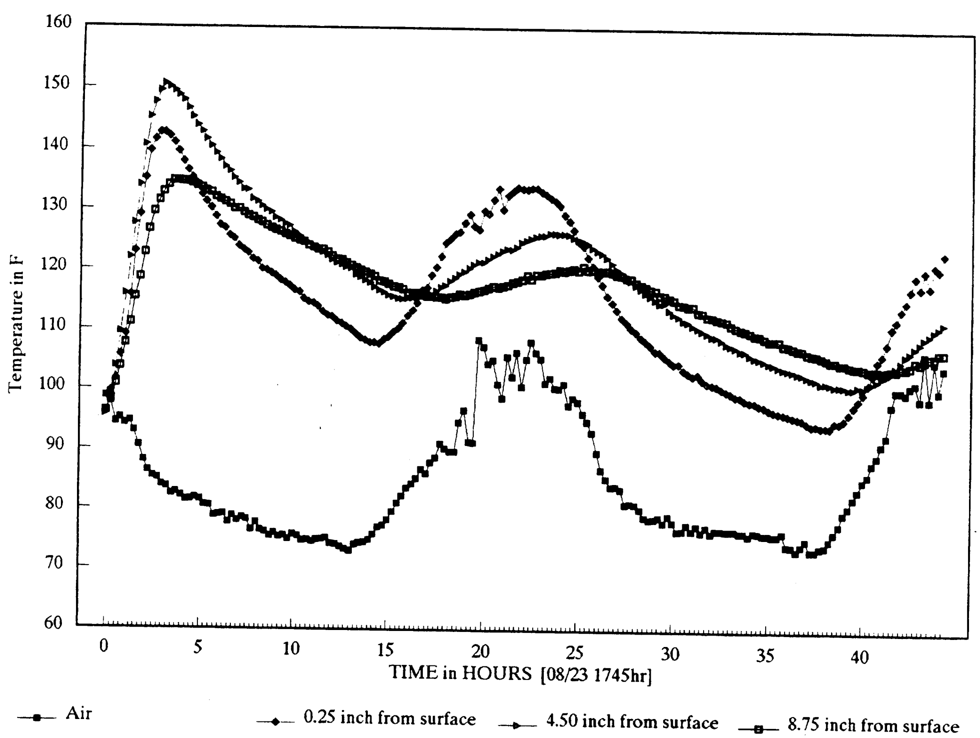

Figure 3 Temperature Variation At Various Depths of Freshly Placed Slab

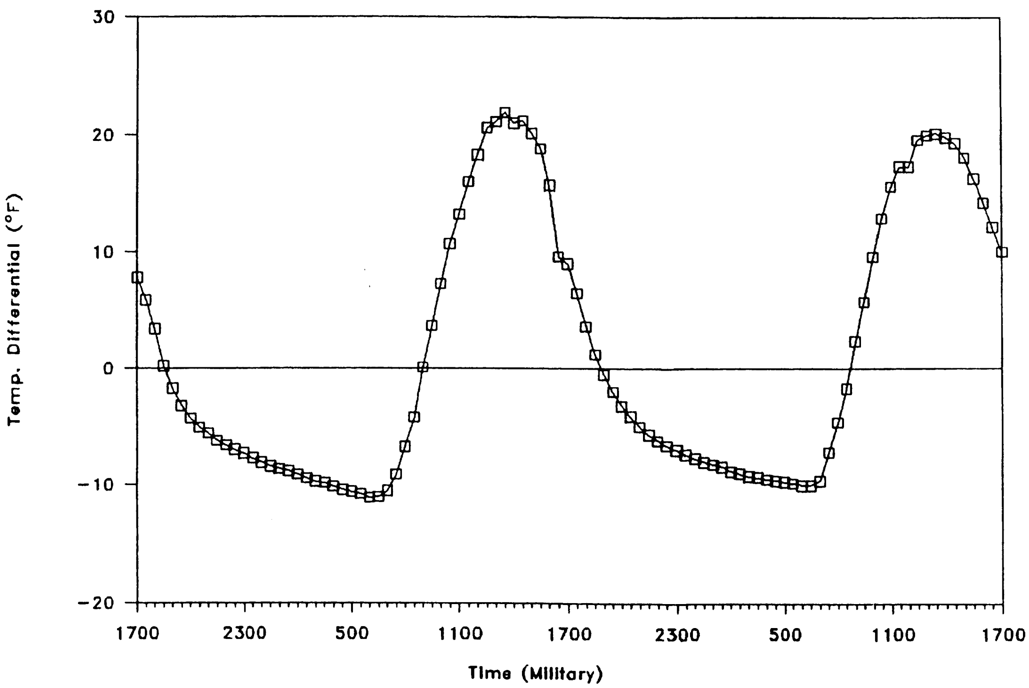

Figure 4 Temperature Differential in a Pavement Slab

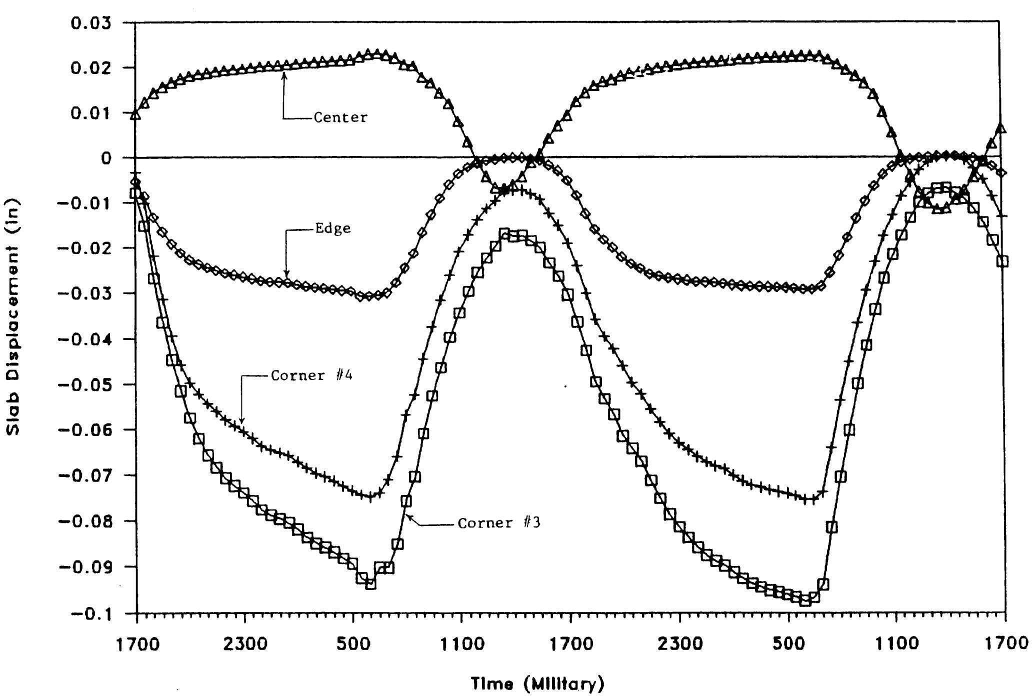

Figure 5 Vertical Displacements in a Pavement Slab

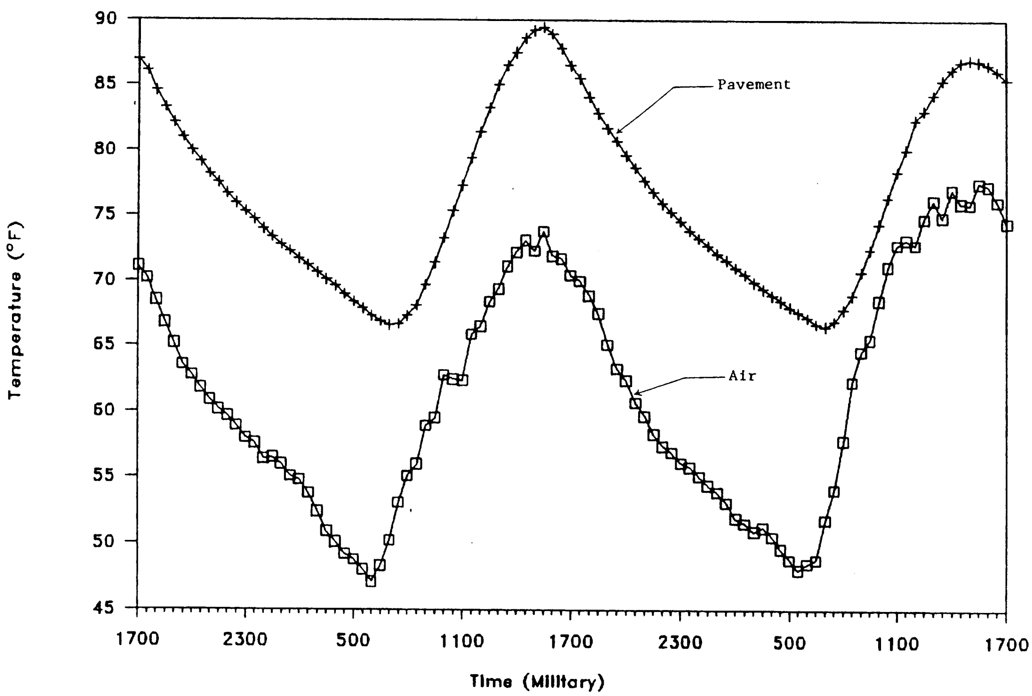

Figure 6 Pavement and Air Temperatures

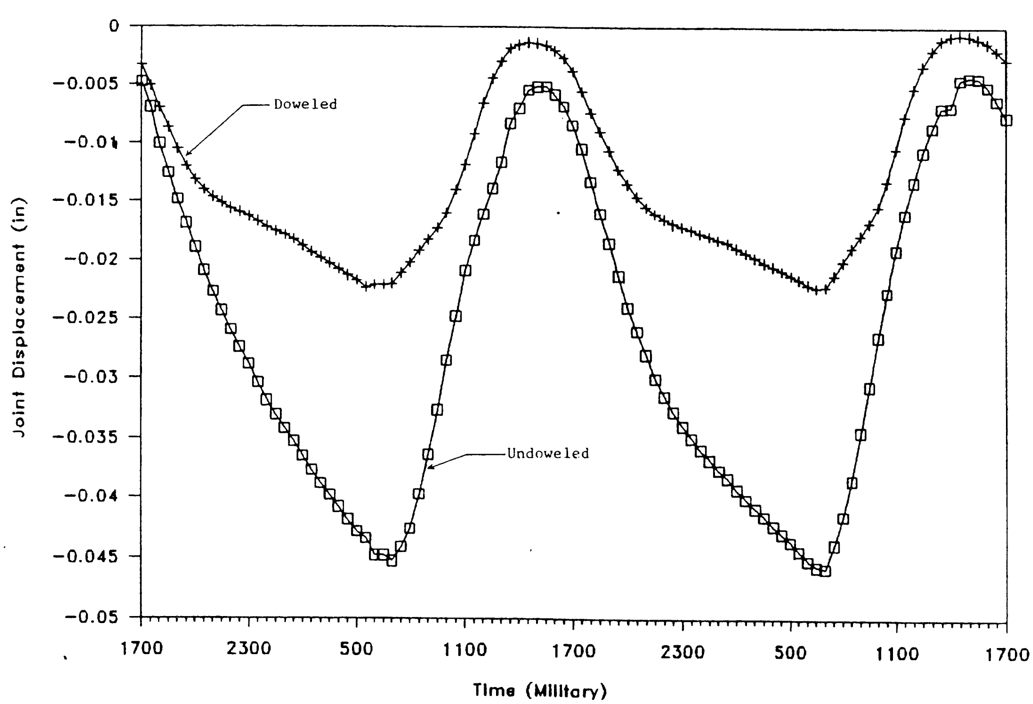

Figure 7 Horizontal Displacements at Doweled and Undoweled Joints

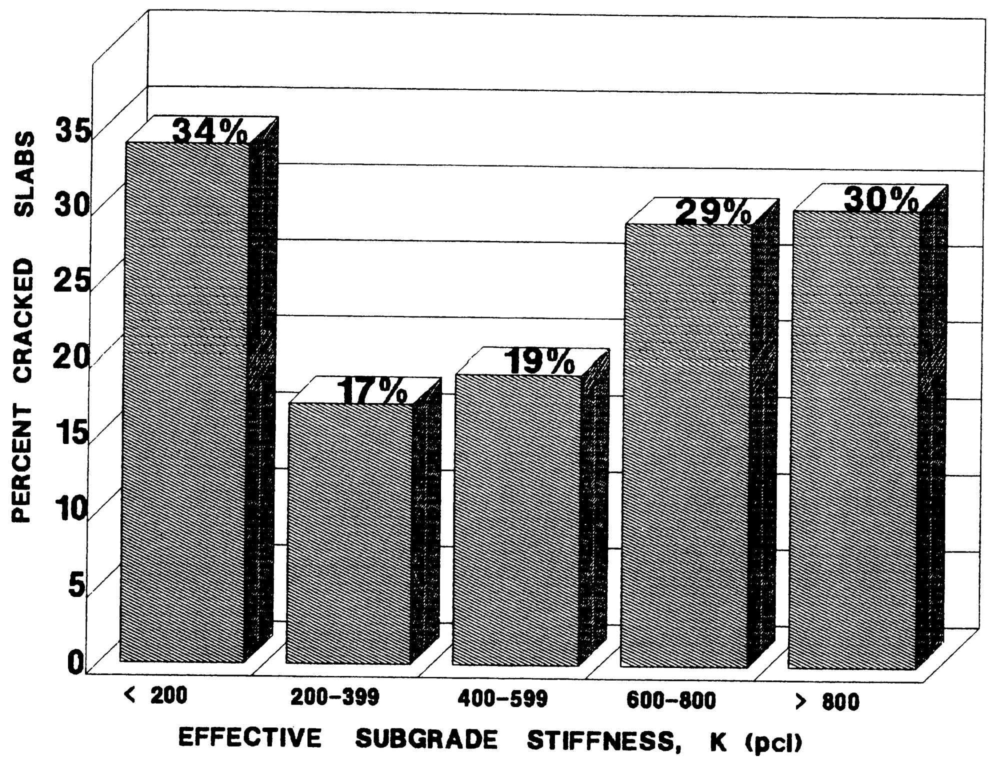

Figure 8 Effect of Subgrade Stiffness on Pavement Cracking