

GUIDELINE RECOMMENDATIONS FOR TIMING CONTRACTION JOINT SAWING OF PCC HIGHWAY PAVEMENTS

Paul A. Okamoto, Peter J. Nussbaum
Kurt D. Smith

CTL, Inc., Skokie, IL
ERES Consultants, Inc., Savoy, IL

Timing of contraction joint sawing is essential to avert ravelling at sawcut edges and uncontrolled cracking of concrete pavements. The objectives of the study, sponsored by FHWA, were to determine the "near" and "far" joint sawcutting window of opportunity and to evaluate nondestructive testing methods and strength indicators that will assist in determining when sawcutting should be initiated. To determine "near" sawing strength indicators, sawing tests were made on large-scale concrete slabs with different aggregates and cement contents. Relationships were developed between surface ravelling, sawcut acceptance rating, and compressive strength. Recommended minimum concrete strengths were developed as a function of cement content and aggregate type. Observations of sawcutting and strength development at several highway projects provided comparisons between laboratory and construction site strength development and sawcut quality. Restraint axial and curling (bending) stresses were also calculated using early age temperature histories of concrete pavements. Observations of sawcutting and strength development at several highway projects provided comparisons between construction site strength development and monitoring of crack development below sawcuts. Early age strength properties developed as part of the laboratory investigation and strengths measured in the field were used with calculated restraint stresses to develop guidelines which can be used to determine the "far" sawcutting limit of opportunity.

INTRODUCTION

Contraction (control) and warping joints are installed in plain and conventionally reinforced portland cement concrete (PCC) pavements to control random slab cracking due to stresses resulting from restraints to temperature and moisture associated concrete dimensional changes. Limits for the "window of opportunity" for sawcutting are as soon as the concrete has hardened to avert excessive ravelling at sawcut edges and before uncontrolled cracking can occur. For highway pavements, joints are sawcut to create a vertical weakened plane, aligning cracks at predetermined joint locations. Joints reduce spalling, facilitate pavement maintenance and sealing, and with proper spacing and/or mechanical devices, provide slab to slab load transfer. To achieve both maximum production rates and aggregate interlock load transfer, joints should be sawed to the minimum permissible depth that will successfully cause a controlled crack. In the past 10 to 15 years, sawcut depths have remained fairly constant for transverse contraction joints, but have increased somewhat for longitudinal joints as a result of experiences with uncontrolled longitudinal cracking. A survey

of U.S. joint construction practices conducted in 1987 showed most States sawing transverse joints to a depth of $D/4$ where D is the pavement depth. (1) Transverse sawcut depths of $D/3$ are used in a few States. Longitudinal joint depths, however, have increased from the previous typical values of $D/4$ or less to $D/4$ or more, with $D/3$ being the most often reported value.

PAVEMENT RESTRAINT STRESSES

Restraint stresses in pavements are due to prevention of deformations in a manner similar to those of fixed end beams where contraction, expansion, and rotations are prevented. Restraint conditions occur at some distance inward from pavement free edges and ends. At edges and ends, deformations occur and restraint stresses increase from zero as distances from slab edges or ends inward towards slab middle are increased. Early age concrete pavement cracking is attributable to axial contraction and bending deformation restraint stresses occurring after initial concrete set. At slab ends where no restraints occur, the uniform axial deformations are recognized as slab end contraction movements. Bending deformations due to thermal gradients are known as slab curling.

Pavement axial contraction can be attributed to both uniform through-slab cross-section reductions of concrete temperature and concrete drying. Upward bending can be attributed to nonuniform concrete temperature and/or nonuniform concrete drying when near concrete slab surface temperature and/or moisture content is less than those near slab bottom. Axial and curling deformations and restraint stresses due to drying are not considered significant for early age plain concrete pavements' non-loading associated cracking because curing compounds used to assure moist curing are applied immediately following surface texturing. Curing compounds prevent surface moisture evaporation that otherwise could contribute to top surface cooling. Also, prevention of top surface drying temporarily maintains a uniform moisture content throughout the pavement cross-section thus providing a zero moisture gradient that could otherwise cause warping restraint stresses at early ages.

Axial contraction restraint stresses are due to friction resistance between slab bottoms and subbase/subgrade surfaces. Stresses increase from zero at slab ends to a maximum value at slab midlength or when the restraint stresses due to friction resistance build up to the full restraint stress attributable to uniform slab cross-section temperature change. Stress due to friction resistance, σ_f , can be calculated according to eq. 1 shown in Fig. 1. Restraint stress, σ_r , at distances from slab

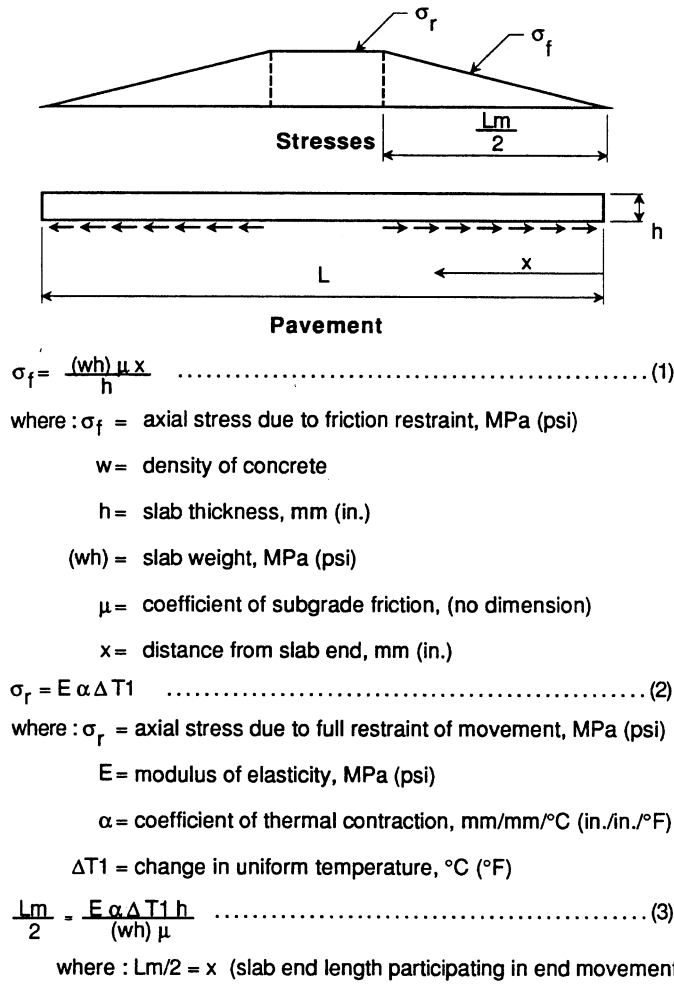


Fig. 1 - Pavement Axial Restraint Stresses

ends greater than the slab length participating in uniform temperature associated movement is shown in eq. 2. Slab end lengths, $L_m/2$, participating in slab end movement can be determined using eq. 3 of Fig. 1.

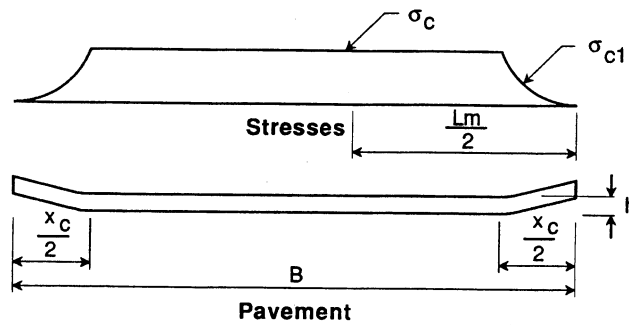
Full bending restraint stresses are due to differences between slab surface and slab bottom temperatures when the stress can not be relieved by curling deformations, that is at greater than critical distances, $x_c/2$, inward from slab edges. At distances less than half the critical distances, x_c , the axial (as opposed to principle) curling restraint stress can be expressed by eq. 4, after Bradbury as shown in Fig. 2.(2) At distances greater than half the critical distance, x_c , the fully restrained axial curling stress is expressed by eq. 5. The coefficient C reaches a maximum value of 1.084 corresponding to a B/L ratio of 8.5. For B/L ratio values greater than 12, the coefficient C is constant with a value of 1.043.

The distance from slab end that full bending (distances greater than $x_c/2$) and axial restraint stresses (distances greater than

$L_m/2$ from slab ends) are attained are 3.1 m (121 in.) and 14.6 m. (576 in.), respectively when eqs. 6 and 3 are solved for the following conditions:

$wh = 0.00599 \text{ MPa}$ (0.868 lb/in. ³)	$E = 13,790 \text{ MPa}$ (2×10^6 psi)
$\alpha = 2.8 \times 10^{-6} \text{ mm/mm/}^\circ\text{C}$ ($5 \times 10^{-6} \text{ in./in./}^\circ\text{F}$)	$\Delta T_1 = 5.6 \text{ }^\circ\text{C}$ (10 °F)
$k = 27.15 \text{ MPa/m}$ (100 lb/in. ³)	$\Delta T_2 = 11.1 \text{ }^\circ\text{C}$ (20 °F)
$h = 254 \text{ mm}$ (10 in.)	$\mu = 2$

The critical distance, x_c , can be calculated by setting $B = 6.7 L$, as shown in Fig. 2 for $C = 1.0$. The error for disregarding C values greater than 1.0 when calculating critical distances is



$$\sigma_{c1} = \frac{CE\alpha\Delta T2}{2} \dots\dots\dots (4)$$

where : σ_{c1} = curling restraint stress for $x < 0.5x_c$, MPa (psi)

E = modulus of elasticity, MPa (psi)

α = coefficient of thermal expansion, mm/mm/°C (in./in./°F)

$\Delta T2$ = temperature difference (slab surface and bottom), °C (°F)

C = curling stress coefficient (Ref. 2)

$$\sigma_c = \frac{1.04 E \alpha \Delta T2}{2} \dots\dots\dots (5)$$

where : σ_c = fully restrained curling stress for $x \geq 0.5x_c$, MPa (psi)

B = slab width or length, mm (in.)

$$x_c = B = 6.7 L \text{ for } C = 1.0 \dots\dots\dots (6)$$

$$\text{where : } L = \left[\frac{E h^3}{12 (1 - \mu_1^2) k} \right]^{1/4} \text{ mm (in.); radius of relative stiffness}$$

h = slab thickness, m (in.)

k = modulus of subgrade reaction, MPa/m (lb/in.³)

μ_1 = Poisson's Ratio

Fig. 2 - Pavement Bending Restraint Stress

8 percent or less. The 14.6 m (48 ft) distance for full axial restraint is reduced to 5.8 m (19 ft) when a subgrade friction factor is increased to 5. Subgrade friction factors of 1.5 to 3.0 have been determined for slabs over granular subbases, whereas friction values of 5 and greater have been determined for pavements supported by stabilized subbases or lean concrete bases (LCB).

For a two-lane road with shoulders, placed in one pass, the paving width is about 11.6 m (38 ft). Thus, at distances of about 3 m (10 ft) from both edges, a mid-portion pavement width of about 5.5 m (18 ft) will experience full curling restraint stresses ($\mu = 2$). The full bending restraint stress, σ_c , is 717 kPa (104 psi), when eq. 5 is solved for the above conditions. Since one-half the distance of a 11.6 m (38 ft) wide pavement is less than the 14.6 m (48 ft) distance to fully develop frictional restraint stresses, eq. 1 is used to calculate the frictional restraint stress, σ_f . Transverse frictional restraint stress for the above conditions is 276 kPa (40 psi). The sum of axial and bending restraint stresses before longitudinal joint

sawing is 993 kPa (144 psi).

Restraint stresses in the longitudinal direction prior to transverse control joint sawing can similarly be calculated. For portions of the pavement at distances greater than about 14.6 m (48 ft) the full axial restraint stress, σ_r , is 689 kPa (100 psi) and the bending stress, σ_c , is 717 kPa (104 psi). The sum of axial and bending restraint stresses before transverse joint sawing is 1.4 MPa (204 psi). The fully restrained longitudinal stress of 1.4 MPa signals that concrete transverse control joint sawcutting should be done ahead of significant temperature drops that can contribute to restraint stresses.

INVESTIGATION OF EARLIEST JOINT SAWCUTTING

To determine the "near" time after concrete placement that sawcutting can be initiated, slabs were constructed in an exterior area and sawcut to one-third slab depth over a range of

time after concrete placement. Sawing strip slabs, 6 m (20 ft) long, 1.3 m (50 in.) wide, and 254 mm (10 in.) thick were constructed between two concrete strips that acted as longitudinal edge forms. Slabs were constructed using three different coarse aggregates (crushed limestone, crushed quartzite, and rounded river gravel) at two cement contents (297 kg/m³, 500 lb/yd³ and 386 kg/m³, 650 lb/yd³). One slab was replicated to evaluate sawcutting with an abrasive blade. White pigmented curing compound was applied to slab surfaces upon completing light broom surface texturing so that any ravelling occurring as a result of sawcutting could be easily noted and measured.

A 48 kW (65 horsepower) walk-behind saw operated at about 1500 rpm was used for making sawcuts. To minimize operator bias the saw was operated by a technician with limited experience with concrete sawing. Guidance for sawcutting was provided by two saw blade manufacturers. To achieve representative sawcuts, manufacturers each supplied two pre-seasoned 363 mm (14.3 in.) diameter blades. Each supplied blades designated for sawing concrete produced using crushed limestone and hard coarse aggregate. The diamond impregnated blades made approximately 4 mm (0.16 in.) wide sawcuts. Sawcut length was about 5 m (17 ft) for each cut. At midlength of each cut, one manufacturer's blade was removed and the second manufacturer's blade was fixed to the saw mandrel.

Sawcutting was initiated within a time after concrete placement that would produce a sawcut with severe concrete ravelling. About 3 to 6 additional cuts were made to finally produce a sawcut without ravelling. The slab age in hours to final sawcut, that is a sawcut with no ravelling ranged from 3.9 to 12.1 hours. Concrete temperature at last sawcut ranged from 34 to 46 °C (93 to 115 °F).

Sawcut Ratings

Engineers experienced with concrete pavement construction qualitatively rated sawcuts made on each slab. The rating panel consisted of 15 members who were provided with the following guidelines :

Rating = 1 - badly spalled - sawcut way too early
 Rating = 2 - unacceptable
 Rating = 3 - acceptable if sealant reservoir widening is to be done
 Rating = 4 - good
 Rating = 5 - excellent

Measurements were made on sawcuts to determine the surface area of concrete sawcut edge ravelling (excluding sawcut width). Ratings versus average ravelled surface area per unit length of sawcut are shown in Fig. 3. For a sawcut with an "acceptable" rating (R = 3) and a "good" rating (R = 4), the amount of concrete sawcut edge ravelling is 79 mm²/m (24 mm²/ft) and 14 mm²/m (4.3 mm²/ft) of sawcut length, respectively.

Petrographic Examination of Hardened Concrete Sawcut at Early Ages

Three concrete cores were cored from different slabs with sawcuts made at ages of 11, 5.5, and 3.5 hours, respectively. The following conclusions were based on results of the petrographic concrete core examinations:

- If no surface ravelling is observed there are no major internal cracks or spalls associated with sawcutting regardless of time of sawing, cement content,

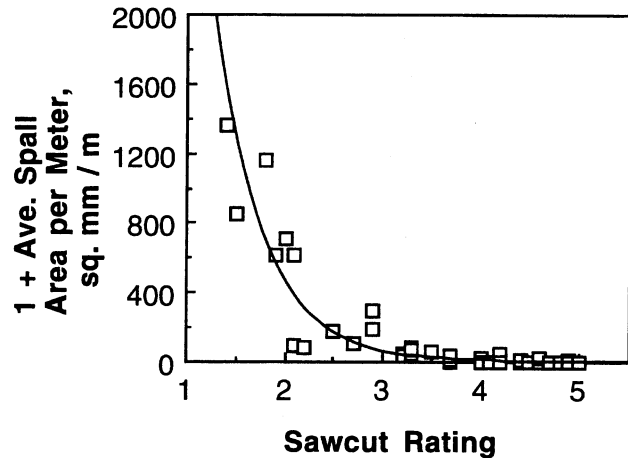


Fig. 3 - Surface Distress Rating Model

aggregate type, or type of saw blade.

- Concrete immediately adjacent to sawcuts (0.5 to 0.8 mm from the edge of sawcut wall) is very slightly eroded. The observed erosion is a minor form of damage that is a result of early sawing of soft, incompletely hydrated cement. The small amount of paste and mortar erosion should not affect integrity or durability of concrete adjacent to the sawcuts.

Sawcut Ratings and Concrete Strength Required for Sawcuts

Compressive strength was selected as a suitable early sawing criteria. Insitu slab compressive strengths were obtained by averaging compressive strength determined with the Nurse-Saul maturity and pulse velocity nondestructive testing methods. Compressive strength was related to sawcut ratings as follows:

$$(f'_c)^{1/2} = 13.9432 + 5.1931 \cdot R + 8.7086 \cdot H + 5.4198 \cdot G - 0.0263 \cdot C$$

$$R^2_a = 0.917 \dots \dots \dots (7)$$

where

f'_c = concrete compressive strength, psi
 (100 psi = 0.69 MPa)
 R = sawcut rating
 H = coarse aggregate hardness (soft = 0, hard = 1)
 G = coarse aggregate geometry (rounded = 0, crushed = 1)
 C = cement content, lb/yd³ (500 lb/yd³ = 297 kg/m³)

Concrete strengths to produce sawcuts with acceptable or better ratings are greater for mixes made with 297 kg/m³ (500 lb/yd³) than those made with 386 kg/m³ (650 lb/yd³) of cement. Higher strengths are also required with harder and/or crushed coarse aggregates. The "round soft" coarse aggregate type was not investigated in the slab sawing study. Effects of this aggregate type should be further investigated since the dummy variables for aggregate hardness and geometry only account for qualitative not quantitative effects on concrete

compressive strength.

Eq. 7 was used to generate required concrete compressive strengths for producing acceptable (rating 3) and good (rating 4) sawcuts. These required strengths are listed in Table 1 for a range of concrete mix constituents. The required strength range to produce acceptable or good sawcuts between 297 and 386 kg/m³ of cement for a given coarse aggregate geometry and hardness can be attributed to amount of cement paste volume. If the amount of paste volume is set proportional to cement content, then a ratio of 297 to 386 or a 0.769 paste volume adjustment factor can be considered for adjusting strength requirements for sawcutting. For example, the concrete mix produced with crushed hard coarse aggregate and 297 kg/m³ (500 lb/yd³) of cement had a required 6.4 MPa (930 psi) strength for making an "acceptable" (rating 3) sawcut. To normalize the required strength by paste volume (referenced to 386 kg/m³, 650 lb/yd³, cement content), the 6.4 MPa is multiplied by the paste volume factor to adjust required strength for the lesser paste volume. The 4.9 MPa adjusted strength is very close to the 4.8 MPa strength determined for the 386 kg/m³ (650 lb/yd³) cement content. Adjustments to account for the reduced 297 kg/m³ (500 lb/yd³) mix paste volume will significantly narrow the spread between strength requirements for 297 (500 lb/yd³) and 386 kg/m³ (650 lb/yd³) mixes observed in Table 1. Similar adjustments can be used to determine minimum compressive strength for acceptable sawcuts at other cement contents.

Table 1 - Required f'c for Acceptable Ratings for Different Mixes

Aggregate Geometry	Aggregate Hardness (2)	Cement Content, kg/cu m	Sawcut Rating (1)	
			3	4
Crushed	Soft	297	3.3	5.0
		386	2.2	3.7
Crushed	Hard	297	6.4	8.8
		386	4.8	7.0
Rounded	Soft	297	1.9	3.2
		386	1.0	2.1
Rounded	Hard	297	4.3	6.3
		386	3.1	4.8

NOTES:

- Rating '3' = acceptable if sealant reservoir is to be widened.
Rating '4' = good
- Minimum concrete compressive strength in MPa.
Estimated "rounded soft" aggregate strength from qualitative dummy variable.
Aggregate type not investigated in sawing study.
- 500 pcy = 297 kg/cu m.

Highway Pavement Sawcutting Observations

To verify and test the joint sawing criteria and nondestructive test methods used in construction of full-scale sawcutting test slabs, three field sites were selected. Details of the three sites are summarized in Table 2. Compressive strength was estimated using pulse velocity relationships developed from early age field cured cylinder data. Specimens were tested in the field using a portable compression machine.

Most spalling observed was at sawcut intersections when longitudinal joint sawing crossed sawed transverse joints. At the Iowa and Utah sites, longitudinal sawing was done immediately following transverse joint sawing. Use of a plastic insert strip in Wisconsin eliminated the longitudinal sawed joint. Spalling at joint intersections consisted of small corner breaks of mortar or aggregate dislodgement, generally less than 3.2 cm² (1/2 in²) area.

Intersecting sawcuts and minor spalling also occurred at the Utah site when spansaw cuts overlap. Multiple blades on the spansaw, used to cut short segments, overlapped to form a single cut joint. Due to slight shifting of equipment and/or alignment of the spansaw frame, cuts did not always coincide and hence small slivers of concrete were formed. The dimensions of concrete wedges were dependent on the degree of horizontal saw misalignment and when the operator raised the spansaw from the pavement. Some small thin wedges of concrete broke off or may potentially break in the future.

Other types of noted distress occurred at sawcuts crossing relatively deep tining marks. Since joints were skewed, the angle of cut crossing tining marks tended to ravel small concrete wedges. These ravelled areas did not appear to be deeper than the tining marks and should not affect the overall future joint integrity. In Wisconsin the use of a weighted ribbon placed on the surface at the joint location prior to tining reduced subsequent sawcut ravelling. At joints where the sawcut did not coincide with the ribbon location, some ravelling at joints crossing deeper tining marks was observed.

In Iowa, small minor amounts of surface joint ravelling due to the abrasive blade was minor and did not appear to extend deeper than the surface mortar layer. Use of the abrasive blades did require frequent replacement. As blade wear occurred the depth of cut was reduced. To maintain the specified minimum sawcut depth and joint depth, blade wear was frequently checked.

Verification of Sawcut Joint Ratings - Compressive Strength Model

Ratings of each sawcut were backcalculated from measured surface distress using Fig. 3. Ratings in Iowa ranged from 2.7 to 5.0 and averaged 3.4 for the 23 joints surveyed. If shallow surface mortar ravelling distress is excluded the average rating increased to approximately 4.0. Compressive strength ranged from 1.4 to 6.9 MPa (200 to 1000 psi) and averaged 3.4 MPa (500 psi) at the time of sawing.

For the Utah study, sawcut ratings ranged from 1.9 to 5.0 and averaged 4.1 for the 74 joints surveyed. If distress due to overlapping gang saw cuts (equipment operation) rather than material properties is excluded, the joint ratings were slightly better. Compressive strength at the time of sawing at the Utah site ranged from 1.7 to 12.1 MPa (250 to 1750 psi) and averaged 6.3 MPa (910 psi).

Table 2 - Field Study Project Details

	Iowa US HWY 169	Utah I-15	Wisconsin I-94
Paving Time	mid-August mid to late morning	late-August mid-morning and late night	early-October early to mid-morning
Weather	upper 70s to mid 80's sunny, windy, humid	low 60s to mid 90's sunny, windy, low humid.	upper 40s to low 70's partly sunny
Slab Thickness, mm	254	254	305
Transverse Joint Type	3.175 cm dia. dowels skewed at 6 m	aggregate interlock skewed at 4.6, 3.4, 3.0, 4.3 m	3.81 cm dia. dowels skewed at 4.0, 5.8, 5.5, 3.7 m
Subbase	granular	lean concrete	granular
Coarse Aggregate Type	crushed limestone	crushed granite and quartzite	crushed limestone virgin and recycled
Cement Content, kg/cu m	289	362.5	314.4
Max. Concrete Temp., °C* (762 mm inward at sawcut elev.)	41	48	37
Sawing Time	early pm	early am and pm	early to late pm
Sawing Equipment	48 kW walk-behind abrasive blade	spansaw and 48 kW saws diamond blade	48 kW walk-behind diamond blade

In Wisconsin, sawcut ratings ranged from 2.8 to 5.0 and averaged 4.3 for the 23 areas (4 joints per sample) surveyed. Compressive strength at the time of sawing ranged from 1.0 to 3.3 MPa (140 to 485 psi) and averaged 2.1 MPa (310 psi). Most ravelling occurred at the skewed joints where the sawcut deviated from the untined surface strip (weighted ribbon placed on pavements prior to tining).

The compressive strengths at sawcutting versus ratings (backcalculated from ravelled areas) are shown in Fig. 4 for the Iowa, Utah, and Wisconsin data. The majority of the ratings data is above the predicted rating indicating that the laboratory compressive strength-sawcut rating model is conservative. The resulting sawcut surface rating was generally greater than what the laboratory model would predict given the compressive strength. For the Iowa, Utah, and Wisconsin field studies, 83, 68 and 100 percent of the joints, respectively, could be cut at a lower strength than that predicted by the sawing strip model. Of the joints with ratings of less than 5, the laboratory developed rating model overestimated by more than one-half a rating point 4, 36, and 0 percent of the joints for the Iowa, Utah, and Wisconsin projects, respectively. Of the 13 joints in Utah where the rating model overpredicted the observed surface ravelling, 7 corresponded to joints where deep tine marks were broken off or where the spansaw blade overlapped at a slight angle. Distress at these joints was caused by equipment rather than material properties. Excluding these 7 joints, the percentage of overestimated ratings for the Utah project decreased from 36 to 26 percent.

INVESTIGATION OF LATEST JOINT SAWCUTTING

Joint sawcutting must be done after the concrete has developed enough strength to prevent ravelling and before combined axial and bending restraint stresses exceed the concrete tensile strength. If joints are not cut deep enough or soon enough random cracking will occur. Field site temperature data were used to investigate strength development and compared to calculated restraint stresses. Temperature data were recorded for about 12 hours from concrete placement at the Utah site, about 10 hours at the Iowa site, and about 14 hours at the Wisconsin site. Temperatures are shown in Figs. 5 and 6 for one joint at the Utah and Iowa projects, respectively. Slab surface temperatures were measured by placement of a thermocouple weighted with a wood block on the slab surface. Thermocouples were also positioned at about 51 mm (2 in.) below slab surface approximately 760 mm (30 in.) from the edge, at slab mid-depth, and near slab bottom. Thermocouples were also placed at the interior of concrete cylinders stored at side of pavement slabs. Ambient temperatures were monitored with a thermocouple located near pavement edge. Temperature data were used to calculate pavement restraint stresses and concrete strength. Slab bottom versus slab surface temperature differences needed to cause cracking below sawcut notches were calculated by balancing concrete tensile strength with sum of restraint stresses.

Temperatures monitored at three joints at the Wisconsin project did not show significant temperature fluctuation for the first 14

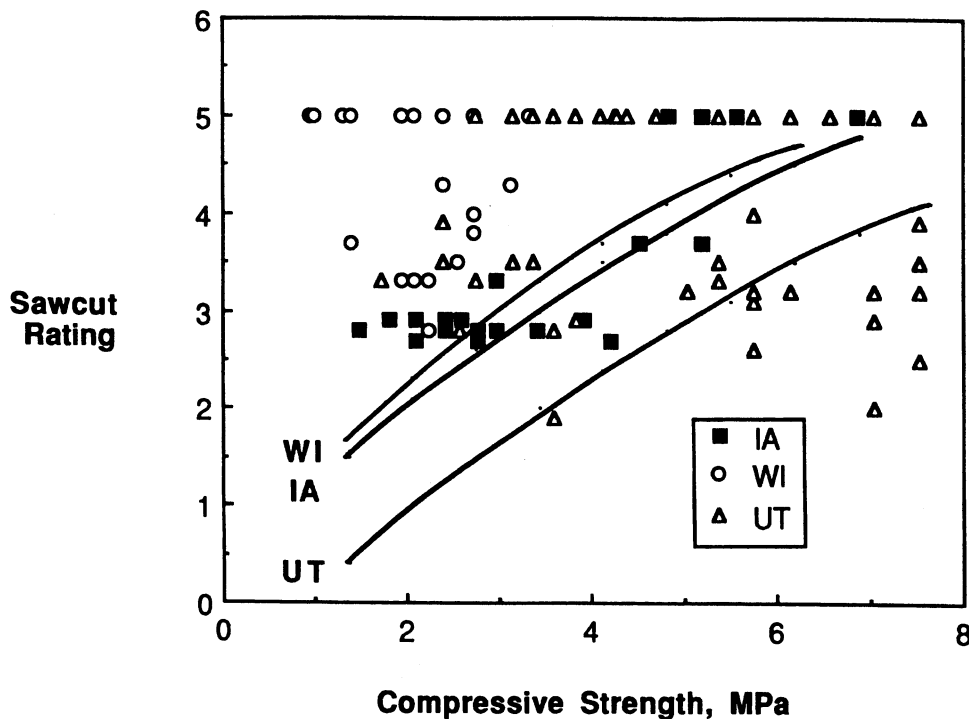


Fig. 4 - Sawcut Ratings vs Compressive Strength

hours after placement. Maximum temperature difference between top and mid-depth was less than 4.2 °C (7.5 °F). Average temperature difference for three joints monitored ranged from 1.8 to 2.1 °C (3.2 to 3.8 °F). Small temperature differentials within the slab did not cause high restraint stresses to initiate cracking below sawcut notches. The low thermal restraint stresses during the first night when split tensile strength is lowest and temperature decrease is relatively high, was confirmed by the lack of joint cracking observed one week after construction. Of the 50 joints surveyed only 29 joints were cracked. Crack widths averaged 2.3 mm (0.090 in.) and were significantly larger than those measured at the Utah and Iowa projects where all joints were active within 20 hours of sawing.

Temperature Observations

For the Utah pavement, as shown in Fig. 5, air and within concrete slab temperature followed a rising trend until about 9 hours after concrete placement. Maximum concrete surface temperature, of 47 °C (117 °F), was attained at about 9.5 hours. Based on temperature data the concrete was in a compression mode at least up to the moment of maximum concrete temperature. Near slab bottom temperatures lagged near surface temperatures and levelled off at 38 °C (100 °F) about 10.5 hours after concrete placement. Maximum cylinder temperature was about equal to maximum slab surface temperature. Cylinder temperature trends followed slab surface trends. Surface temperature showed a precipitous drop starting about 9-1/2 hours after concrete placement and the surface had cooled to 29 °C (85 °F) just after the 11-1/2 hour age. Rapid surface cooling was attributed to pavement surface evaporation or cooling when joint sawing activities

caused pavement wetting. Concrete temperature at 76 mm (3 in.) from the surface followed the same trend as the surface temperature. The temperature below the surface peaked at the same time but was 3 °C (6 °F) cooler than the surface temperature. Air temperatures gradually increased from 20 °C (68 °F) and peaked at 34 °C (93 °F). The air, cylinder, surface, and near-surface temperatures all peaked between 8-1/2 and 9-1/2 hours.

For the Iowa pavement, as shown in Fig. 6, a rising concrete temperature trend was observed to about 6 to 7 hours after concrete placement. The recorded surface temperature was lower than temperatures recorded at 51 mm (2 in.) below slab surface. This was not a reasonable scenario since surface temperatures on clear days with summertime solar radiation exposure are usually higher than below surface temperatures. To obtain near surface and near slab bottom temperatures, the cylinder temperature data was used as a surrogate for surface temperature. The bottom of slab thermocouple at the Iowa site provided inconsistent data and was not analyzed. Slab bottom temperature was estimated at the time of maximum surface temperature by assuming a linear temperature gradient passing from slab top (cylinder) through mid-slab temperature to slab bottom. For a maximum 43 °C (109 °F) surface (cylinder) temperature at age 6.6 hours and 42 °C (108 °F) at mid-slab, the bottom temperature was estimated at about 41 °C (106 °F). Bottom slab temperature can be assumed to be constant, similar to the Utah condition, for several hours following top surface maximum temperature observations. The top surface temperature and midslab temperatures indicate that slab cooling started at about 6.5 hours. At 9.6 hours, slab top (cylinder) had cooled to about 33 °C (91 °F) and slab bottom had cooled to about 39 °C (102 °F) from 41 °C (106 °F) at concurrent top

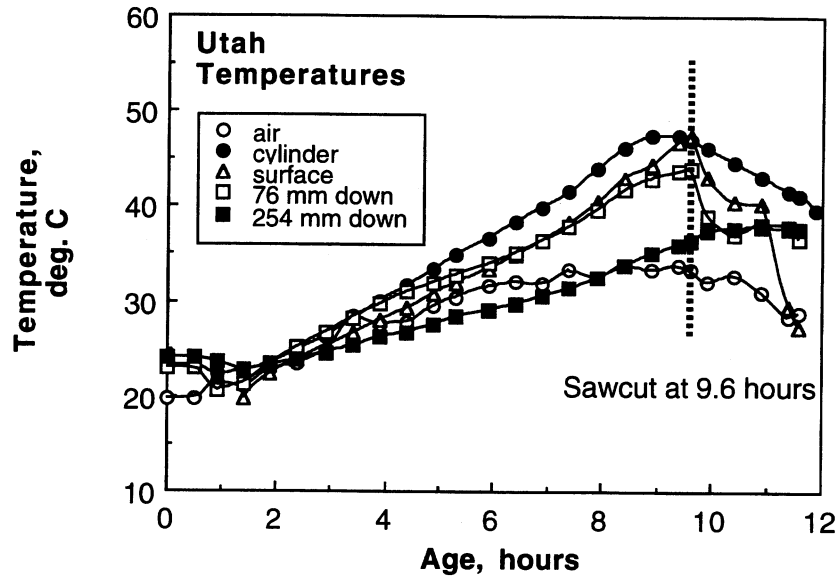


Fig. 5 - Utah Temperatures

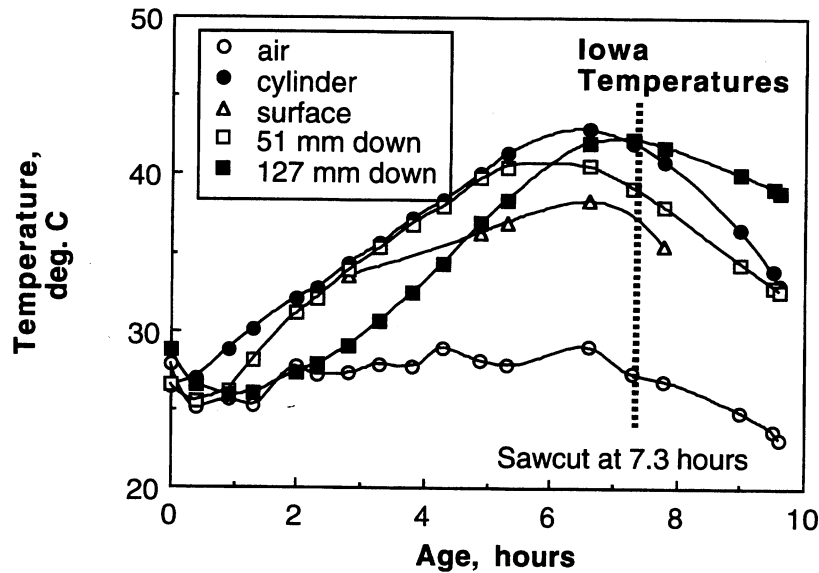


Fig. 6 - Iowa Temperatures

surface maximum temperature condition. Slab bottom temperature was assumed equal to temperature at mid-depth.

Pavement Restraint Stresses

Shortly after initiation of concrete cooling, the concrete slabs are considered to pass from a state of compression to a state of tension. Pavement restraint stresses can be calculated using eqs. 1 and 2 in Fig. 1 (axial) and eqs. 5 and 6 in Fig. 2 (bending). Compressive strength was monitored using site-specific NDT relationships developed from early age field

cured cylinder data. Modulus of elasticity and split tensile strengths were estimated using relationships developed from early age laboratory test data.(3) A coefficient of thermal contraction of 2.8×10^{-6} mm/mm/°C, 5×10^{-6} in./in./°F, and a concrete density of 2400 kg/m^3 (150 lb/ft^3) were used in the calculations. A modulus of subgrade reaction of 67.9 MPa/m (250 lb/in.^3) and 190.0 MPa/m (700 lb/in.^3) was assumed for the Iowa (granular subbase) and Utah (LCB) pavements, respectively.

Restraint Stresses at Time of Utah Joint Sawcutting

Joint sawing, as shown in Fig. 5 was done at an age of 9.6 hours. At that moment concrete surface temperature peaked at 47 °C (117 °F). At slab bottom concrete temperature was about 37 °C (98 °F) and increasing. No slab cooling had occurred prior to sawcutting and slab near surface temperatures exceeded near slab bottom temperatures. Thus, the concrete was in compression when sawing was done.

Restraint Stresses at 2 Hours after Utah Joint Sawcutting

Curling restraint stresses at 11-1/2 hours in the transverse direction for the 254 mm (10 in.) thick pavement were about 0.6 MPa (88 psi) for the 9 °C (17 °F) slab bottom to top temperature differential. Since 1/2 the pavement width was greater than the 1.9 m (6.2 ft) minimum distance required to fully develop stresses, eq. 5 shown in Fig. 2 was used to calculate bending restraint stress. A 13,790 MPa (2 million psi) modulus of elasticity for the 11 hour age obtained from Fig. 7 was used for the curling stress calculation. Axial restraint stress in the transverse direction, using a slab to subbase friction value of 5 and average temperature drop of 8 °C (15 °F), was 0.7 MPa (99 psi) for the 11.6 m (38 ft) wide pavement. Axial restraint was calculated using eq. 1 since 1/2 of the 11.6 m (38 ft) pavement width was less than the 8.8 m (29 ft) needed to develop full axial restraint stresses. The total calculated maximum restraint stress (mid-width) was 1.3 MPa (187 psi) for the 254 mm (10 in.) pavement. The longitudinal joint in closest proximity to pavement mid-width was 4.9 m (16 ft) from a free edge. At this distance fully developed bending restraint stresses still occurred. Total calculated restraint stress at the longitudinal joint alignment was 1.2 MPa (171 psi) for the above conditions. After sawcutting the joint to 1/3-slab depth, total restraint stress at the reduced section was increased by 50 percent to 1.8 MPa (257 psi). This was greater than the approximately 1.3 MPa (190 psi) insitu concrete split tensile strength estimated from Fig. 8, for the 11-1/2 hour age. Slab compressive strength, as shown in Fig. 7, was estimated using pulse velocity data. Modulus of elasticity and split tensile strength were estimated using

prediction relationships developed in the laboratory study of early age concrete properties.

Fully developed axial restraint stresses at 11-1/2 hours in the longitudinal direction using eq. 2 were 1.0 MPa (150 psi) for an average temperature drop of 8 °C (15 °F). Average temperature (top, near top, and bottom) at peak surface temperature was 42.8 °C (109 °F) and at 11-1/2 hours was 34 °C (94 °F). Full bending restraint stress was 0.6 MPa (88 psi). Total full section restraint stress was 1.6 MPa (238 psi). After sawcutting the total restraint stress was increased by 50 percent to 2.5 MPa (357 psi). Since the reduced section stress was greater than the 1.3 MPa (190 psi) strength some transverse joints within two hours after sawcutting would be cracked to relieve restraint stresses. If every other joint cracked, the effective slab length was reduced to approximately 7.6 m (25 ft) for the staggered joint spacings. At 3.8 m (12.5 ft) from cracked joints in the longitudinal direction, axial restraint calculated using eq. 1 (partial restraint) was reduced to 0.4 MPa (65 psi). Total full section restraint was 1.1 MPa (153 psi). Reduced section restraint stresses of 1.6 MPa (230 psi) exceeded the 1.3 MPa (190 psi) strength.

After cracking at all transverse joints axial restraint stresses were reduced to 0.2 MPa (33 psi). Total full section restraint stresses for a 8.3 °C (15 °F) temperature differential were reduced to 0.8 MPa (121 psi). Reduced section restraint stresses of 1.3 MPa (182 psi) were less than the concrete strength two hours after sawing.

Restraint Stresses at Time of Iowa Joint Sawcutting

Joint sawing, as shown in Fig. 6, was done at 7.3 hours concrete age. At that moment the surface temperature (surrogate cylinder) was 42 °C (108 °F). At slab mid-depth, temperature was also about 42 °C. Slab bottom temperature was about 41 °C (106 °F). Concrete temperature had, on average, dropped by less than 0.6 °C (1 °F). Thus, it was concluded that the slab was at or very near a zero stress condition, that is it was in transition from a compression mode coinciding with rising average concrete temperature to a tension mode coinciding with cooling average concrete

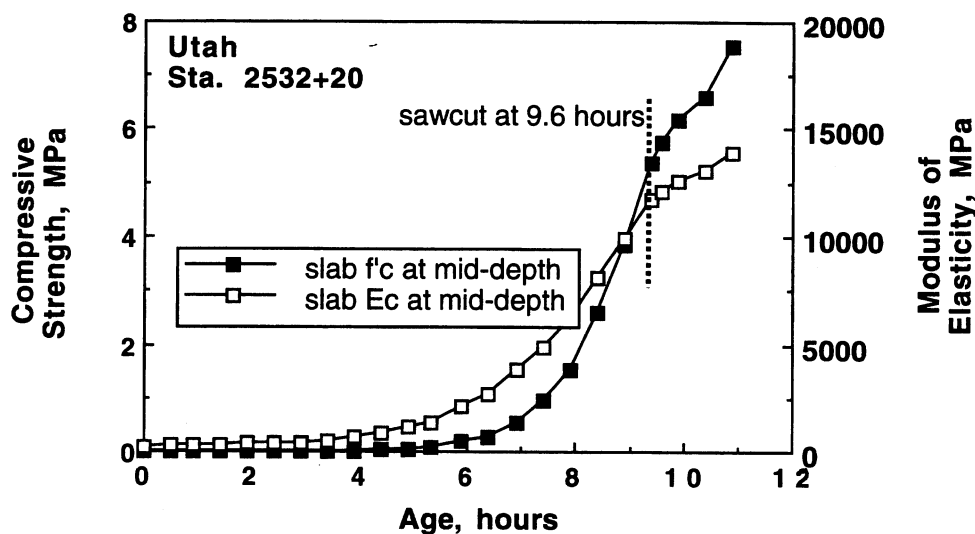


Fig. 7 - Utah Compressive Strength and Modulus of Elasticity Development

temperature.

Restraint Stresses at 2 Hours After Iowa Joint Sawcutting

Curling restraint stresses in the transverse direction for the 254 mm (10 in.) thick pavement were 0.5 MPa (69 psi) for the 6 °C (11 °F) slab bottom to top temperature difference. Since 1/2 the 7.3 m (24 ft) wide pavement is greater than the 2.6 m (8.4 ft) distance to develop maximum bending restraint, eq. 5 was used. A 16,550 MPa (2.4 million psi) modulus of elasticity obtained from Fig. 9 for the approximately 9.3 hour concrete age was used for the curling stress calculation. Axial restraint stress in the transverse direction was 0.3 MPa (37 psi). Partially developed axial restraint stresses for the 4 °C (8 °F) average temperature drop were calculated using eq. 1 since 1/2

the pavement width was less than the 9.4 m (31 ft) needed to develop full restraint. A friction value of 3 was used for the crushed stone subbase as the concrete will key to subbase surface. Total full section restraint was 0.7 MPa (106 psi) in the transverse direction. Joints were sawcut to 1/3-slab thickness and the total restraint stress at the reduced section was increased by 50 percent to 1.1 MPa (159 psi). This was less than the 1.4 MPa (210 psi) split tensile insitu concrete strength as shown in Fig. 10 for the 9.3 hour age. Slab compressive strength, as shown in Fig. 9, was estimated using maturity data. Modulus of elasticity and split tensile strength were estimated using prediction relationships developed in the laboratory study of early age concrete properties.

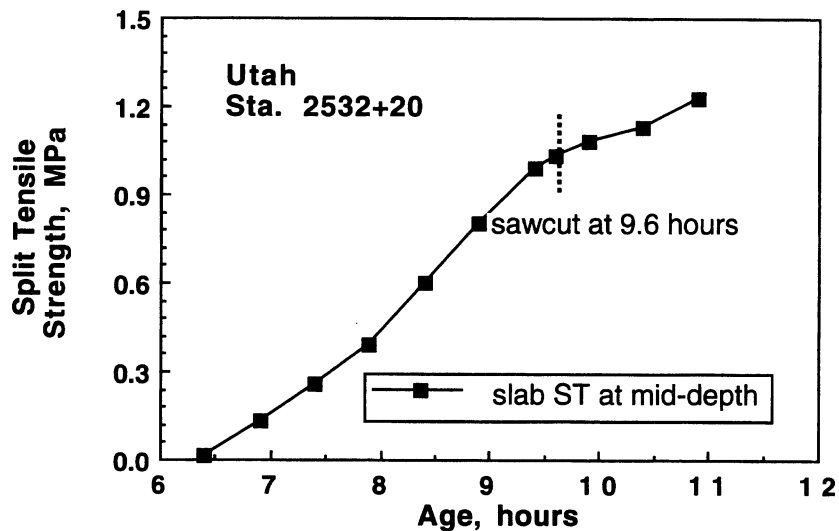


Fig. 8 - Utah Split Tensile Strength Development

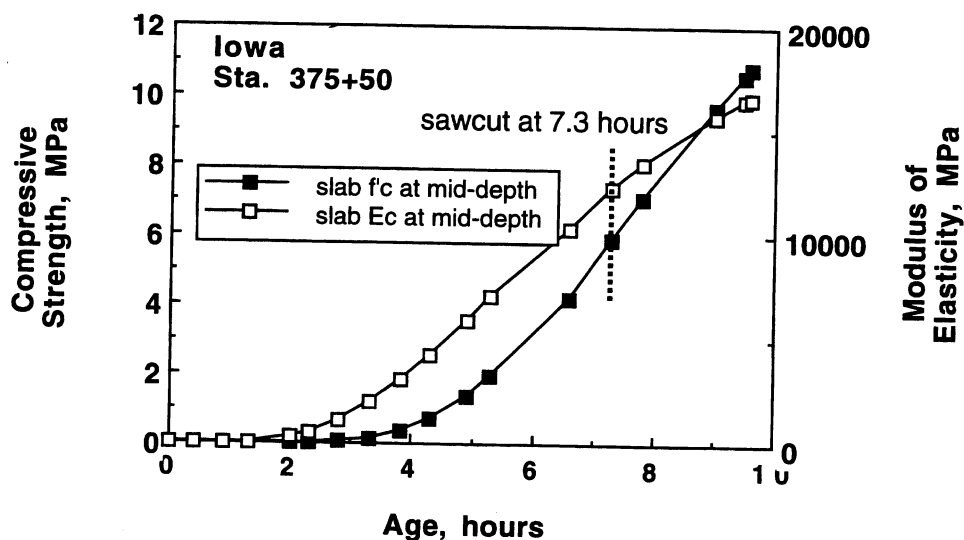


Fig. 9 - Iowa Compressive Strength and Modulus of Elasticity Development

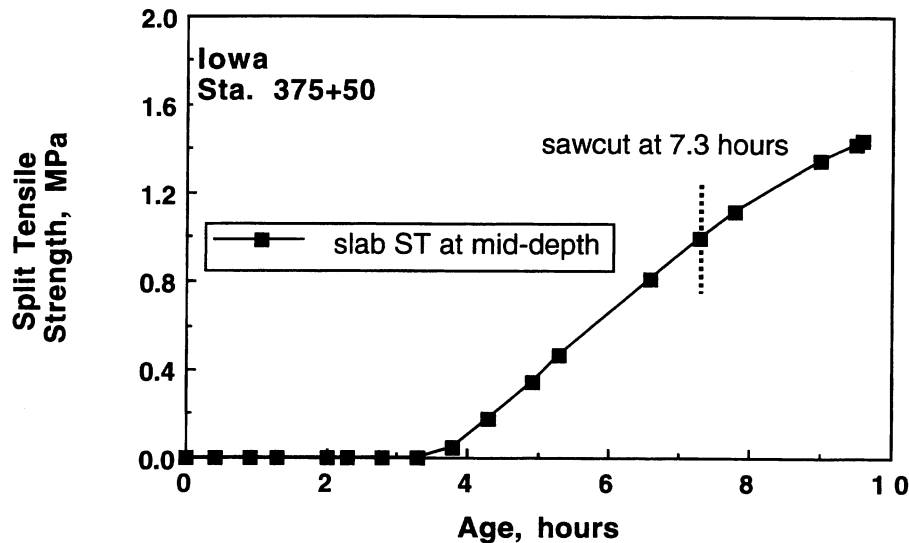


Fig. 10 - Iowa Split Tensile Strength Development

Curling restraint stress for the 6 °C (11 °F) temperature differential in the longitudinal direction as calculated above was 0.5 MPa (69 psi). Fully developed axial restraint stress was 0.6 MPa (96 psi) as calculated using eq. 2 with an average temperature decrease of 4 °C (8 °F). Average temperature (top, near top, middle, and bottom) at peak surface temperature was 42 °C (107 °F) and at 9.3 hours was 37 °C (99 °F). Total full section restraint was 1.1 MPa (165 psi). Reduced section restraint stresses of 1.7 MPa (248 psi) exceeded the 1.4 MPa (210 psi) concrete strength.

If every other transverse joint cracked the effective slab length becomes 12 m (40 ft). At 6 m (20 ft) from cracked joints partially developed axial restraint stress was 0.4 MPa (62 psi). Total restraint stress at the sawcut location midway between joints with assumed cracks was 0.9 MPa (131 psi). Reduced section restraint stresses were 1.36 MPa (197 psi). This was less than the 9.3 hour age 1.45 MPa (210 psi) split tensile strength.

Cracking Below Sawcut Notches

Cracks were observed below all transverse joint sawcut notches within 20 hours concrete age, that is the morning following the paving day for both the Utah and Iowa pavements. Split tensile strength is considered to be equivalent to direct tensile strength. For a slab without sawcuts at the moment of incipient cracking, split tensile strength balances the sum of curling and axial restraint stresses as shown below:

$$ST = \sigma_c + \sigma_f \dots \dots \dots (8)$$

where

ST = split tensile strength
 σ_c = bending restraint stress (curling)
 σ_f = frictional restraint stress (axial)

Using eq. 1 in Fig. 1 and eq. 5 in Fig. 2 and transposing:

$$\Delta T_2 = 2 (ST - wh\mu x/h) / (1.04E\alpha) \dots \dots \dots (9)$$

where

ΔT_2 = slab top to bottom temperature differential, °C (°F)
 ST = split tensile strength, MPa (psi)
 wh = weight of concrete, MPa (psi)
 h = slab thickness, mm (in.)
 μ = coefficient of subgrade friction
 x = distance from slab end, mm (in.)
 E = modulus of elasticity, MPa (psi)
 α = coefficient of thermal expansion, mm/mm/°C (in./in./°F)

The slab bottom versus slab surface temperature difference, ΔT_2 , at time of transverse joint crack formation is obtained for a full-depth slab cross section. Where the pavement cross section is reduced by a sawcut notch the axial and curling restraint stresses are increased at the weakened plane cross section by the ratio of slab thickness to slab depth below sawcut. To determine slab bottom to top temperature difference when cracks occur below sawcuts the following equation is used:

$$\Delta T_2 = 2 (ST - w\mu xn) / (1.04nE\alpha) \dots \dots \dots (10)$$

where

n = h/(h-z)
 z = sawcut depth, mm (in.)

The following values were used in the cracking analysis for the Utah pavement :

$E = 13,800 \text{ MPa}$ (2.0 million psi) assuming cracking at about 10 to 12 hours concrete age
 $x = 3048 \text{ mm}$ (120 in.) for shortest transverse joint spacing of staggered joints
 $ST = 1.38 \text{ MPa}$ (200 psi)
 $z = 254/3 = 85 \text{ mm}$ (3.3 in.) sawcut depth

Cracking below sawcut notches occurred for a slab bottom to slab surface temperature difference of about 9°C (16°F). If the slab bottom temperature remained at 38°C (100°F) then slab surface temperature cooled to about 29°C (84°F) at time of below sawcut notch concrete cracking.

The following values were used in the cracking analysis for the Iowa pavement :

$E = 17,240 \text{ MPa}$ (2.5 million psi) assuming cracking about 9 to 10 hours concrete age
 $x = 6096 \text{ mm}$ (240 in.) for 6 m (20 ft) joint spacings with cracks
 $ST = 1.6 \text{ MPa}$ (225 psi)
 $z = 254/3 = 85 \text{ mm}$ (3.3 in.) sawcut depth

Cracking below sawcut notches occurred for a slab bottom to slab surface temperature difference of about 7°C (13°F). If the slab bottom temperature cools from maximum bottom temperature of 41°C (106°F) to about 39°C (103°F), the slab surface temperature cooled to about 32°C (90°F) at time of below transverse joint sawcut notch concrete cracking.

RECOMMENDATIONS FOR TIMING OF JOINT SAWCUTTING

To facilitate the decision-making process for determining the near limit for sawcutting, surrogate tests to compressive strength determinations were selected. Choice of NDT methods to monitor insitu concrete pavement compressive strength includes the pulse velocity and maturity monitoring. Temperature monitoring and pulse velocity tests should be done at the bottom of joint elevation. Either method can be correlated well with compressive strength. Maturity and pulse velocity relationships will change with aggregate source, cement type, cement source, admixture types, and paste volumes.

Compressive strength requirements for various aggregates and cement contents to produce sawcuts with good or acceptable ratings are listed in Table 2. The range of cement of 297 to 386 kg/m^3 (500 to 650 lb/yd^3) concrete covers the amounts of cement specified by most State DOT's. For amounts of cement falling between 297 and 386 kg/m^3 (500 to 650 lb/yd^3), required compressive strength can be interpolated by direct proportions of cement amount and required strength. Observations of surface joint raveling during initial concrete placement days should become the basis for adjusting near limits for sawcutting.

Joint sawcuts should be installed ahead of occurrence of restraint pavement stresses that are in excess of pavement strength. Both average temperature drops and temperature gradients contribute to random cracking. As shown in Figs. 5 and 6 the temperature at 51 or 76 mm (2 or 3 in.) depth does not decrease as rapidly as the surface temperature. Bending restraint stresses will commonly be more sensitive than average slab temperature decreases (frictional restraint) to surface temperature changes. Equations presented in Fig. 2 indicate that significant restraint stresses can occur when cooling occurs from top surface. The application of curing

compound mitigates potentials of surface moisture evaporation cooling effects. In the absence of curing applications, evaporation from pavement surface may increase cooling due to ambient effects in afternoons and evenings following concrete paving. Top pavement surface cooling attributable to rain is in many instances avoided by construction planning. Paving operations should be planned so that concrete placed ahead of anticipated rainshowers can be sawcut before significant surface cooling.

Factors influencing far sawcutting limits include restraint stress increases associated with cooling from top surfaces and increases in concrete slab strength at early ages. Fortunately, insitu concrete strength gain is relatively rapid on days with large magnitudes of concrete temperature increases attributable to ambient and hydration effects. Very often, ambient events associated with rapid strength gains are followed by relatively large temperature decreases due to rapid cooling. Conversely, when temperature rises of concrete slabs are limited by relatively cool ambient conditions, subsequent slab cooling effects are also mitigated. Rapid strength gains permit not only early "near" limit of the window of opportunity sawcutting, but also provides the tensile strength capacity needed to counterbalance the buildup of pavement restraint stresses due to cooling.

Using relationships determined as part of the laboratory early age (4 to 24 hours) tests, split tensile and modulus of elasticity was related to compressive strength by the following expressions: (3)

$$ST = 5.94 (f_c')^{1/2} - 36.1 \dots \dots \dots (11)$$

$$E = 61000 (f_c')^{1/2} \dots \dots \dots (12)$$

where

ST = splitting tensile strength, psi
 f_c' = compressive strength, psi
 E = modulus of elasticity, psi
 $100 \text{ psi} = 0.69 \text{ MPa}$

The general relationships independent of aggregate type and cement content of compressive strength with respect to split tensile strength and modulus of elasticity were established for a range of concrete mixes under controlled laboratory conditions. The development of a general equation was investigated since at ages of less than 24 hours the specimen fracture planes passed around rather than through the coarse aggregate. Since the mortar content for all six mixes (three coarse aggregate types and two cement contents) did not vary over a wide range, development of an aggregate and mix independent model could be expected. The models from data developed in the study were developed to investigate the influence of mix design parameters (aggregate type, geometry, cement contents) and curing conditions (temperature) at early ages. These models were derived to fit the database used in the study. Application of models to other project-specific mixes using other cement contents, cement sources, aggregate sources, and admixture contents and type may not yield reliable results. The models developed should be viewed more as an investigative tool and demonstration of mix-specific applications. Mix-specific models should be developed using similar techniques demonstrated in the study. For calculations shown in this study, a coefficient of contraction of 2.8 millionths $\text{mm/mm}/^\circ\text{C}$ (5 millionths $\text{in./in.}/^\circ\text{F}$) was used.

Calculations using eqs. 9, 11, and 12 were made to determine magnitudes of temperature differences that can be tolerated

before uncontrolled cracking occurs in pavements for a range of split tensile strength and associated moduli of elasticity. Calculations were made for 11.6 and 7.3 m (38 and 24 ft) wide pavements, with coefficient of subgrade friction magnitudes of 2, 5, and 10. The plotted calculation results shown in Fig. 11 indicate that pavement width or distance from pavement edge or end (frictional restraint) has a significant impact on the magnitude of temperature difference between slab top and bottom at incipient uncontrolled cracking, that is the temperature difference when concrete pavement tensile strength balances restraint stresses. Figure 11 also indicates that as concrete pavement strength increases, temperature differences that impact on balancing tensile strength with restraint tensile stress increase. Thus, if cooling is delayed, benefits of concrete strength gain from early cement reaction are accrued and are available to balance concrete restraint stress.

Figure 11 assumes that fully restrained stresses are not developed. Elastic moduli at sawcutting were approximately 13,800 MPa (2 million psi) at the Utah and Iowa test sites. For a 1.1 °C (2 °F) average temperature drop, the length participating in slab movement is 2.9 and 1.2 m (9.6 and 3.8 ft) for coefficients of subgrade friction of 2 and 5, respectively. Since Fig. 11 is based on longer lengths of 3.7 and 5.8 m (12 and 19 ft) for 7.3 and 11.6 m (24 and 38 ft) wide slabs, there is some conservatism in calculating frictional restraint stresses. Maximum restraint stress using eq. 2 (fully restrained) for a 1.1 °C (2 °F) average temperature drop is 138 kPa (20 psi) for a modulus of elasticity of 13,800 MPa (2 million psi) and coefficient of contraction of 2.8 millionths mm/mm/°C (5 millionths in./in./°F). Using eq. 1 (partially restrained) in the development of Fig. 11 the frictional restraint stresses were higher (conservative) ranging from 0.2 to 0.7 MPa (25 to 99 psi) for coefficients of friction of 2 and 5 and pavement widths of 7.3 and 11.6 m (24 and 38 ft).

From the point of view of averting uncontrolled cracking and widening the sawcutting window of opportunity, paving

should start in very early morning hours (or even at night) and should be completed by about 10:00 to 11:00 a.m. to minimize top and bottom slab temperature differentials, to minimize average slab temperature drops, and to maximize concrete strength gains ahead of developing tensile restraint stresses.

Results plotted in Fig. 11 can be used to estimate the far limit window of opportunity sawcutting time in terms of insitu concrete pavement strength properties when sawing should be completed. For example, measurements by pulse velocity or maturity can indicate that insitu concrete pavement strength is equivalent to 6.9 MPa (1000 psi). Entering Fig. 11 horizontally at 6.9 MPa (1000 psi), the curve intercept is at 12 °C (22 °F) for a 11.6 m (38 ft) wide pavement on a granular subbase with estimated subgrade friction value of 2. Using a factor of safety of 2 with respect to temperature, sawing thus should have been completed before a 6 °C (11 °F) temperature differential occurs. When pavements adhere to subbases, higher effective friction factors to first movement are encountered. For example, a pavement over an LCB treated with a medium cure asphalt application may have an effective subgrade friction factor of 5. For the 6.9 MPa (1000 psi) strength and a 11.6 m (38 ft) paving width, the curve intercept is at 6 °C (11 °F). For a factor of safety of 2 sawcutting should be completed before a 3 °C (5 °F) temperature difference occurs. Pulse velocity or maturity to concrete strength predictions should be checked to assure that valid relationships are used. Temperature monitoring and pulse velocity testing is commonly done at mid-depth or at bottom of joint elevation when monitoring strength and elastic modulus development.

It should be recognized that the targeting of temperature differences between slab surfaces and bottoms as the time by which sawcutting should be finished, begs the question of how much sawing time is available before the "allowable temperature difference" event occurs. Temperature measurements made on pavements in Utah, for example, as shown in Fig. 5 showed that a pavement top to bottom

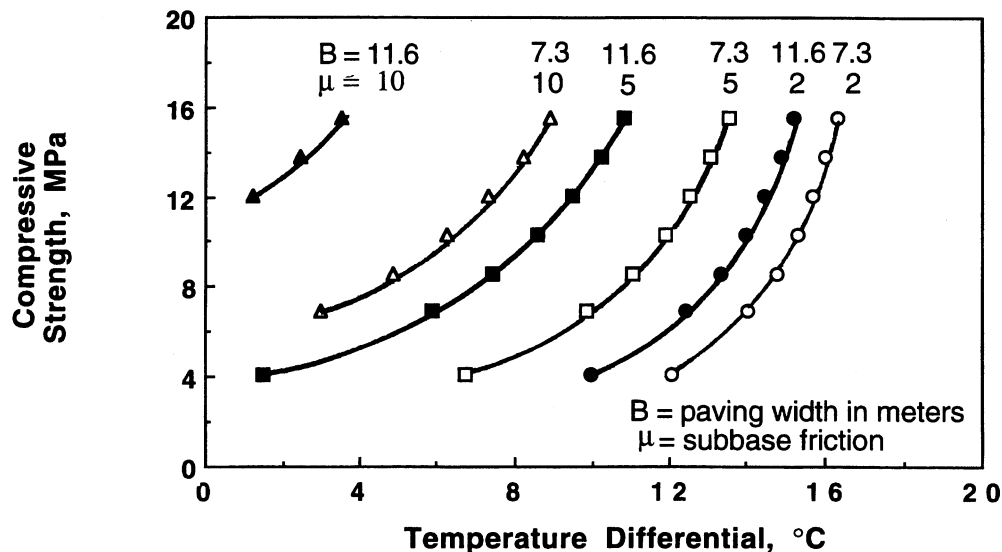


Fig. 11 - Balance Between Compressive Strength and Tolerable Temperature Difference

temperature change of 8 °C (15 °F) magnitude occurred within a span of approximately one hour. The rapid concrete surface cooling was attributed to surface wetting associated with joint sawcutting. Similar rapid surface cooling can occur due to rain showers. Thus a good rule of thumb may be to start sawcutting as early as possible, that is at the "near" limit and no later than the time when surface cooling starts.

SUMMARY

Guidelines were established to determine the window of opportunity for control joint sawcutting. A model was developed to target minimum compressive strength to achieve a given surface ravelling rating dependent upon aggregate hardness, geometry, and cement content. Field verification indicated that the model is somewhat conservative, as desired, and could be used to set initial strength targets. Compressive strength requirements can then be adjusted during construction based on initial sawcuts.

Guidelines were also developed to prevent random cracking associated with late sawing. Random cracking results when bending restraint (temperature differential) and axial restraint (average temperature drop) stresses exceed concrete tensile strengths. Allowable temperature differentials between slab top and bottom were computed for different compressive strengths, coefficients of subbase/subgrade friction, and pavement widths. These guidelines were based on general relationships developed in a study of early age concrete properties. Relationships may not apply to mixes using other sources, types, or quantities of coarse aggregate, fine aggregate, cement, fly ash, and admixtures.

ACKNOWLEDGMENTS

Work was conducted by the Construction Technology Laboratories, Inc. (CTL) under the sponsorship of the Federal Highway Administration (FHWA) as part of a study entitled "Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements." The authors extend their thanks to Dr. Stephen W. Forster and Mr. Roger M. Larson of FHWA for their many comments and suggestions which were incorporated into the study.

The contents of this paper reflect the views of the authors who are responsible for the accuracy of the data presented herein. The contents do not necessarily reflect the views or policy of the Department of Transportation or Federal Highway Administration.

REFERENCES

1. N.J. VanNess, "Summary of State Highway Practices on Rigid Pavement Joints and Their Performance," memorandum to regional Federal Highway Administrators, Washington DC, May, 1987.
2. R.D. Bradbury, "Reinforced Concrete Pavement," Wire Reinforcement Institute, Washington DC, 1938.
3. P.A. Okamoto, P.J. Nussbaum, K.D. Smith, M.I. Darter, T.P. Wilson, C.L. Wu, and S.D. Tayabji, "Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements," FHWA-RD-91-079,080, Federal Highway Administration, Washington DC, October 1991.