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Optimal Sawcutting Methods for Hydrating Concrete Pavements

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Abstract

The details of an approach to account for the factors that have been found to affect the ability and the probability to control cracking due to sawcutting in newly constructed concrete pavements are presented. Several factors such as material strength parameters, method and quality of curing, slab and subbase stiffness, and concrete shrinkage affect the probability of crack initiation. Others are relevant to concrete mixture characteristics that affect development of early aged stresses caused by shrinkage and thermally induced contraction. This paper presents the results of a probabilistic analysis of the factors that affect crack control using sawcut notches. Cost analyses on both conventional and early-entry sawcutting methods are shown to support the results of the probabilistic analysis. From both an operational and cost standpoint, it is evident for the environmental conditions considered that early-entry sawcut methodology holds a significant advantage over conventional methods.

Keywords: probability, sawcut, stress, strength, temperature, relative humidity, aggregates, cost

1. Introduction

The purpose of a sawcut notch is to initiate cracking at the notch location, due to drying shrinkage and temperature effects. Drying shrinkage has both reversible and irreversible components. However, with time and drying and rewetting cycles, the process becomes mostly reversible. Usually the irreversible part of shrinkage represents between 30 and 60 % of the total drying shrinkage.[2)] The fully reversible shrinkage is due to additional links within the C-S-H gel during drying, when closer contact between the gel particles occurs. If the cement paste has hydrated to a high degree before drying, it will be less affected by their contact. Reversible shrinkage is related with capillary stress, disjoining pressure, and change in surface free energy within the C-S-H gel. Irreversible shrinkage is mostly dependent on porosity and increases as drying increases. The factors which affect irreversible shrinkage are pore size, bonding in C-S-H, and pore water distribution. Different kinds of shrinkage occur in concrete due to the loss of water from the concrete due to evaporation. Plastic shrinkage may also contribute to cracking particularly when the evaporation is greater than the bleeding rate. As will be discussed, the bleed channels maybe contribute to cracking by causing a point of weakness in the matrix of the hardening concrete. The bleed channels, in effect, are small flaws. These flaws lead to stress concentrations in a very small volume under shrinkage strain ultimately causing the strength to be exceeded in the material with a consequent of microscopic fracture. Since concrete is a notch sensitive material, a notch in the surface of a concrete pavement can initiate a crack. As a result, crack propagates from the tip of the notch to the bottom of the slab. As this occurs, other stresses in the slab due to environmental effects are reduced.

Fig. 1 is a close up of a sawcut notch. Fig. 2 (a) is a close up of notch tip and cracks are propagating from the notch tip because of the stress concentration. Greater porosity was shown at the aggregate perimeters than in cement paste as shown in Fig. 2 (b). This greater porosity coincides with the matrix bleed channels and is consequently a source of cracking in early aged concrete.

The control of cracking using sawcut notches in the surface of a concrete pavement is a complicated process involving several material, construction, and weather related

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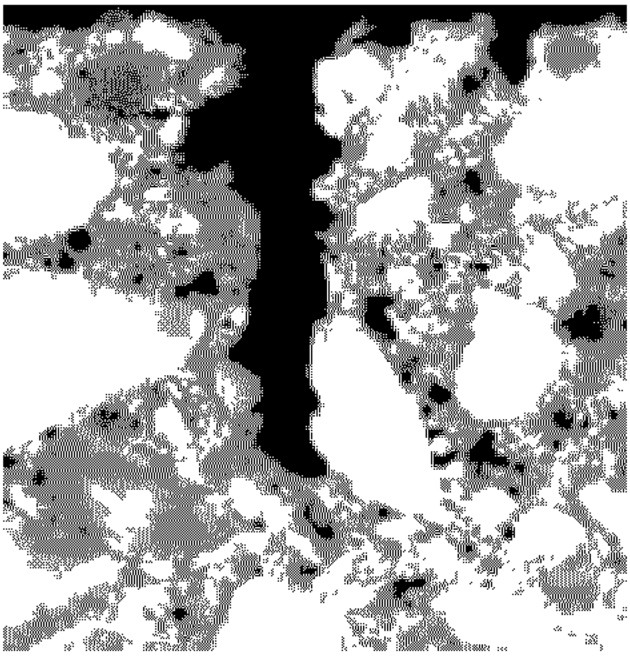
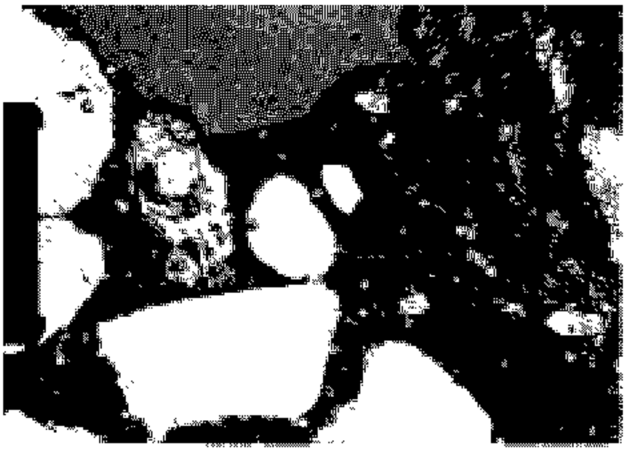
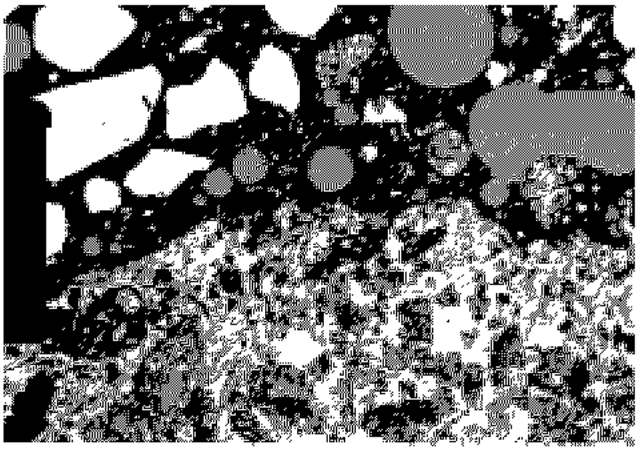


Fig. 1 Close up of a sawcut notch



(a) At notch tip



(b) At aggregate perimeter

Fig. 2 Cracks follow capillary channels

factors. The successful control of cracking is further complicated by placement of the notch in appropriate time and depth combinations. The approach taken in this paper was to focus on the factors that have been found to affect the ability of paving contractors to control cracking in newly constructed concrete pavements during sawcutting operations. Many of these factors are relevant to concrete mixture characteristics that affect in one way or another development of early aged stresses caused by shrinkage and thermally induced contraction. These factors consist of:

1. Amount of water used in the concrete mixture
2. Amount of cement used in the concrete mixture
3. Method and quality of curing
4. Type of coarse aggregate used in the concrete mixture
5. Weather conditions at the time of construction
6. Time and depth of sawcutting
7. Type of slab base support and joint configuration
8. Slab thickness
9. Method of sawcutting/crack control

Sawcutting methods are categorized as either conventional or early-entry. Conventional methods rely on the use of large, self-propelled saw machines that consist of water-cooled saw blades. The saw blades on these machines rotate forward, with respect to the direction of movement of the machines and cannot place a sawcut notch in the concrete surface until after sufficient hardening has occurred to prevent raveling and to ensure the durability of the joint. Although, the type of coarse aggregate has an effect, most concrete mixtures must achieve a minimum of 3.45 MPa (500 psi) compressive strength to prevent unsightly raveling damage. Early-entry saw machines are light-weight in comparison to water-based saws and do not require an external source of water to cool the blade. Early-entry saw blades rotate backward, with respect to the direction of movement of the machines which make use of a patented skid-plate to prevent raveling. Typically, the notches placed with an early-entry saw can be placed as soon as one can walk on the concrete, which coincides with approximately one-half to two-thirds of the elapsed time between initial and final setting of the concrete. Concrete compressive strengths at this point in time are perhaps in the range of 0.17 to 0.34 MPa (25 to 50 psi).

The cracking analysis at a sawcut notch for a newly constructed jointed concrete pavement systematically considers key factors at two different levels. The factors included within the scope of this format were limited within a restricted range of slab thickness and climatic factors as configured within a 2^3 factorial design that consists of 8 combinations of placement temperature, ambient relative humidity, and concrete aggregate type each at two different levels. The parameter levels are noted in Table 1. These combinations were considered for 3 different pavement thicknesses of 7.6, 15.2, and 22.9 cm (3, 6, and 9 inch) which included a special case of 8 additional combinations (relative to a 43.2 cm (17 inch) airfield pavement) where two levels of subbase friction were substituted for two levels of coarse aggregate type. The remaining factors not included in Table 1 were assigned constants that represent typical concrete mixtures, placing conditions, subgrade strengths, and curing methods for slab-on-grade construction.

2. Stress and strength at sawcut notch

The process undertaken for this paper is to mathematically characterize the strength gain of the concrete for comparison to the stress development in the slab as a function of time. The characterization of the strength gain with time was done on a maturity basis where the relationship shown in Fig. 3 was used to represent the gain in strength of a 5-sack concrete mixture during the curing and hardening process.[1)]

Table 2 lists the ultimate split strength values used in the analysis. Young's modulus was based on the compressive strength of the concrete which was determined from the split tensile strength. Maturity is a parameter to represent the age of the concrete that correlates well with its strength over time. Concrete maturity is directly related to the temperature history of the concrete and consists of units of time and temperature. The temperature history of the concrete is affected by the heat of hydration and the ambient climatic conditions at the time of placement.[2-4)] In this paper, temperature modeling was conducted over a 30-hour period, which yielded the temperature patterns in the concrete as a function of time and location below the slab surface. And the patterns allowed for the resultant maturity to be calculated. The temperature history was determined using the TMAC^2 software[5)] as a function of the heat of hydration during the curing of the concrete.

The determination of stress was based on mathematical models representing the curling and warping behavior of a concrete slab during the hardening process.

$$f_t = \frac{CE\varepsilon_{Tot}}{2(1-\nu)} \tag{1}$$

where

f_t = tensile stress
C = stress coefficient
E = elastic modulus
ε_{Tot} = unrestrained curling and warping strain
[= $\alpha_t \Delta T_{eq} + \varepsilon_\infty \Delta(1\text{-}RH^3)_{eq}$]
ν = poisson's ratio of concrete (=0.15)
α_t = coefficient of thermal expansion of concrete
ε_∞ = ultimate shrinkage strain

The ΔT_{eq} and $\Delta(1\text{-}RH^3)_{eq}$ terms are equivalent temperature and relative humidity difference between the pavement surface and bottom based on formulations given by Mohamed and Hansen.[6)] These equivalent differences are suggested to account for non-linear effects in either the temperature or humidity gradients on the curling and warping stress. In the case of temperature gradient, ΔT is defined at four locations below the pavement surface. The coordinate z is zero at mid depth of slab where upward is negative and downward is positive and used in order to define coefficients B and D based on:

$$\Delta T_{eq} = -12\left(\frac{Bh}{12} + \frac{Dh^3}{80}\right) \tag{2}$$

From these coefficients, ΔT_{eq} can be determined as:

$$\Delta T(z) = A + Bz + Cz^2 + Dz^3 \tag{3}$$

A similar approach can be applied to $\Delta(1\text{-}RH^3)_{eq}$. The results from Eq. (1) are compared to those of Eq. (4) to assess if cracking as occurred. The sensitivity of the concrete to crack initiation will depend upon the coarse aggregate type, concrete age, and the depth of the notch.

Table 1 Factorial design of key sawcutting factors

Parameter	Placement temperature	Relative humidity	Aggregate type
Level	16 to 27°C	10 to 50%	Limestone
	29 to 38°C	50 to 95%	River gravel

Table 2 Ultimate split tensile concrete strength (MPa)

Coarse aggregate type	Low temp. cure	High temp. cure
Limestone	5.45	4.28
River gravel	4.91	4.47

[note: Split tensile strength = $0.62\sqrt{f_c'}$]

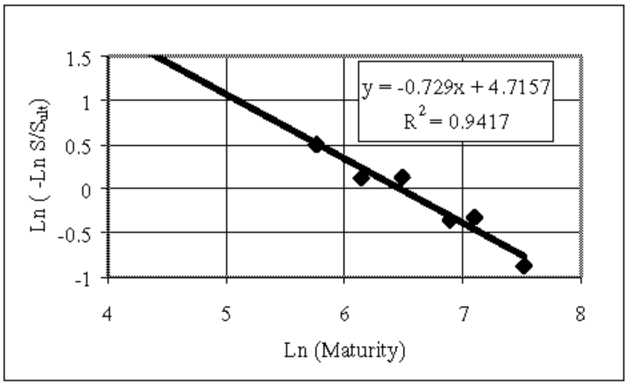


Fig. 3 Assumed strength gain characteristics for a 5-sack concrete mixture
[note: $y = Ln(-Ln\ \alpha)$; $x = Ln\ (Maturity)$]

Recent developments using fracture mechanics strength theories and a modified version of ASTM C 496[7] have resulted in new approaches, specimen geometries, and strength parameters that have allowed engineers to qualify the early-aged concrete strength relative to the bond between the aggregate and the paste. Use of fracture mechanics theories relates to crack development at an early age, which is inherently sensitive to coarse aggregate characteristics as they may relate to the aggregate-mortar bond. This sensitivity is referred to in terms of two fracture properties known as fracture toughness (K_{If}) and the length of the fracture process zone (c_f - a factor related to the brittleness of the concrete). Concrete brittleness is descriptive of a material's resistance to crack growth or the rate at which a crack may grow and, at an early age, is very sensitive to the type of coarse aggregate used in a concrete mixture. A test method based upon a modified split tensile specimens based on ASTM C 496 determines K_{If} and c_f from 3 specimens (zero notch, notched, and notched with a hole) of the same size (diameter).

$$f_t' = c_n \frac{K_{If}}{\sqrt{g'(\alpha_0)c_f + g(\alpha_0)d}} \tag{4}$$

where,

f_t' = tensile strength of the concrete
K_{If} = fracture toughness ($FL^{-2}L^{1/2}$)
c_n = a constant based on specimen geometry (=1.0)
α_0 = initial crack ratio ($=a_0/d$)
d = slab thickness
a_0 = sawcut depth (L)
$g(\alpha) = \pi\alpha c^2{}_n F^2(\alpha)$
$g'(\alpha) = \pi F^2(\alpha) + 2\pi\alpha c^2{}_n F(\alpha)F'(\alpha)$
$F(\alpha) = 1.120 + 0.203\alpha - 1.197\alpha^2 + 1.930\alpha^3$
$F'(\alpha) = 0.203 - 2.394\alpha + 5.790\alpha^2$

The functions $g(\alpha)$ and its derivative $g'(\alpha)$ are dependent upon specimen geometry and are evaluated where $\alpha=\alpha_0$. The two material factors, K_{If} and c_f, and the geometry functions evaluated at $\alpha=\alpha_0$, are used in Eq. (4) to determine the nominal strength σ_N of concrete corresponding to a particular fracture toughness. The nominal strength evaluated at a $\alpha=0$ will be equivalent to the split tensile strength of the concrete as determined by ASTM C 496. Both K_{If} and c_f are time dependent and are consequently sensitive to aggregate bond strength at early concrete ages. Therefore, the concrete toughness parameters, K_{If} and c_f, are effected by both curing conditions and coarse aggregate type as shown in Table 3.

Several factors which contribute to the variability of stress and strength were also taken in account. Each factor shown in Table 4 was assumed to have normal distribution at any time of analysis. Standard deviation over average of each factor was used to calculate coefficients of variation and they are presented in percentage as shown in Table 4. The normally distributed factors effected on the variation above and below the mean of each stress and strength. Based upon this distribution, the probability that the difference between the stress and the strength of the concrete at the tip of the sawcut notch was greater than zero was determined as a function of time from zero to 30 hours after placement of the concrete. In order to calculate this difference, both the variance of the distribution of stress and the strength of the concrete at the tip of the sawcut needed to be defined.

Table 3 Concrete toughness parameters, K_{If} (MPa-m$^{1/2}$) and c_f (m)

Coarse aggregate type	Low temp. cure	High temp. cure
Limestone	0.99/0.69	0.90/0.61
River gravel	0.77/0.53	0.69/0.48

Table 4 Stress variance factors

	Factor	COV(%)
Stress	Young's modulus	15
	Slab thickness	20
	k-value	20
	CTE	5
	Temperature difference	5
	Relative humidity difference	5
	Ultimate shrinkage	15
Strength	K_{If}	10
	c_f	10
	Sawcut depth to thickness ratio	10

The variances were developed from mean expression of stress and strength previously noted and the first order, second moment method:

$$Var\{Y\} = \sum_i \left[\frac{\partial Y}{\partial X_i}\right]^2 Var(X_i) + \sum_j \sum_k \frac{\partial Y}{\partial X_j} Var(X_j) \frac{\partial Y}{\partial X_k} Var(X_k)\rho \qquad j \neq k \tag{5}$$

where

Y = stress or strength,
X = variance factor (listed in Table 4), and
ρ = correlation factor.

Random crack occurs when tensile stress at top surface of concrete pavement becomes larger than tensile strength at the same position. But, the random crack can be controlled in the case that tensile stress at notch tip becomes larger than tensile strength earlier than the random cracking. For a given set of environmental conditions and slab thicknesses, an example of these cracking probabilities and their associated trends with time for a given case is shown in Fig. 4. The charts in Fig. 5 represent differences in these probabilities at selected times (which is used to define the probability of crack control). The advent of random cracking was based only on the amount of shrinkage in of the concrete at the pavement surface due to the loss of moisture. The prediction of cracking at the sawcut notch was based on a combination of shrinkage and thermally-induced strains.

$$\sigma_{surface} = \left[\left(0.98 - RH^{3}\right)\varepsilon_{\infty} - \varepsilon_{crp}(t)\right]E(t) \qquad (6)$$

where $\varepsilon_{crp}(t)$, creep strain as a function of time, was calculated [8] and varied from 25 to 100 microstrains over the 30 hour period.

The analysis of the cracking probability for 15.2 cm (6 inch) and greater thickness of concrete pavement was based on a 4.6 m (15 feet) of joint spacing and an average stiffness of subgrade. The cracking charts for the 7.6 cm (3 inch) thickness were based upon the behavior of a thin-bonded overlay typical of what may be placed on low-volume road consisting of an asphalt surface. Since these surfaces manifest greater stiffness than the average subgrade, an above average stiffness was used in the 7.6 cm (3 inch) thickness analysis. The analysis was also based upon the average cracking behavior of a concrete slab as it would occur under assumed trends in the temperature and humidity patterns within the designated limits previously noted.

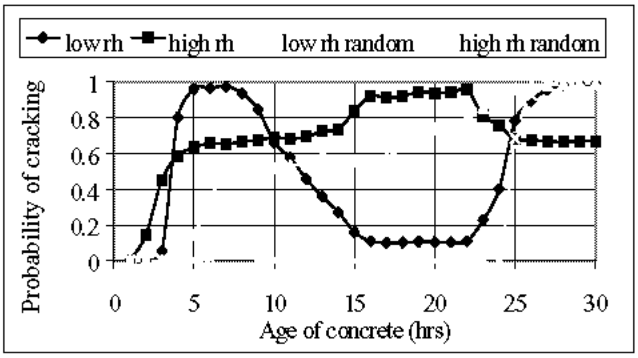


Fig. 4 Stress and strength pattern at a sawcut notch depth to slab thickness ratio of 0.1 as a function of time under low temperature placement conditions

Table 5 Time of sawcutting (hours after placement)

Coarse aggregate type	Method of sawcutting	Low temp. placement	High temp. placement
Limestone	Early-entry	5	3
	Water-based	8.5	7
River gravel	Early-entry	5	3
	Water-based	9	8

Given the premise that the scales of the climatic limits represent high and low extremes of the ranges in placement temperature and relative humidity, it can be reasonably assumed that, on the average, typical pavement cracking behavior will fall somewhere between the results associated with these extremes.

3. Cracking probabilities

Table 1 itemizes the components of 8 combinations and each combination was repeated each time for thickness 7.6, 15.2, and 22.9 cm (3, 6, and 9 inch) as previously noted. The analyses focus on the control and incidence of transverse cracking as defined in terms of the difference between the probability of initiating a crack at the sawcut notch and the greatest probability of a random crack developing at or prior to the time of initiation. The differences associated with each of the cases are illustrated in bar charts provided in Fig. 5 with respect to early-entry method of sawcutting, conventional method at the near-limit, and conventional method 24 hours after placement. The point of entry used for the early-entry method and the near-limit for the water-based saw is noted in Table 5. A moderate level of raveling was used as a basis for selecting the time associated with the near limit although, comparatively speaking, very little raveling damage typically results from use of the early-entry method. The near limit occurs approximately 8 hours after placement of the concrete near the end of the day. And it is the earliest that a conventional or water-based saw can be feasibly used depending upon joint durability.

Fig. 5 contains results for 7.6, 15.2, 22.9, and 43.2 cm (3, 6, 9, and 17 inch) thickness, where results for 43.2 cm (17 inch) are associated with airfield pavement construction. The 43.2 cm (17 inch) case considered only limestone aggregate but included subbase friction effects at high and low levels. This was done by adding a friction component to the stress analysis. In most instances, the differences are positive which means cracking can be controlled by sawcutting but in cases where the differences are negative, cracking cannot be controlled by sawcutting.

Each chart in the Fig. 5 clearly indicates the superiority of early-entry sawcutting over conventional methods relative to the control of random cracking in jointed pavement construction. The results of each case shown in the Fig. 5 represent a bound in the range of cracking behavior that may occur over the climatic conditions delineated in Tables 1 and 4. The results relative to each of these bounding conditions are helpful in identifying limits associated with sawcutting operations. Typical cracking behavior can be derived from various combinations of the results at each climatic limit as to whether or not cracking can be con-

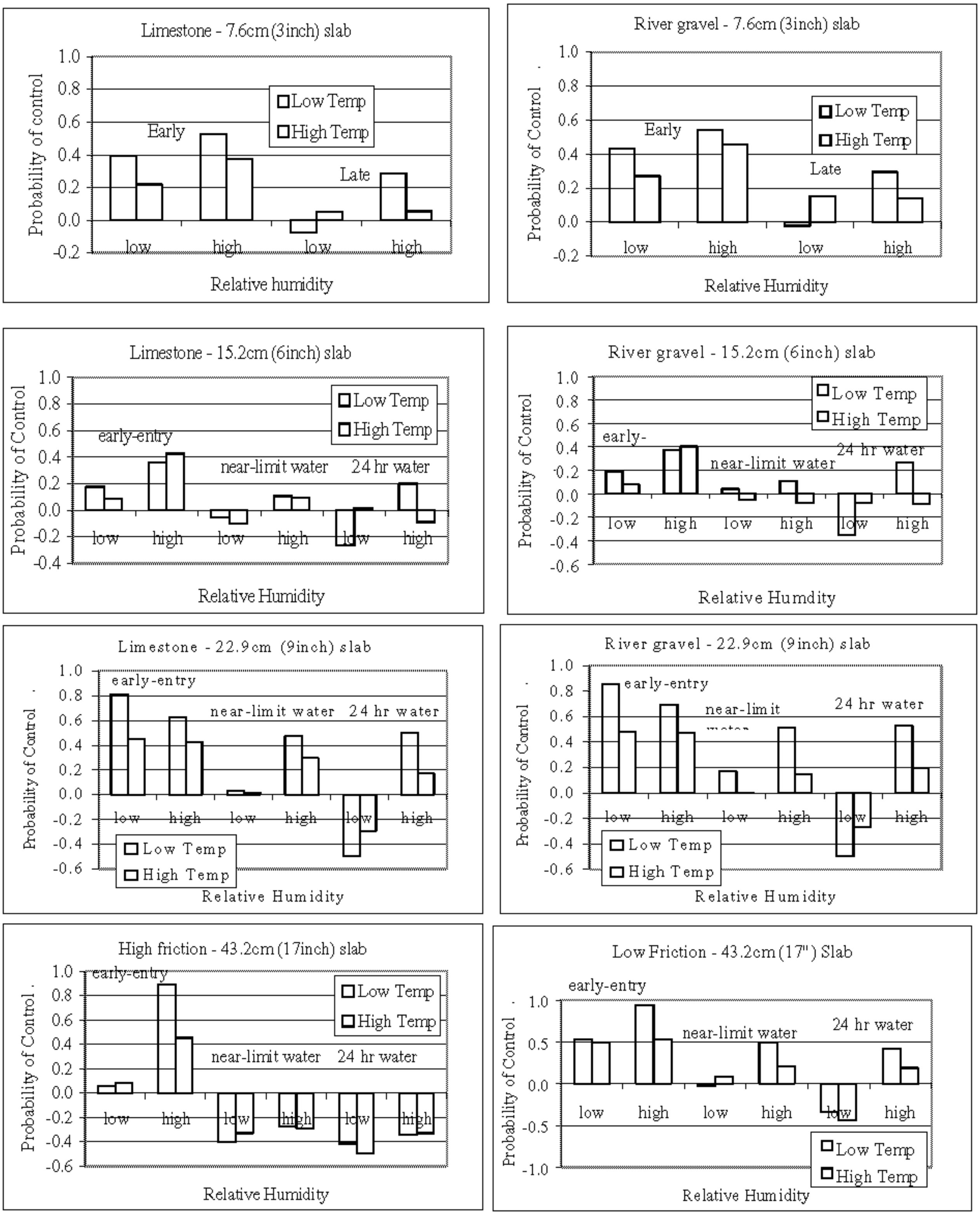


Fig. 5 Differences in the probability of a crack occurring at a sawcut notch versus at a Random location

trolled. In this respect, certain findings and conclusions can be drawn from considering each of the charts shown in the Fig. 5. It is pointed out that certain patterns in cracking behavior are repeated from chart to chart. Thus, the discussion of only a chart is necessary except where cracking behavior deviates from those elucidated below.

As expected, the charts for the 22.9 cm (9 inch) slab using limestone or river gravel as coarse aggregate show greater potential for crack control under the early-entry system due to characteristically lower fracture toughness at an early age. The chart of 22.9 cm (7.6 inch) slab using limestone aggregate for a paving mixture compares the probability of crack control in a slab between early-entry and conventional sawcutting at the near limit. These results are shown at both a high and low concrete temperature and a high and low relative humidity conditions at the time of paving. Use of the early-entry method shows similar results over this range of climatic conditions. Use of the conventional method shows much lower potential particularly at the low temperature placement conditions. The lower potential in this instance is due to the notch depth extending too far below the effect of the stress gradient that is caused by the prevailing curing conditions. A similar set of circumstances exists for conventional sawcutting 24 hours after paving with the exception at the low humidity condition where cracking cannot be controlled. Similar conclusions and findings can be drawn from the comparisons made in the results shown in other charts in Fig. 5. Exceptions to these trends are subsequently noted below.

It is interesting to note the most stringent conditions for conventional sawcutting occurs with low temperature placements while the most stringent conditions for early-entry varies between high and low temperature conditions depending upon the slab thickness. It is also evident from the data shown in Fig. 5 that the thicker the pavement the easier it is to control cracking, particularly when the early-entry method is used and this observation agrees with cracking behavior as predicted by fracture mechanic theories. Similarly with respect to coarse aggregate type, cracking is easier to control in concrete using river gravel aggregate in comparison to limestone aggregate, as previously noted.

Referring to the results, the 22.9 cm (9 inch), high temperature placements at both low and high relative humidities using limestone aggregates show greater probability to initiate cracking by conventional sawcut methods while there is a greater probability of control of cracking by early-entry methods. In other words, the probability of crack initiation may be greater in some cases for deeper sawcuts. Other similar results can be found in the 15.2 cm (6 inch) cases for high relative humidity placements using both limestone at both low and high temperature and river gravel aggregates at low temperature only. For 7.6 cm (3 inch) placements, similar results can be seen under the high temperature, low relative humidity conditions for 7.6 cm (3 inch) placements using both limestone and river gravel aggregates.

The 7.6 cm (3 inch) early-entry placements were determined at a sawcut depth of 1.3 cm (0.5 inch). Results for the 43.2 cm (17 inch) cases indicate early-entry method is the only feasible method to control cracking on high friction subbases although the chances of control are slim at low relative humidity conditions.

Table 6 Categories of sawcutting costs (per 1 m of length)

Cost category	Water saw [per 2.54 cm (1 inch) of depth]		Early-entry	
	Lime-stone	River gravel	Lime-stone	River gravel
Saw maintenance/operation	$0.33	$0.33	$0.30	$0.30
Labor	$0.49	$0.66	$0.49	$0.66
Blade	$0.33	$0.82	$0.36	$0.56
Total	$1.15	$1.80	$1.15	$1.51

4. Sawcutting costs

On most paving projects, the cost of sawcutting and sealing the joints is 1.5 to 2 percent of the total project cost which may suggest that sawcutting operations are rather unimportant to the overall construction process. But to the contrary, sawcutting and control of cracking is one of the most important aspects of the paving construction and performance. Assuming a 15 percent profit margin for sawcutting and sealing joints, it is estimated for a given project, the cost of repairing up to 4 percent of the joints (routing and sealing random cracks) where cracking was not controlled would exhaust the margin of profit. If slab replacement is required, the cost of one patch would exhaust the margin of profit.

Sawcutting costs used by Soff-Cut International Inc., one of the largest sawcutting companies in United States, are itemized with respect to 3 categories in Table 6 for both methods of cutting and the type of coarse aggregate type. Costs for conventional sawcutting are on a per 2.54 cm (1 inch) of depth basis but costs for both methods are given on a per linear meter of sawcutting basis. The costs represented in Fig. 6 are provided with respect to the total costs listed in Table 6. The costs are also given with respect to the probability of control to provide a cost-based comparison in terms of the risk of success to control cracking. Sawcutting costs divided by differences in the probability of a crack occurring at a sawcut notch versus at a random location represent the expected construction and maintenance costs of joints well. Considering the probability of control, early-entry sawcutting method has a considerable advantage in cost over conventional methods as shown in Fig. 6.

5. Conclusions

1) Variable climate conditions and material characteristics were used as factors in a probabilistic approach for cracking control due to sawcutting to find the most desirable sawcut depth and timing.
2) In many of the cases considered, early-entry sawcut notches maintained greater potential to initiate and control cracking than notches placed at later concrete ages

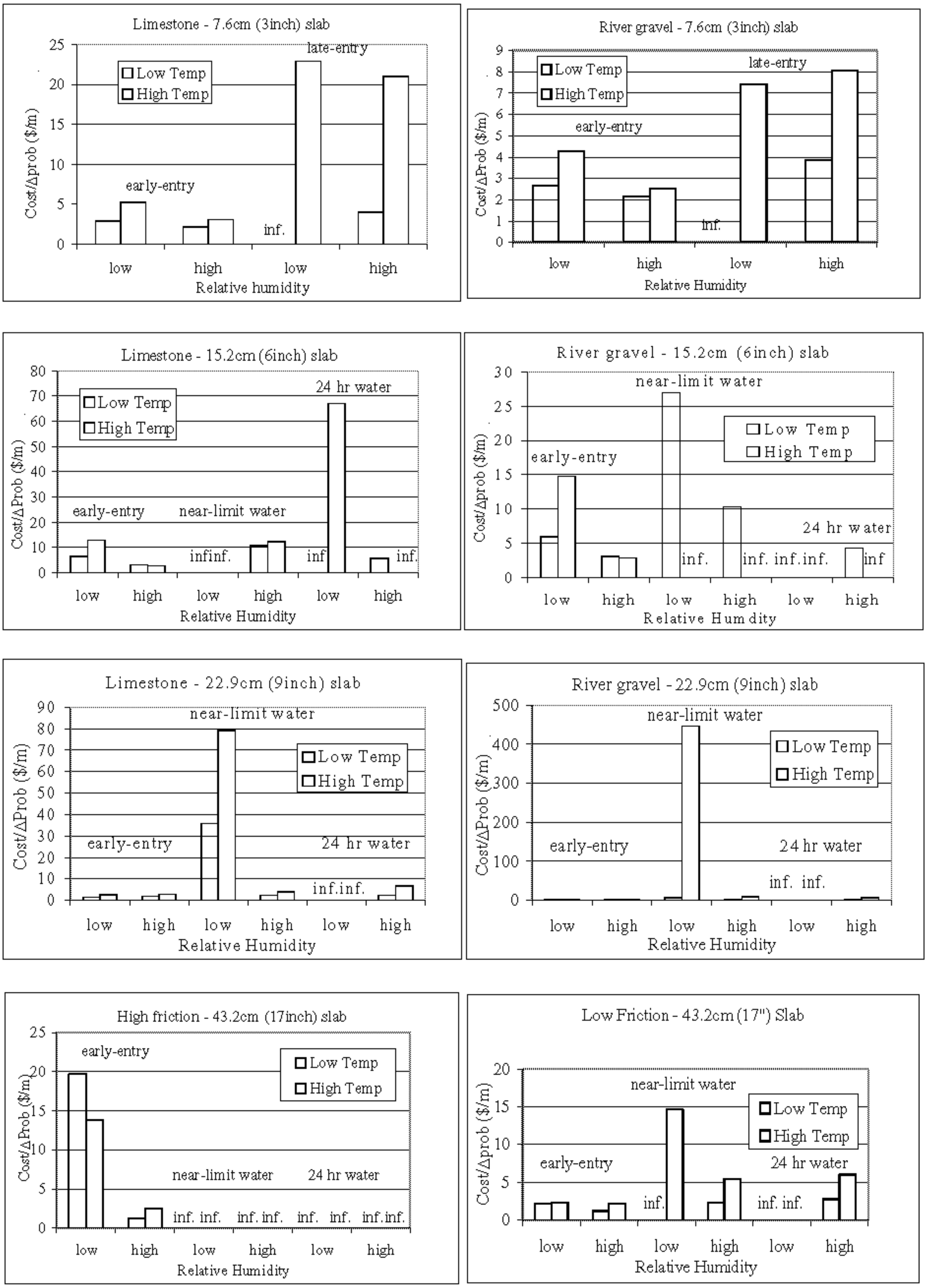


Fig. 6 Sawcutting costs per unit length of conventional and early-entry methods based on the probability of cracking control (note: inf. = infinite, Δprob = probability of control)

and at greater depths.

3) From both an operational and cost standpoint, it is evident for the environmental conditions considered that early-entry sawcut methodology holds a significant advantage over conventional methods.
4) On the average, this translates into lower risks, lower costs, and greater profit margins when early-entry sawcut methods are used in the construction of jointed concrete pavements.

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