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16. Abstract

This report documents a review of Texas Department of Transportation (TxDOT) design and construction practices with regard to accelerated concrete pavement construction of heavily travelled intersections. Special measures taken by TxDOT at the design and construction level to address the needs presented by overcoming the impact of reconstruction of such pavement facilities were the focus of this review. The review consisted of a field investigation that considered current construction specifications, concrete (fast track) mixture qualification, and construction practices. The field investigation facilitated development of guidelines based on an assessment of the impact present practices may have on performance of the constructed pavements.

It was determined the use of fast track paving techniques require coordinated construction planning to take advantage of the benefits offered by this construction process. Concrete mix proportioning can be supplemented by special admixtures to accelerate the time of set, but must also meet the workability requirements associated with the transportation, placement, finishing, and curing of concrete.

It is also of benefit to the construction supervisor to qualify the concrete mixture with respect to strength gain for a given set of weather conditions. Laboratory work was conducted to support the development of the mix qualification process.

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GUIDELINES FOR THE CONSTRUCTION

OF

FAST TRACK CONCRETE PAVING INTERSECTIONS

by

Jason L. Johnson
Dan G. Zollinger
Sungchul Yang

Research Report 1385-1F
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Sponsored by the
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IMPLEMENTATION STATEMENT

The findings of this study determined that with proper procedure and evaluation criteria, Fast Track concrete can be used in all facets of concrete paving to construct concrete pavements in a shorter time frame than under conventional paving procedures. Appropriate evaluation and paving methods should be considered when implementing Fast Track to reach the full potential of the procedure.

Methods for the evaluation of Fast Track paving criteria may be implemented to allow prediction of strength gain under in-situ climatic conditions. These methods of evaluation allow for the rapid placement and early opening that are inherent benefits provided by Fast Track concrete pavement construction practice.

The procedures and testing outlined should aid in the construction and planning of Fast Track pavement and result in the pavement system reaching its maximum possible design life.

DISCLAIMER

ACKNOWLEDGEMENT

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SUMMARY

This report presents the findings of an effort to review past Fast Track Concrete Pavement design and construction experience as practiced both in and outside the State of Texas. This effort was supplemented by field and laboratory investigations to isolate different noted distresses and associated causes as they related to past construction practice.

Recommendations were prepared in light of available information and practices that addressed the mechanisms or causes of distress. The recommendations provided herein pertain not only to fast track, but also to aspects of concrete pavement construction, such as joint details at construction joints between existing and new pavement sections, measurement and maintenance of sufficient workability of fresh concrete during placement operations, induction of appropriate crack (or joint) intervals in concrete pavement, and procedures to implement non-destructive procedures to monitor strength gain of the concrete.

INTRODUCTION

Fast track paving or accelerated pavement construction includes the rapid placement of portland cement concrete pavement which facilitates the expedient reopening of the pavement to traffic in a specified time. To determine the minimum time for opening the pavement section to traffic, a method for determining when the specified opening criteria is achieved is suggested. The time of opening may take into account the rate of strength gain, weather conditions, mixture design factors, and admixtures used in the concrete mixture. Current specifications typically use strength-based criteria. The purpose of this research is to suggest relevant early opening criteria, an approach to construction quality control, relevant design details for accelerated paving, and implementation of these criteria in terms of guidelines for fast track paving.

Fast track paving is particularly useful in intersection construction and is a relatively new construction concept that has only recently begun to be implemented. Apparently, no widely accepted standard for the opening criteria has been established for fast track concrete pavement construction; therefore, the testing procedures for conventional concrete construction have been used. The procedures used to determine the time to open conventional concrete pavements to traffic typically involve the casting of concrete test beams and the subsequent breaking of those beams at specific time intervals (i.e. 7 days, etc.) (1). Beam tests provide an indication of the flexural strength of the concrete in the pavement. A minimum flexural strength serves as opening criteria and is established by the contract agency responsible for the project. Once it is verified that the specified flexural strength has been reached by the concrete in the pavement, the concrete pavement is considered ready for opening to traffic. However, some quality control procedures with respect to opening criteria may be impacted by the effects of ambient weather conditions or the effect of some admixtures on the rate of strength-gain or hydration of the concrete mix.

In some instances, the standards for opening to traffic criteria may not be consistent with the goals for accelerated paving. First, the mix design of the fast track concrete may involve the use of additional quantities of cement or rapid hydrating cement with, in some cases, the addition of an accelerator. A concrete mix of this nature tends to hydrate at a much greater rate than a conventional concrete paving mix due to the above noted differences in the mix design. Also, the use of conventional testing techniques requires frequent breaking of beams to determine the earliest point in time when the concrete mix obtains sufficient strength to meet the opening criteria. This approach may be cumbersome and time-consuming for field personnel to manage effectively. However, other methods are available to monitor the concrete pavement with non-destructive testing devices (i.e. maturity meters) that indicate when the concrete meets the specified opening criteria (2,3,4,5,6,27,29).

To further comply with the rapid placement of concrete pavements at intersections, the "one pass" approach is a method currently being used. The one pass method is basically a formed paving method without the placement of base or subbase. Consequently, the concrete is placed directly on the subgrade. Currently, the Federal Highway Administration (FHWA) encourages the placement or the use of a drainable subbase or subgrade. However, in areas that remain saturated (or are poorly drained), a drainage layer may not be appropriate from a pavement performance standpoint if the pavement system otherwise maintains constant moisture conditions.

Fast track construction concepts focus on opening the pavement section when certain monitored material properties reach specified limits, which may vary depending on the conditions at the time of construction. Using the concepts of maturity, concrete strength gain characteristics can be developed and relationships predicted, within certain limits, for the individual concrete mixes for varying atmospheric conditions (2,5,7,8,29).

Not only must the attainment of proper strength (opening and ultimate) be achieved, but joint saw cutting must also be accomplished at the proper time. The main function of cutting joints with saws in concrete pavement is to control and induce cracking at specific locations in the pavement slab. The cracks are further propagated by the expansion and contraction of the slab during hydration of the concrete and serve to relieve other environmentally induced stresses developed in the pavement. Pavements constructed with fast track concrete mixes can be ready for saw cutting in as little as three hours after placement, using the appropriate saw cutting or crack control techniques. Appropriate crack control requires the cutting to be done at an early age to prevent random crack initiation. The appropriate age is a function of the setting characteristics and the ambient weather conditions.

The effects of admixtures play a very important role in the setting characteristics of a concrete mix. The performance of an admixture added to a mix is affected by the environmental conditions at the time of placement. For example, adding a non-chloride accelerator to a concrete mix will normally increase the rate of hydration. The increase in the rate of hydration may cause two side effects: a reduction in the ultimate strength and an increase in pore volume of the cement paste (1). The increased rate of hydration may cause a rapid loss of moisture. If the concrete does not have sufficient moisture to hydrate sufficiently, the concrete may harden with a higher than normal amount of unhydrated cement particles present. This condition may result in the concrete not reaching the strength or durability it could have attained if adequate moisture had been present. The second effect of an accelerator is the increase in pore volume of the concrete. Increased pore volume has also been shown to negatively affect the durability of hardened concrete (1).

The focus of this report is to develop design guidelines for use in fast track paving construction at intersections. These guidelines should be useful to pavement engineers and contractors to construct and evaluate fast track concrete pavements more effectively. This report is divided into four sections. The first section, entitled "Design Considerations for Fast Track Construction," documents mix materials, mix characteristics, construction techniques, and current pavement types used for fast track concrete pavement construction. The second section, entitled "Field and Laboratory Investigation," summarizes testing conducted in this study to evaluate fast track pavement construction and to serve as a tool in developing the design guidelines. The third section, "Evaluation of Opening Criteria to Traffic," describes methods for evaluating and suggesting new techniques in considering opening criteria. Finally, section four, "Design Guidelines for Fast Track Pavement Construction," summarizes the three preceding sections in a format that can be implemented to construct and open fast track concrete pavements at intersections.

DESIGN CONSIDERATIONS FOR FAST TRACK CONSTRUCTION

Several highway and government agencies were visited to examine and gain information about different practices with respect to the design and construction of concrete pavements as they relate to intersections and whether they used normal or accelerated (fast track) type concrete mixes. This section summarizes the noted practices with respect to intersection construction, using concrete materials, design and proportioning of fast track concrete (FTC) mixes, and the thickness and joint design of pavement constructed at intersections.

In many instances, where fast track concepts were employed, the contracting agency had taken only limited advantage of the fast setting and strength characteristics afforded to the user or limited the scope of the application to simply "patching" type operations focused on pavement "block-outs" located in critical areas of an intersection traffic lane (Figure 1). Based on successes in the application of FT concrete paving concepts, intersection construction should be phased to eliminate the formation of "block-out" areas. Appropriately employed fast track segmental construction should avoid construction difficulties of this nature, decrease the time of construction of the overall project, and decrease the impact of re-construction on the traveling public.

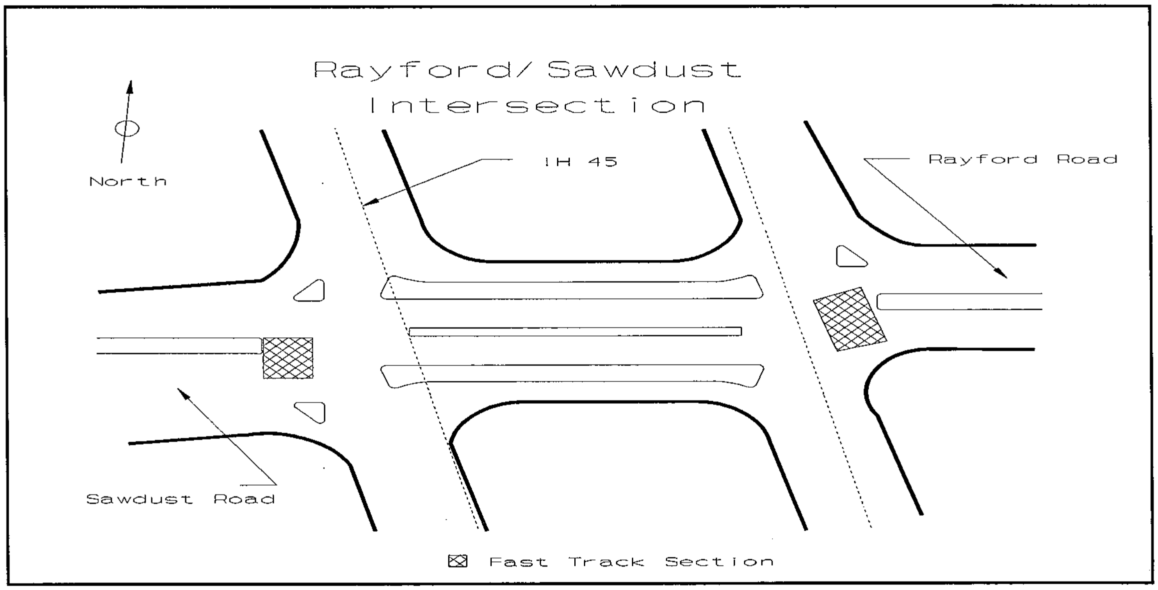

Figure 1. Fast Track Placement.

MIX MATERIALS

Fast track (FT) concrete mixtures typically do not require special materials or out-of-the-ordinary techniques. However, in some instances, material selection requires more attention than normal portland cement concrete. Locally available cements, additives, admixtures, and aggregates can be adapted to produce the required high-early strengths. While no established mix design proportioning or standard combination of materials exists for FT paving applications, consideration should be given to the quantity of cement, the quantity of fly ash (if it is used), the type of cement, the type of fly ash, and the ambient temperature conditions expected during the paving operation with respect to the specified strength and opening requirements.

Other factors are also important for the development of high-early strength concrete, such as: water-cement ratio, alkali content of the cement, heat of hydration, aggregate particle size distribution, curing, etc. Once material and construction design constraints have been established, the concrete materials must be proportioned to the particular project needs. For example, if an eight hour opening is required for a particular intersection segment, curing blankets may be necessary depending on the cement characteristics and the ambient temperature. However, if the ambient temperature is too high during the first 24 hours, undue cracking may initiate deterioration of the pavement slab which could continue throughout the life of the pavement.

Fast track mixes are expected to produce very durable concrete. This expectation is based upon the FT mix use of a low water-cement (w/c) ratio in the FT mix design which is important in achieving high-early strength and low concrete permeability. The latter characteristic is enhanced by the use of fly ash (1,6).

It is recommended that prior to specifying FT mix proportions, a laboratory mixture design procedure be conducted to characterize the properties or qualify the concrete materials (cement, admixtures, aggregates, etc.) in terms of the specific project requirements and climatic conditions at the time of construction. There is no current standard that qualifies the materials for use in FT mix proportioning. To achieve this, a procedure of this nature will need to incorporate laboratory procedures which will establish a degree of climatic and project compatibility. Therefore, this process will indicate proportioning of materials to meet the needs of a specific project incorporating the highest degree of design flexibility, yet achieving a durable concrete pavement (9).

Cement

All portland cements manufactured are subject to variability which is usually dependent on the source and manufacture procedure of the cement. The selection of the type of cement used in pavement construction should be based upon desired results to be achieved in the field. However, a prescribed qualification process should ensure that the rate of strength gain will meet the given project requirements. Not all cements provide the same rate of early strength gain which should be ascertained before actual placement operations. Some state highway agencies have limited fast track concrete mixtures to the use of Type III cement, but successful mixtures have used Types I and II cements. There are also several cements which can be obtained from proprietary sources that develop the accelerated mix properties necessary to be very useful in FT applications (9). Cement selection is dependent on many factors, such as (1,6,9):

1. Fineness,
2. Impurities oxides,
3. Workability,
4. Durability, and
5. Early/long term strength.

The hydration of portland cement is a function of the interaction of the components that comprise a particular cement. C_3A and C_3S are the most reactive components in the cement producing most of the heat generated from the cement-water reaction. The rate of hydration can be directly related to the concentrations (percent by weight) of these components in a cement mix. For instance, a Type III cement mix will have more C_3S than a Type I or a Type II cement mix (shown in Table 1).

Since fast track paving may take advantage of many different cement types (Types I, II and III), different considerations apply to each cement type. For example, to compensate for the slower hydration time of a Type I cement, more of the Type I cement may be added to the mix to decrease the set time of the concrete (12). The heat of hydration of portland cement is an important factor that determines the rate of strength gain and may be affected by the temperature of the mixing water. Cement

Table 1. Typical Composition and Fineness Values (1).

	Type I	Type II	Type III
C_3S (%)	50	45	60
C_2S (%)	25	30	15
C_3A (%)	12	7	10
C_4AF (%)	8	12	8
CSH_2 (%)	5	5	5
Fineness (cm^2/gm)	3500	3500	4500
1 day Compressive strength psi	1000	900	2000
Heat of hydration (7 days, (J/g))	330	250	500

fineness affects the heat of hydration. Typical fineness values are represented in Table 1 (1,2,9,10). With the increased early strength effects of increased fineness, come concerns such as:

1. decreased workability,
2. lower long-term strengths,
3. reduced durability to freeze thaw cycles, and
4. greater need of gypsum due to increased C_3A available during reaction.

As the grind of the cement becomes finer, the contact between the cement particle and water increases which increases the rate of hydration and the formation of hydration products (1,2,9,10). The Blaine fineness value is an indicator of fineness of the cement. This value gives an indication of area per unit weight (cm^2/gm). For a Type I cement, the values range from 3,000 to 4,000 cm^2/gm. For a Type III cement, the Blaine values range from 4,500 to 6,000 cm^2/gm. Difficulties can arise from the increased hydration reaction of a fine cement. Due to the increased hydration of a fine cement with water, the cement may require more water to complete the hydration.

Increasing the rate of early strength gain with cement modifications or additives will not necessarily increase the strength at later ages. Increased cement content may also negatively affect the durability of hardened concrete. Durability is not a function of early strength but is directly affected by the water-cement ratio and permeability. To obtain good permeability and durability, it is suggested that the water-cement ratio be approximately 0.35 (1,11).

Liquid and Mineral Admixtures

In addition to the standard materials that make up concrete, other materials can be added or mixed to achieve specific results. These materials are commonly called admixtures. Admixtures can do many things, but in terms of concrete mixtures used for accelerated construction they accelerate, decelerate, increase workability, add color, or minimize the loss of water from the surface of the pavement (1,6,9). Many desirable properties can be achieved with the addition of an admixture; however, care must be taken to test the admixture to ascertain whether the admixture reacts chemically with the aggregates used or causes other side effects not desired.

Fly Ash

Fly ash is a common mineral admixture used to replace portions of the cement used in mixes. However, in a fast track mix, fly ash is considered more of an additive than a replacement for the cement. Fly ash tends to react with calcium hydroxide (CH - hydration products of the cement-water hydration) to form calcium-silicate-hydrates (CSH) which may provide improved bonding at the aggregate/paste interface. Fly ash consists of spherical particles that tend to promote workability while reducing water demand and improving overall pavement performance.

Fly ash is classified in two general groups, Type C and Type F. Type F fly ash is more of a pure pozzolan, requiring the products of the cement-water reaction to react. However, Type C fly ash reacts more extensively in the early hydration phases. As a result, Type C fly ash can be used as a partial replacement for cement in concrete mixtures. However, in terms of performance, concrete made with Type F fly ash typically exceeds concrete made with Type C fly ash in strength and durability.

Experience has shown that Type C fly ash, considered compatible with a given cement, contributes to lower water demand, improved workability, and increased long-term strength gain. Although most fast track concrete mixes employ Type C fly ash, Type F may also produce acceptable results and may be considered after sufficient evaluation.

Accelerators

The primary function of an accelerator is to increase the rate of strength gain in a concrete mix. Early strength gain may be a requirement for intersection construction where the flow of traffic can only be compromised for a short period of time, thus warranting the use of accelerating admixtures. One of the most common accelerators is calcium chloride ($CaCl_2$); however, it may be corrosive to embedded steel. Other non-chloride accelerators are available which come in a nonhydroscopic powder or in concentrate form (1,6,9,10).

The effects of accelerators must be carefully monitored. When using an accelerator, the cement should be fully dispensed in the mixer when the admixture is added to the mix. Undispersed cement particles that remain in concrete can cause "pop-outs" and dark spots in the surface of the pavement. The accelerator can be mixed with the mix water to better dissolve and dispense it to avoid the conditions noted above. Adding an accelerator during periods of high ambient temperature conditions may cause the concrete to set before the finishing operations are completed. Some accelerators are capable of decreasing the time allowed for workability of the fresh concrete to as little as 10 minutes (1,6,9).

Retarders

A retarder extends the setting time of the cement in the concrete mix. A retarding admixture is usually required when more time is needed to work and finish the concrete. Justification for a retarder can be factors such as high ambient temperatures or cement with a high rate of hydration (Type III). The more commonly known retarders are carbohydrate derivatives and calcium ligninsulfonate (1,6,9,10).

Air Entraining Agents

Entraining a certain amount of air into a concrete mix improves workability, eases placement, increases durability, increases resistance to frost action, improves flow during placing operations, and reduces bleeding and water gain.

There are many kinds of air entraining agents. Air entraining agents made from modified salts of a sulfonated hydrocarbon will have the effect of plasticizing a mix. Some air entraining agents are made from a vinyl resin more commonly used in highway pavements (1,6,10).

Super Plasticizer

When cement and water are combined, the cement particles tend to bind together into agglomerates. The binding action of the cement inhibits thorough mixing in the water. This causes incomplete hydration and reduced workability. The bound particles cause rough abrasive surfaces that require a larger water demand to provide needed workability and increase the w/c ratio, which in turn may result in increased bleeding and potentially a loss of durability.

A plasticizer coats the cement particles allowing them to segregate and mix freely with the water. The overall effect of a plasticizer is increased water reduction (up to 40%), higher early strengths, increased workability, reduced permeability, and increased durability. Super plasticizers have none of the corrosive agents associated with accelerators.

Three common types of plasticizer are:

1. sulfonated naphthalene formaldehydes (SNF),
2. sulfonated melamine formaldehydes (SMF), and
3. sodified ligninsulfonates.

Generally, plasticizers will have no adverse effects on concrete mixes which are sometimes attributed to admixtures. In some instances, a super plasticized mix will lose slump quickly. However, for a given set of circumstances, this situation may be minimized by adjusting the combined gradation, discussed below. Super plasticizers should be tailored to the individual job requirements by using standard slump techniques or by using the consistency technique discussed in Appendix F (1,6,10).

Aggregates

Most aggregates approved by state highway agencies can be used in fast-track paving. Usually, very little adjustment must be made to standard mix designs. Adequate concern should be taken on the selection of gradation and particle size distribution in the mix design (1,6,10).

Gradation

The gradation of the combined aggregates can have an impact on the performance of a concrete mix (grading by sieve analysis is specified by ASTM C136). In the past, little attention may have been given to the effect that aggregate particle size distribution (i.e. intermediate particle sizes ranging from ⅜" (0.95 cm) to #16 sieve size) can have on the workability of concrete mixtures. Although current aggregate gradations may yield appropriate strengths, consistency of the fresh concrete may be lacking. The gradation limits suggested by current ASTM standard C33 tend to promote a shortage of one or more intermediate sized materials, which is referred to in this report as "gap-graded." Gap-graded aggregates may be used to produce concrete mixtures which have certain characteristics; however, gap-graded materials may cause difficulties, such as segregation, during placement that may require special care in handling to overcome.

Intermediate size aggregates can be used as a means to produce concrete mixtures which will have greater workability and consistency at a lower water demand. In fact, the amount of these sizes of aggregates can also allow the design to tailor or improve the mixture to the specific requirements of a given paving project. Intermediate aggregates typically fill voids filled by mortar. This improves the efficiency of the mortar to coat the aggregates, increasing workability and consistency of the fresh concrete. Intermediate aggregates also aid in finishability or consistency by allowing the larger aggregates to roll as ball bearings. A typical mix including intermediate sized aggregates is shown versus a gap-graded mix in Figure 2. Producing an optimized mix to achieve better consistency through use of intermediate aggregates results in:

1. lower water demand and improved strength through a reduction in mortar needed to fill void space;
2. augmented durability characteristics through reduced avenues for water penetration in the hardened mix;
3. reduced wear on equipment; and
4. increased workability allowing for more ease in finishing operations.

Particle distribution may need to be varied depending on the method of placement. For example, a slip-formed pavement may require a more gap-graded mix design versus a mix which benefits from a more bell-shaped particle size distribution.

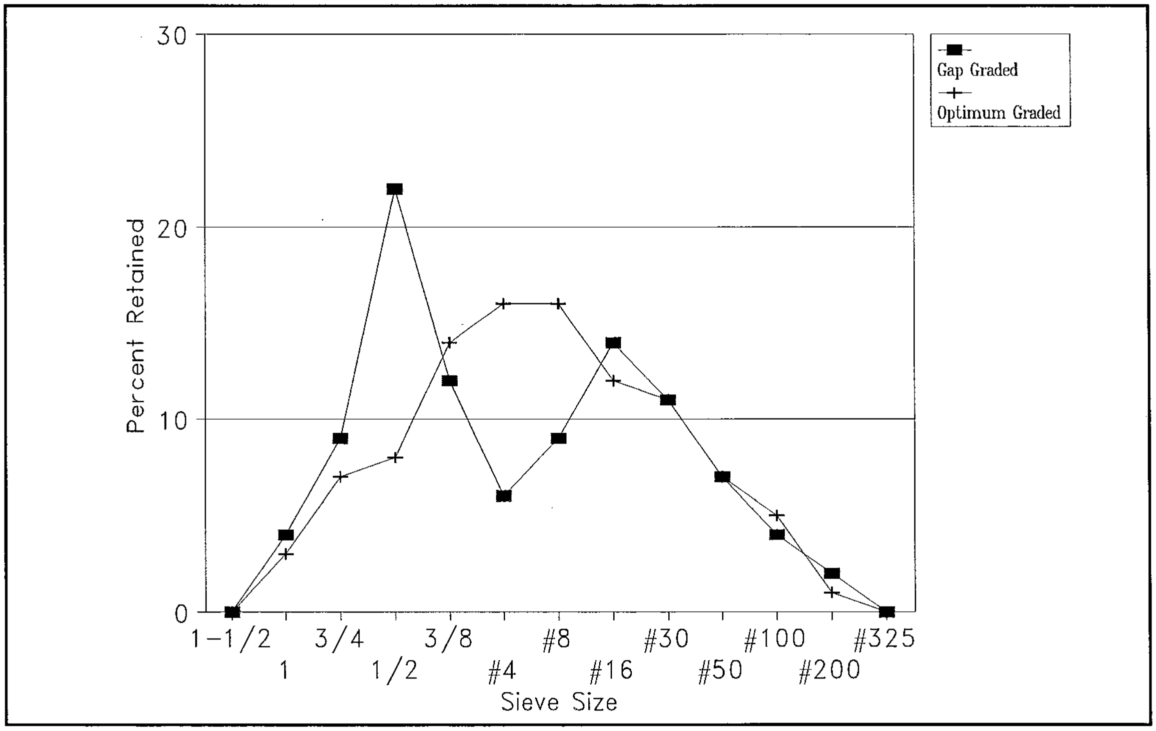

Figure 2. Uniform Gradation of Aggregates (28).

Tendency towards a bell-shaped particle size distribution also influences concrete slump. Typical slumps range from 1½ to 3 inches. The Texas Department of Transportation (District 12 in Houston, Texas) specifications require that the concrete have a slump of 1 ~ 3 inches at the time of placement. It may be possible to maintain slumps in this range by providing sufficient intermediate particles in the mix which may permit a reduction in mix water while maintaining an appropriate mix consistency.

The shape and surface texture of the aggregate influence the properties of fresh concrete. Sharp and angular aggregates will require more paste than rounded aggregates. However, rounded flat aggregates are harder to finish. The ideal aggregate is cubical and has a rough surface. River gravels tend to exhibit cubical and smooth surfaces, while crushed aggregates tend to yield angular shapes with rough surface textures.

Particle Size Distribution in Mix Design

The analysis of aggregate gradation and the combining of aggregates to obtain the desired gradation are important. Factors such as combined gradation and particle shape can have a significant effect on plastic and hardened concrete properties. The fineness modulus of fine aggregate is typically required for mix proportioning since sand gradation has a significant effect on workability. The fineness modulus for fine aggregate should be between 2.3 and 3.2 and may be a useful measure of the consistency of mix gradation, but the gradation analysis shown in Figure 2 may have greater utility. However, a fine sand (low fineness modulus) has a much higher paste requirement for good workability (12).

The amount of fine aggregate passing the No. 50 and No. 100 sieves affects workability; adequate fine material is needed for good cohesiveness and plasticity. This fraction may be reduced if the concrete contains workability enhancing admixtures such as fly ash or air entraining agents.

It is desirable to minimize the cost of concrete by balancing the cost of the aggregate against the cost of cement. Size distribution is related to the workability and economy of the mix. The significance of aggregate gradation is best appreciated by considering the percent retained on each sieve, as shown in (Figure 2) and the amount of mortar used in the mix. Gap-graded mixes tend to be more difficult to work, place, and control. Concrete mixes may be optimized to develop the best combination of aggregate particles with the cement paste to minimize the voids between particles, increase the density of the mix, and improve the overall workability. However, as stated earlier, mixes graded with respect to the application may require a gap-graded mix as the most optimized design.

Reinforcement

Jointed concrete pavements are normally classified as plain or reinforced, depending on whether or not the concrete contains distributed reinforcement. Plain pavements may be divided into those with or without load transfer devices at the joints. Those with load transfer devices are usually referred to as plain-doweled pavements. The presence or absence of reinforcement affects joint design.

When joint spacings are in excess of those that will effectively control shrinkage cracking or when subgrade conditions cause nonuniform slab support, distributed reinforcing steel is used to control the opening of resulting intermediate cracks. The sole function of the steel is to hold the fracture faces together if cracks should form. The quantity of steel varies depending on joint spacing, slab thickness, coefficient of subgrade resistance, and tensile strength of the steel (1,6).

In order for the steel to be effective, a good bond between the steel and the concrete must be achieved. Bond strength is developed from friction between the concrete and steel. It is difficult to measure the bond strength of concrete to steel reinforcement; however, there is a pull-out test (ASTM C234) that offers a comparison of different concretes based on their pull-out strengths (13,14).

MIX CHARACTERISTICS

Changes in mix materials or environmental factors affect the mix characteristics. The effects of mix materials have been discussed in previous sections, and are subsequently presented in greater detail.

Workability & Durability

Workability, as defined by the Texas Department of Transportation Standard Specifications, is defined as concrete that can be placed without honeycomb and without voids in the surface of the pavement after a specified finishing process is complete (15). The term workability is often associated, in varying degrees, in terms of placeability, mobility, pumpability, compatibility, finishability, and harshness. Each of these terms refer to a form of workability depending upon the construction application.

The most important factor in workability is the water content of the mix. Increasing the water content of the concrete mix increases the ease with which concrete flows can be consolidated. However, workability should be obtained without producing a condition such that free water appears on the surface of the slab during finishing operations. Depending upon the application and method of concrete placement, the required amount of mortar (sand, cement, and water) will vary and may affect the finishability of the pavement surface. It may also be possible to achieve optimum workability through appropriate selection of aggregate proportions. Excessive slumps, low workability or other conditions related to the consistency of the concrete mixture may require re-proportioning or adjustment of the mixture ingredients. Adjustment of the entrained air content will also affect concrete workability in addition to bleeding potential and strength. Other factors affecting workability are related to shape and texture characteristics of the coarse aggregate. All these properties are important including the effects of additives on the composition and the performance of the concrete mix (1,6).

Permeability

Permeability is mainly influenced by two mixture parameters, aggregate gradation and the water/cement ratio. The water/cement (w/c) ratio has the largest degree of influence on permeability. As the w/c ratio decreases, the porosity of the paste decreases and the concrete becomes more impermeable. This impermeability plays an important role in the durability of the hardened concrete. Also, the freeze/thaw action of the pore water can effectively destroy a pavement placed in a freezing environment. As the amount of hydration increases, the porosity of the paste decreases and the overall permeability is reduced. Use of a well graded aggregate, which tends to fill in the gaps between the larger aggregates, may also reduce the overall concrete permeability (1,6).

Durability Factors in Mix Design

The durability of aggregates can be conveniently related to physical and chemical factors. The resistance of an aggregate depends on whether high internal stresses develop when the water inside the aggregate freezes and causes a volume increase. This stress is a function of the porosity of the aggregate, its permeability, the degree of saturation, and size. The durability of FT concrete is enhanced by a low water/cement ratio since this improves permeability by limiting the supply of water needed to create a deleterious alkali-silica gel (1).

Pozzolanic admixtures are commonly used to control the reactions associated with the alkali-aggregate attack. Pozzolan reacts with the calcium hydroxide in the paste and lowers the ph of the pore solution. Consequently, fly ash is used to control the alkali-aggregate reaction since the replacement of fly ash for cement has an effect on reducing concrete expansion. Likewise, concrete expansion can be controlled by using low alkali-cements. Lithium and barium salts have been used as additives to control alkali-aggregate expansions; however, the use of these salts is not recommended (1,6,11,16).

CONSTRUCTION TECHNIQUES

In several instances of intersection construction, concrete materials have been placed using the vibrating screed method (Figure 3). This method is inherently labor intensive and requires that the workability of the concrete be sufficient to allow enough time for placement and finishing in order to avoid improper compaction or honey combing (Figure 4). Apparently, very few intersection construction projects make use of slipform placement. However, it is anticipated that this form of placement may be used in future projects and that the mix design using accelerating admixtures may be different (with respect to concrete workability) depending upon the method of placement. If the accelerating characteristics of the concrete are improperly managed, the concrete may set prematurely and adversely impact finishing operations (Figure 5). Due to the high cement content and quick setting characteristics of FT concrete, the time of placement is significantly reduced in comparison to conventional paving mixes.

Experience with FT concrete pavement construction indicates that the finishing and saw cutting operation can commence as early as two to three hours after placement particularly if using early-aged sawcutting techniques (rather than the typical 8 to 12 hours associated with conventional mixes for sufficient stiffening and hardening to occur). Properly managed, these characteristics can lead to greater efficiency and allow construction work to proceed in a timely manner, in terms of accelerated paving requirements.

With respect to pavement types, paving sequence and steel layout in accelerated intersection construction of continuously reinforced concrete (CRC) pavement are critical factors. CRC pavement, by definition, contains large amounts of continuous steel reinforcement. The purposes of the longitudinal reinforcement in this pavement type are to maintain small crack widths and not to allow the cracks to deteriorate into wide cracks. By keeping the crack widths to a minimum, good aggregate interlock along the transverse cracks can be achieved. The construction of an intersection typically involves intersecting lanes where the longitudinal steel for the intersecting pavement may become the transverse steel for the crossing pavement. In these instances, the paving lane (the direction of the slab placement) should be orientated in the direction of the longitudinal steel. If the paving lane is orientated perpendicular to the longitudinal steel, poor crack patterns may, and often do, result.

The location of the steel in relation to the surface also has an important impact. It has been noted in field surveys that when the longitudinal steel is placed too close to the surface, increased surface cracking will occur.

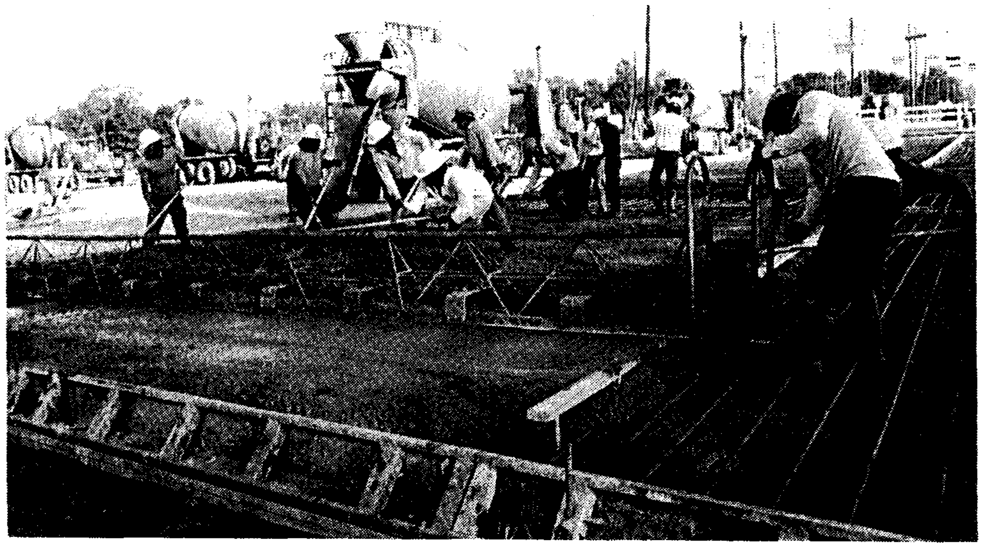

Figure 3. The Placement of Concrete with a Vibrating Screed.

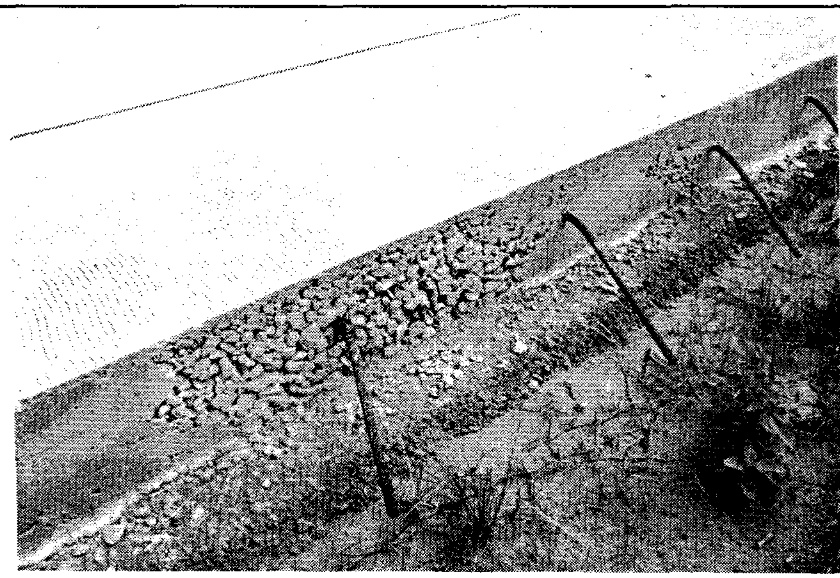

Figure 4. An Example of Improper Construction, "Honey Combing".

Figure 5. The Impact of an Improperly Managed Accelerator on Finishing Operations.

At construction joints where the existing pavement section and the new pavement construction section are of different thicknesses, various methods have been implemented to address this discontinuity in design. One method currently being used is to divide the steel of the construction section (which may be thicker than the existing pavement) into two layers (where required by design) and to tie one layer into the steel of the existing or adjoining pavement section. This method has not been found to be entirely satisfactory. An alternate approach is to use a transition slab to provide a transition between the different pavement thicknesses and the different steel percentages. The transition slab serves as a couple between the two pavement sections making it unnecessary to bend the steel for either section to connect the two sections together. Details on this type of jointing are provided in Appendix A.

Construction joints (shown in Figure 6) formed against the existing pavement provide a stiff reaction, comparatively speaking, for newly placed CRC pavement sections. This means that the crack pattern may be somewhat erratic at these locations due to the comparatively large differences in pavement stiffness and strength. Placement of a controlled crack pattern by saw cutting transverse notches in the pavement surface is suggested as a method to counterbalance the effect of the above differences. Based on

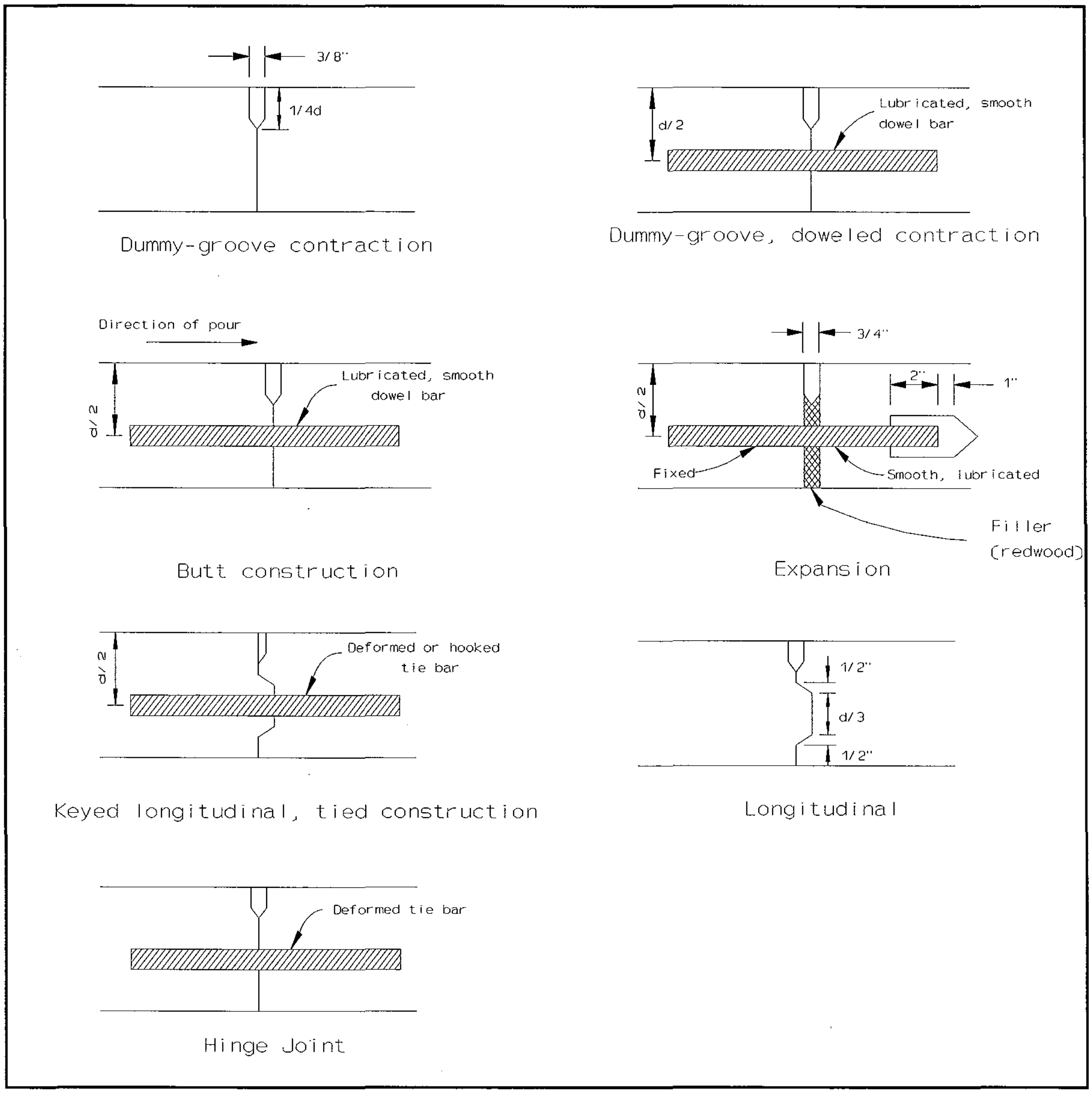

Figure 6. Example of Joints Used in Rigid Pavements.

limited experience, the controlled crack pattern can be formed by shallow notches at given intervals using early-aged saw cutting techniques.

Mix Design Development

Some departments of transportation specify concrete mixes by recipe. A typical fast track mix may consist of 710 pounds of Type III cement, 45 percent fine and 55 percent coarse aggregates. Up to 10 percent fly ash may be used as a cement replacement, except during cooler periods of the year since the peak temperature increase for a Type C fly ash may only be 18 to 26°F. Water reducers and air entrainers are typical additives for FT mixes. FT concrete paving has been successfully completed using Types I, II and III cements. However, the use of admixtures to promote early and long-term strength gain may be useful for Type I and II cements.

Mix Design Qualification

Mix design qualification is the verification of a mix design as it pertains to its strength gain characteristics under certain field conditions. For example, an accelerated mix behaves differently under cool versus hot weather conditions. To obtain a specific performance (strength, workability, and durability) under varying field conditions, the mix design may need modification. This modification may take the form of a change in the curing practice or the addition of admixtures. However, before implementing any change of this nature, adequate test procedures should be employed to account for specific conditions.

Testing FT mixes may consist of mechanical strength testing methods (flexure, compression, and pull-out) or of non-destructive methods of pulse velocity and maturity testing. The ultrasonic pulse velocity method consists of measuring the time it takes an ultrasonic pulse to pass through the concrete between two points. The relationship between pulse velocity and strength is affected by a number of variables such as surface moisture condition, aggregate to cement ratio, type of aggregate, and steel location. The correlation of pulse velocity to the flexural or compressive strength of concrete should be developed from laboratory or field data.

Maturity testing for pavement opening time has potential for both conventional and FT concrete quality control. Maturity concrete is the summation of the products of time and temperature. The maturity of testing indicates the development of concrete strength and the development of the degree of hydration of concrete, as well as serving as a useful means for estimating the in-situ strength of concrete at an early age.

FTC Mix Design

A list of typical field-placed FTC mix designs (accumulated during field surveys) is shown in Table 2 (taken from reference 9). A characteristic of these mixes is the high content of cement. Some of these mixes contained Type III cement which may be more

Table 2. Field Placed Mix Designs (9).

Mix Design	Cement Type	Cement Quantity (lbs/cy)	Target W:C Ratio	Fly Ash (lbs/cy)	Coarse Aggregate (lbs/cy)	Fine Aggregate (lbs/cy)	Admixtures		
							AE*	WR**	AC***
A	I	641	n.a.	73	1420	1420	YES	YES	NO
B	II	658	0.39	0	1698	1145	YES	YES	NO
C	II	658	0.39	99	1575	1062	YES	YES	YES
D	III	710	0.373	0	1528	1358	YES	YES	NO
E	III	640	0.425	70	1413	1413	YES	YES	NO
F	III	640	0.425	70	1413	1413	YES	YES	NO
G	III	641	0.425	73	1414	1409	YES	YES	NO
H	III	743	0.40	82	1308	1313	YES	YES	NO

* AE = Air Entraining Agent
** WR = Water Reducer
*** AC = Non-chloride Accelerator

n.a. = Not available
lbs/cy = pounds per cubic yard

appropriate for cool weather placement and not necessarily ideal for hot weather placement. Type III cement, when improperly used, may lead to severe, temperature induced random cracking. Also, some mixes contained approximately 10 to 15 percent (by weight of cement) of fly ash. Very few of these mixes used a non-chloride accelerator. Based on the quantity of coarse aggregate, it is noted that the coarse aggregate factors (CAF) are relatively low in comparison to typical paving mixes which range from 0.70 to 0.76. The low CAF can aid in improving the workability of the mix design (1,22).

Temperature and setting conditions may also be controlled by paving at night or avoiding the placement of a fast track mix between the hours of 10:00 am and 4:00 pm during the hotter portions of the year (typically from April to October). Appendix D provides details of an FT project that made use of night paving using accelerated mixes and superplasticizers to control the temperature of the mix.

Typically, quality control and traffic opening is determined by beam strength tests. The opening strength ranges from 350 to 500 psi (24.61 to 35.15 kg/cm^2). However, some agencies use compressive strength as opening criteria. Equivalent compressive strengths (in terms of the previous flexural examples) are 2000 to 4400 psi (140.61 to 309.35 kg/cm^2) (1,6,9,10).

Opening to traffic may be impacted by joint sawing operations. Saw cutting that uses conventional techniques may result in spalling if it is commenced too early before sufficient strength has developed. Problems of this nature are discussed later in greater detail. In order to minimize the impact of the saw cutting operation, the use of early-aged methods is recommended. The development of cracking at the sawcut is very sensitive to the type of coarse aggregate used in the concrete mix.

Some specifications for FT concrete indicate that the pavement section can be opened as early as eight hours and as long thereafter as specified by the engineer. Under certain mitigating circumstances (such as deleterious weather conditions), the engineer has the prerogative to postpone the opening of a pavement section to traffic. The engineer also has the discretion to open the lane early to traffic in the interest of the traveling public. However, such sections may only be opened provided that the concrete mix has reached or exceeded the specified flexural strength.

Mix qualification procedures to verify strength gain and performance prior to placement may deserve greater consideration. Currently, most agencies specify casting of a given number of test specimens to verify attainment of the specified strength within the specified time constraints. This approach is somewhat limited since it is subject to the conditions under which the test specimens were cast. Some questions with respect to the test results may arise since the conditions under which the beams were cast will seldom match exactly the conditions which exist at the time of placement. Therefore, strength gain criteria may not provide adequate verification to qualify a mix design for

FT paving operations. This same argument applies to test specimens that are cast in the field or the laboratory. This suggests that non-destructive test (NDT) methods, such as maturity concepts, should be employed to both qualify the mix design prior to construction and to control the quality during construction.

Factors associated with the mix materials in the concrete mix design are often the most variable factors in pavement construction quality. As shown previously, the gradation, the type of aggregate, and the addition of cement and additives can be significant factors affecting the fast track concrete mix design. For example, a greater amount of drying shrinkage may be induced with the addition of an accelerator, as was used in the Houston fast track test section described in the Field and Laboratory Investigation section of this report. An accelerator, known as Daraset, was used in this section (JFK and Sawdust/Rayford) and was stored in a large drum (shown in Figure 7) and put directly into the concrete mix at the construction site.

The water content of a mix also plays a major role in the shrinkage potential of a cement paste. Fresh concrete should be placed with as low a water/cement ratio as possible to minimize shrinkage, yet meet slump and finishing requirements. Difficulty has been experienced in the placement of 2 inch slump FTC mixes in hot weather conditions. An example of a fast tracking paving is provided in Appendix D.

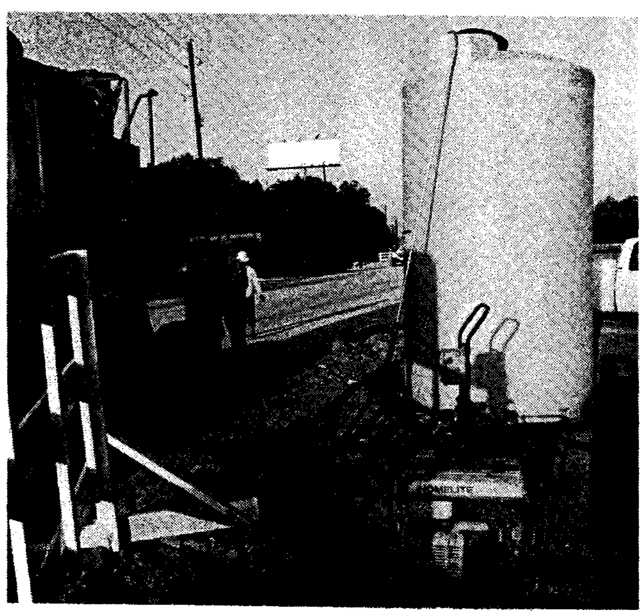

Figure 7. On Site Accelerator Application.

Pavement Thickness and Joint Design

Several factors influence the performance of concrete pavement whether it is jointed or CRC pavement. The major factors are (1,6,9):

1. the type and amount of traffic,
2. pavement thickness,
3. pavement drainage,
4. jointing layout, and
5. subbase and subgrade design.

Some intersection pavements constructed in urban areas using FT construction methods and mixes, may be subjected to high volumes of traffic consisting of heavy and light traffic loads. Due to the nature of intersection traffic, some design procedures, such as the AASHTO Design Guide, are not entirely applicable. It is speculated that, at least for jointed pavements, the design should consider both joint faulting and fatigue cracking, neither of which are directly predicted by the AASHTO design procedure. However, fatigue failure (and in some cases, dowel bar bearing) may be the overriding concern immediately after opening. At this age of the concrete, stress determination in the concrete should focus on load, moisture, and temperature factors. Detailed stress analyses suggest that subbase materials have little effect on load stresses as long as uniform support is provided throughout the design life. The justification for a stabilized subbase should not be founded on load stress alone since drainage and erosion factors should be taken into account as well. These factors should be kept in mind since the AASHTO procedure is an empirical design, based on the development of surface roughness, and may not be entirely applicable to a pavement design with no subbase or other drainage related factors. It is recommended that pavement drainage be provided in accordance with local drainage conditions (1,6).

The concrete thickness design is a direct reflection of the load carrying capacity of the slab in which the subbase normally has very little effect unless non-uniform support conditions develop. The primary function of a subbase is to limit erosion and provide uniform support. The subbase provides the following functions (19):

1. furnishes a stable construction platform,
2. prevents erosion of pavement support,

3. provides uniform slab support,
4. increases slab support,
5. facilitates drainage, and
6. controls the depth of frost penetration.

The load stresses which result from poor slab support may go beyond what can be considered in design, but the pavement may still perform beyond expected levels. Therefore, to obtain the greatest service from the pavement, it is important to consider the effects of the subbase/drainage design on the long term performance throughout the pavement design life. Type and thickness of the subbase are usually governed by climatic and drainage conditions. For fast track pavement applications, an open graded granular material (stabilized or unstabilized) may be appropriate in some instances, and possibly may not interfere with the concept behind accelerated pavement construction, having little impact on the pavement thickness design. Even with a subbase excluded from the pavement design, little increase in pavement thickness may be warranted if sufficient pavement support can be afforded which should tend to enhance the "one pass" pavement construction concept. The pavement design should also consider the increase in strength due to the extra cement in the concrete mix (18).

With respect to joint considerations, there are three general types of joints commonly used in the construction of pavement concrete intersections: contraction, expansion, and construction. These joints and their functions are as follows (1,6,9):

1. Contraction of weakened-plane (dummy) joints are provided to relieve the tensile stresses due to temperature, moisture, and friction, thereby controlling cracking. If contraction joints were not installed, random cracking would occur on the surface of the pavement.
2. An expansion joint provides space for expansion of the pavement, thereby preventing the development of compressive stresses which can cause a buckling of the pavement. These joints are probably unnecessary in intersection construction.
3. Construction joints are required to facilitate construction. The spacing between longitudinal joints is usually related to the width of the driving lane.

Similar joint types are applicable to fast track intersection construction. However, due to the nature of FTC pavement, delays required by some specifications on placement of these joints may not be consistent with early opening requirements.

Joint sawing for fast track concrete is the most commonly used method for installing contraction joints. The saw cut joint can be cut either by conventional or early-aged methods. Conventional methods to cut concrete use a diamond impregnated blade after the concrete has aged enough to cut. Early-aged cutting allows cutting of the concrete pavement prior to final set and shortly after initial set. Previous experience from pavement test sections have shown that early-aged cuts only need to be ¾ to 1 inch to adequately control random cracking in concrete pavements. Therefore, the depth of cut is not nearly as significant as the timing of the cut since a shallow surface notch is sufficient to initiate a crack, particularly prior to a significant gain in strength which should be reflected in the construction specifications. This can be accomplished by eliminating the depth of cut requirement and specifying a time related requirement (i.e. cutting should commence within 30 minutes after the initial set has occurred as determined by non-destructive testing methods such as correlation between initial set and concrete maturity).

The early-aged sawcut method, shown in Figure 8, also allows for earlier opening times and results in much smaller construction costs in working hours and equipment (sawblades). A dry cut saw utilizes a silicon carbide or carborundum blade.

Figure 8. An Example of Early-Aged Sawcutting.

CONCRETE PAVEMENT TYPES

Concrete pavement normally consists of a pavement slab and/or subbase material which is used primarily to promote drainage away from and underneath the pavement or to provide a non-erodible support for the slab. The pavement slab may or may not contain reinforcement or may be constructed with or without monolithic curbs.

Jointed Concrete Pavements

Jointed concrete pavement is constructed in two basic types: jointed plain concrete (JPC) or jointed reinforced concrete (JRC). JPC pavements typically have a joint spacing of 20 feet or less. JRC pavements usually have a joint spacing ranging from 20 to 100 feet.

Jointed concrete pavement with a joint spacing in feet longer than the slab thickness in inches should expect cracks to form at intervals between 12 and 20 feet (1). This crack forms a hinge that relieves stresses formed by moisture loss and thermal differentials (curling and warping) (19).

Reinforcing steel is typically placed at or near mid-depth in concrete pavement slabs. This reinforcement is not placed in a structural capacity but rather is placed to control crack deterioration. If cracks form, the steel is intended to keep the cracks closed, thus promoting load transfer across the joints through aggregate interlock.

Typically, if JRC pavement designs consist of contraction joints at 45 foot intervals or greater, two transverse cracks can be expected to form between each joint. Because cracking creates a natural hinge that relieves stress between joints, the pavement design thickness should be based upon the length of the slab between cracks, rather than the distance between joints. This would make the thickness designs of most pavements based on slab lengths of 30 feet or less (19).

A method to manage uncontrolled or random cracking is to create a crack at the desired location through the use of sawcutting. By sawcutting, a notch is cut into the slab transversely which causes a stress intensity that will initiate a crack or a hinge to occur through the slab thickness. By so doing, a hinge forms as a straight line which can be sealed in the same manner as a dowelled, sawcut joint. Consequently, since it is known where the hinge joints will form, additional reinforcing steel can be placed at these locations (and perhaps reduced or eliminated at other locations) to aid in holding the hinge joint tightly closed and reduce the probability of rupture of the steel from corrosion. Similar technology can be applied to sawed longitudinal joints (19).

This type of pavement is usually recommended where the construction phases may be less than 200-300 feet, since it is difficult to develop a satisfactory crack pattern in alternate concrete pavement types (i.e. CRC pavement) over short construction lengths of this nature.

Continuously Reinforced Concrete (CRC)

CRC pavement, which characteristically develops a crack pattern at close intervals, should be designed to eliminate or minimize the development of punchout distress or any of the preliminary distresses (loss of subbase support, spalling, etc.) which lead to the development of this distress. Past experience and research indicate that crack width and subgrade support play a significant role in the performance of CRC pavement (20). Consequently, the design of this pavement type should stem from a provision of establishing sufficiently narrow crack widths and the assurance of good pavement support. The quality of pavement support is related to the adequacy of the internal subgrade drainage system, which is dependent upon external drainage conditions. Efficiency of the subgrade drainage is enhanced by good surface drainage, if it is available, which limits the amount of time water is allowed to stand on the pavement surface. Otherwise, other approaches must be taken to provide maximum protection of the subgrade.

The key to obtaining good performance from a CRC pavement is the development of a well and evenly distributed crack pattern and the provision of uniform subbase support. To this end, concrete strength gain can have a significant effect on how well the crack pattern develops, particularly if it is too widely spaced. Some benefit may be gained, with FT CRC pavements, by cutting crack control notches at given transverse spacing to promote the development of an adequate crack pattern. The crack notches are intended to promote an even crack distribution (20).

FIELD AND LABORATORY INVESTIGATION

In order to form a base of information to investigate the current methods of fast track paving, a program consisting of field and laboratory testing was undertaken. Selected field sections were surveyed to determine areas of focus for the investigation in the laboratory. The goal of the laboratory work was to investigate the uses of maturity and consistency methods as applied to fast track pavement construction. Under the section "Summary and Recommendations," further recommendations for future testing are given. These recommendations are based upon results of the field survey and discussions with construction supervisors.

DESCRIPTION AND PURPOSE OF FIELD TEST SECTIONS

The field survey investigated existing pavement sections that used fast track mix designs. Given the placement conditions (e.g. weather, materials, methods of construction), crack patterns, and the level of distress, important information regarding the causative mechanisms related to the distresses were documented. With this information, methods that minimize these distresses were examined and provided as recommendations for construction procedures and techniques.

To evaluate cracking on chosen pavements sections, five different categories of information were considered:

1. crack surveys,
2. concrete cores,
3. FWD data,
4. setting characteristics, and
5. consistency factors.

Crack and Coring Tests

Crack surveys were conducted at two intersections: one at Beltway 8 and JFK, and the other at I-45 and Rayford/Sawdust Roads in the vicinity of Houston, Texas. The results from these surveys are shown in Figures 9 through 11. The crack surveys indicated erratic cracks, corner cracking, and cracks developing from expansion joints. Several items of information can be obtained from examination of these figures. Random cracks of this nature may result in early slab breakup due to the loss of load transfer, pumping, and punchouts. Several of these cracks are yet to extend through the slab thickness.

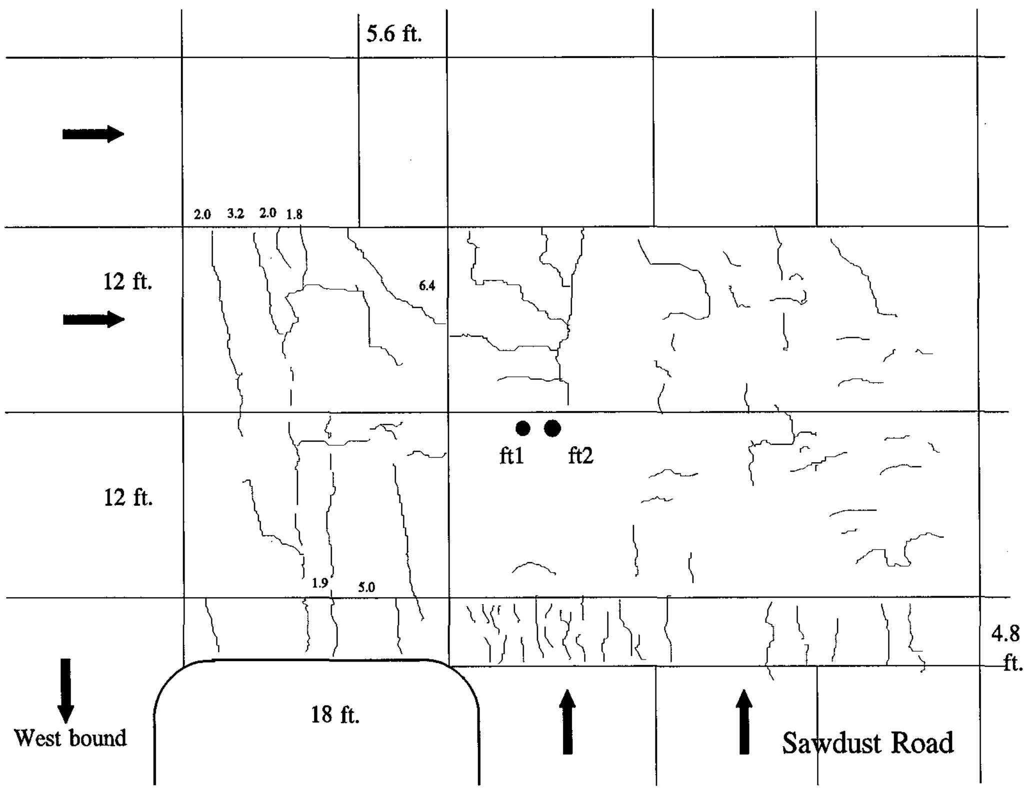

Figure 9. Erratic Cracks in Sawdust Frontage Road with Fast Track.

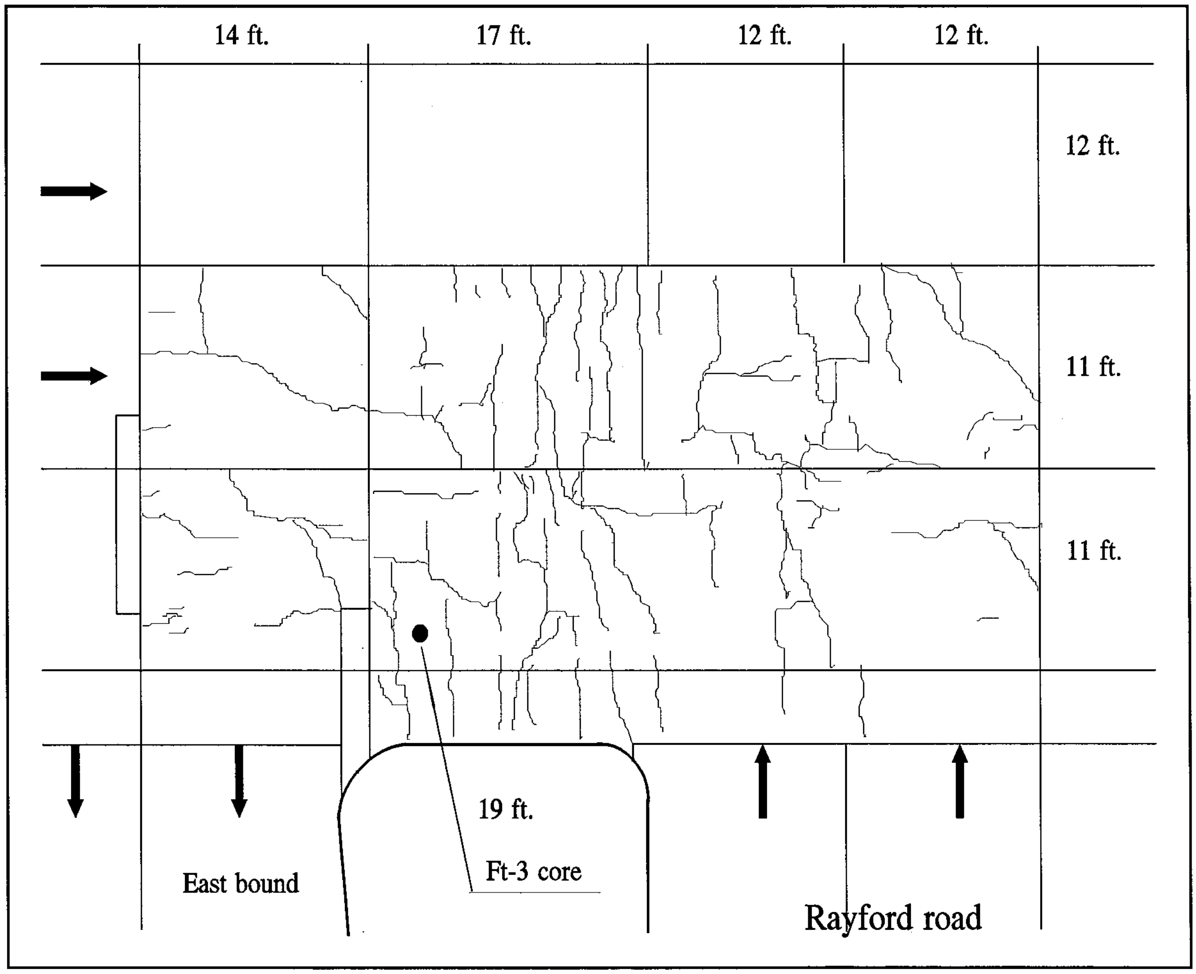

Figure 10. Erratic Cracks in Rayford Frontage Road with Fast Track.

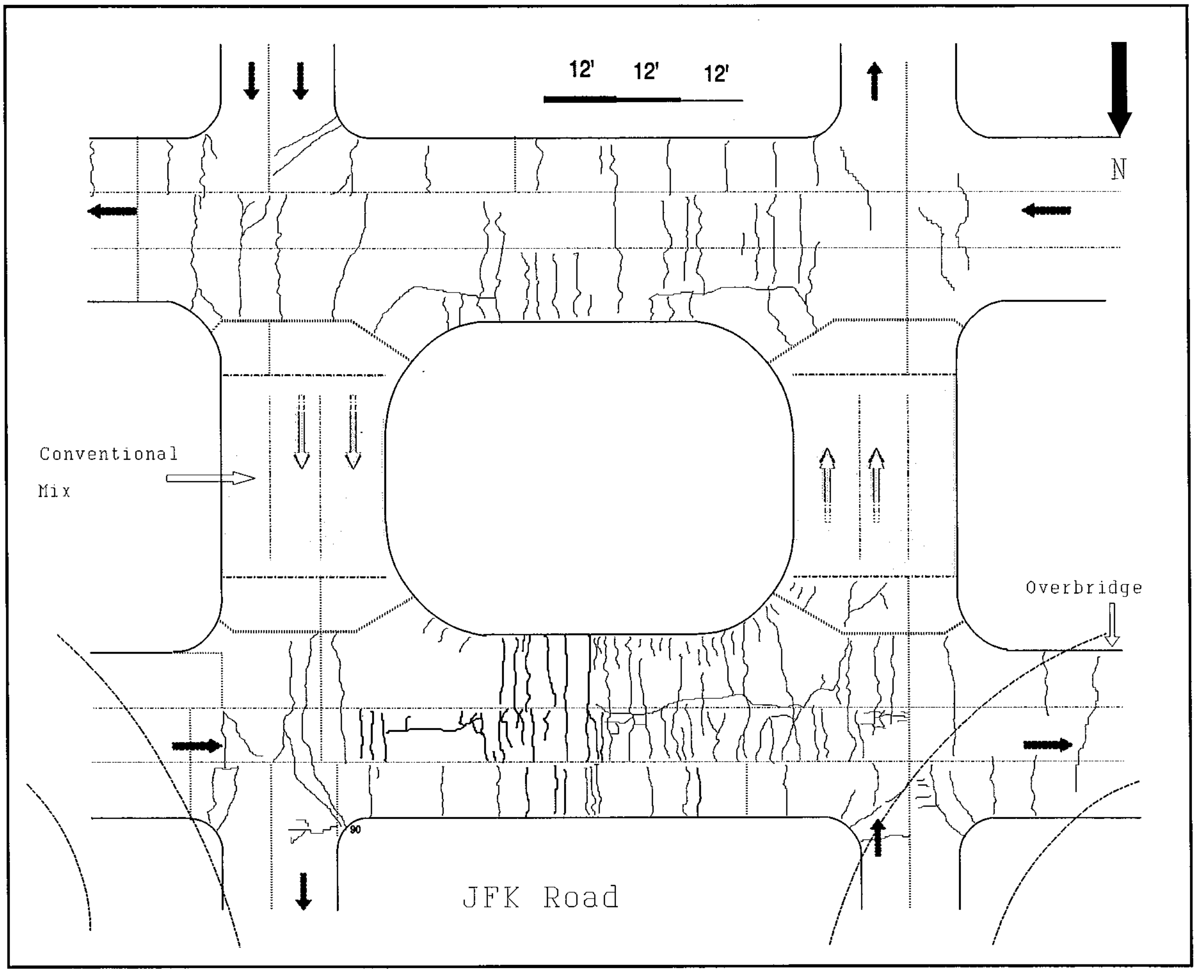

Figure 11. Surveyed Crack Pattern of BW-8 and JFK Intersection.

The probable causes for such random cracking are:

(1) paving perpendicular to the direction of the longitudinal reinforcing;

(2) mix design, gradation, workability;

(3) admixtures; and

(4) environmental conditions at the time of the construction.

Figure 12 illustrates the cracking observed in a core removed from one of the FT sections paved at the Rayford/Sawdust intersection. Other core samples were taken to allow a closer look at the cracking distress. The locations of the steel reinforcement are noted in Table 3. From the data obtained by observing the cores, as illustrated in Figure 12, it can be observed that the crack depth typically terminated at or near the top layer of steel reinforcement.

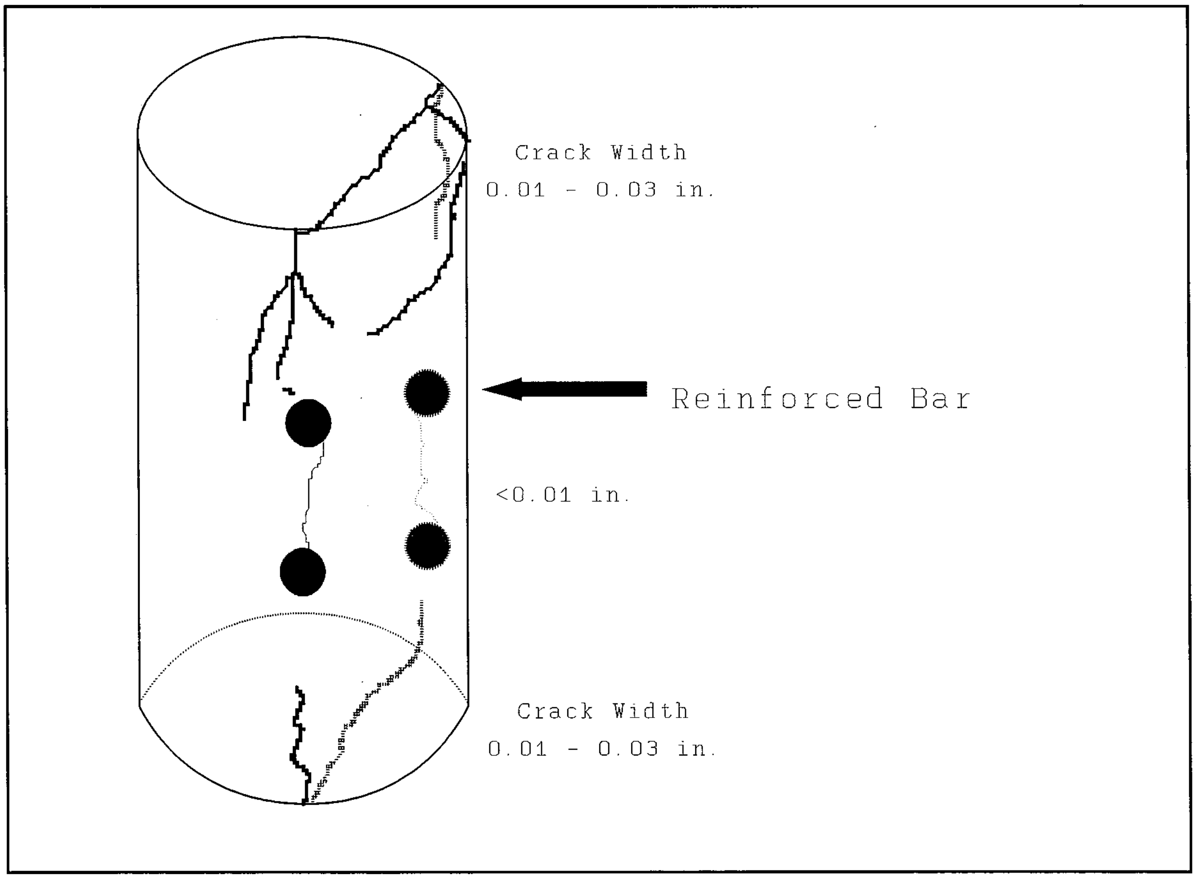

Figure 12. Section Cracks of Core R-4 from Rayford Frontage Road.

Table 3. Pavement Section Layout and Crack Data from Cores in Sawdust and Rayford Roads.

Location	Core Name	Slab Thickness (in.)	Transverse Steel from top (in.)		Longitudinal Steel from top (in)		Crack growth (in.)			Crack Width (in.)
			Top	Bottom	Top	Bottom	Top	Bottom	Rebar	
Sawdust	S-1	14½	6¼	10	5½	9¼	.15	No	No	.01
	S-2	14¾	6¼	10¼	5½	9⅜	6	No	No	.01 -.03
	S-3	>14	6¼	8⅞	-	-	5½	No	No	.01 - .03
Rayford	R-1	14¾	-	-	4½	11¼	No	No	No	No
	R-2	-	6½	-	5½	-	6½	-	No	.01 - .03 (c.01 - .02)
	R-3	>15	6⅛	10½	5½	11½	4 - 6*	1	Yes	.01 - .03 (c.01 - .02)
	R-4	>15	7	10½	-	-	4 - 7*	2½	Yes	.01 - .03 (c < .01)

The temperature during construction of the fast track sections at the Sawdust/Rayford locations (these are the cross-hatched patches shown in Figure 1) was reasonably mild, ranging from 60°F to 70°F, which typically is expected to provide for excellent placement conditions. However, as can be seen in Figures 9 and 10, acceptable temperature conditions do not always yield an acceptable crack pattern. The cause of this distress was not completely evident, however the authors speculate that the use of a non-chloride accelerator (Daraset), the mix proportioning and the cool weather conditions (causing a large temperature drop in the hydrating concrete) were primary contributors to the cracking patterns exhibited in these sections. The JFK intersection concrete was placed under high temperatures which can be deleterious to the placement of a rapid hydrating cement. During a field visit to the JFK fast track intersection project (Figure 11), it was determined that the north outside lane, which exhibited a more normal crack pattern, was placed at a greater slump than the adjacent lanes. Based on interviews with DOT construction personnel, it appears that the amount of water available or present in the concrete at the time of placement had an effect on the cracking behavior exhibited at this intersection.

Not to be contradictory, but the nature of the cracks noted in the cores suggests that drying shrinkage strains may be the primary cause of the poor crack pattern since most of the cracking exists in the upper portions of the slab. A potentially negative side effect of the high cement content mixes is high drying strain which should be controlled through proper curing. For high cement content concretes, an adequate curing should be provided to ensure sufficient hydration. Obviously, a delicate balance exists between, for sufficient water for workability and placement versus that needed for hydration while minimizing the potential of shrinkage cracking.

Field surveys have also indicated a tendency for long crack spacing (which is undesirable) to develop in intersection CRC pavement sections. These sections tend to be short (300-500 feet) and are subjected to a lower range of stress than longer pavement sections (2,500 feet or more) are subjected. The use of FT concrete may magnify this problem to a greater extent due to the inherent rapid strength gain associated with FT concrete where the strength may exceed the induced stresses from environmental effects over that which may occur with conventional mixes. Therefore, the use of early-aged crack control techniques may minimize the incidence of long crack spacing.

Aggregate type can significantly affect crack development for concrete pavement. Construction sections monitored under this investigation used a limestone coarse aggregate which exhibited greater shrinkage and tensile strain capacity than river gravel aggregates. This suggests that this type of aggregate will develop longer crack spacing, unless controlled, which may also cause excessive stresses in steel ties located at construction joint locations. In this respect, the use of river gravel aggregates may be more appropriate for jointed concrete applications to enhance the breaking of joints at the sawcut notch locations.

The spalling distresses that were noted in jointed FT sections appeared to be related to saw cutting operations. Spalling, shown in Figure 13, possibly resulted from the use of conventional sawcutting techniques prior to adequate strength development. It is advisable to use early-aged sawcutting techniques to avoid similar problems in the future. These techniques will allow for joint sealing operations and the early opening of a lane or intersection in a timely manner.

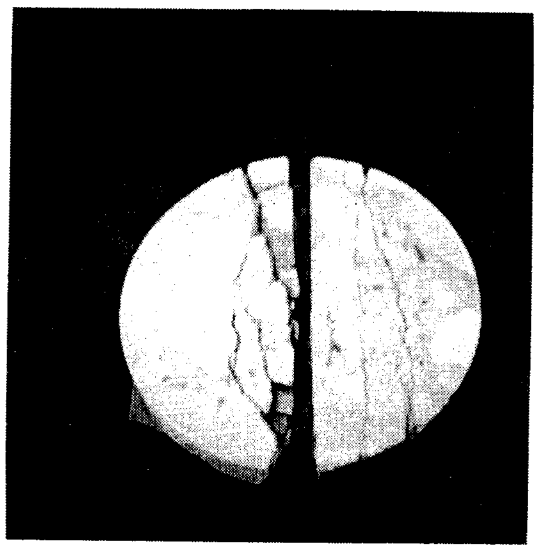

Figure 13. US-59, Spalling Due to an Early Saw Cut.

FWD Testing and Analysis

Falling weight deflectometer (FWD) testing was conducted to evaluate crack patterns and joint types which occur in FT concrete pavements. Analysis of FWD data has been used as a method to evaluate the structural capacity of jointed or CRC pavement systems. The FWD test has been predominantly used for JRC pavement systems, but has also been applied in the successful evaluation of CRC pavement systems.

The results of FWD testing can be used to estimate material properties of the in-place pavement system. Specifically, the modulus of elasticity (E) and the modulus of subgrade reaction (K) are "back calculated." Both of these material properties can be used to describe a useful pavement property known as the radius of relative stiffness (ℓ_k). The radius of relative stiffness incorporates material and geometric properties of a concrete pavement system to describe the structural capacity. The equation for ℓ_k is given by the equation:

$$\ell_k = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}} \tag{1}$$

where

μ = poisson ratio

h = pavement thickness

E = modulus of elasticity

k = modulus of subgrade reaction

To back-calculate the E and k values, a combination of finite element analysis (ILLI-SLAB-ref. 30) and Westergaard analysis is used to calculate a deflection basin that is compared to the deflection basin measured by the FWD. The E and k values are adjusted until the deflection basins match, completing the back-calculation process. Using Westergaard analysis and the ILLI-SLAB data, a relationship (Figure 14) can be established correlating the area of the deflection basin to the radius of relative stiffness of the pavement system. Using the FWD test data, the deflection basin can be determined directly from the field data and used to back-calculate the values of E, k and ℓ_k (20,21).

FWD data was obtained from Rayford-Sawdust/I-45 and Bissonet/US-59 pavement sections in Houston, Texas. The Sawdust and Rayford section was CRC pavement and the Bissonet section was JRC with redwood expansion joints at 60.5 feet (18.44 meters) and hinged joints at approximately 15 foot (4.6 meters) intervals. All three sections were tested under moderate to cool temperatures in which the joints and cracks were open and critical load transfer conditions existed. This normally occurs in the early morning hours.

Another useful parameter derived from the FWD data is load transfer efficiency

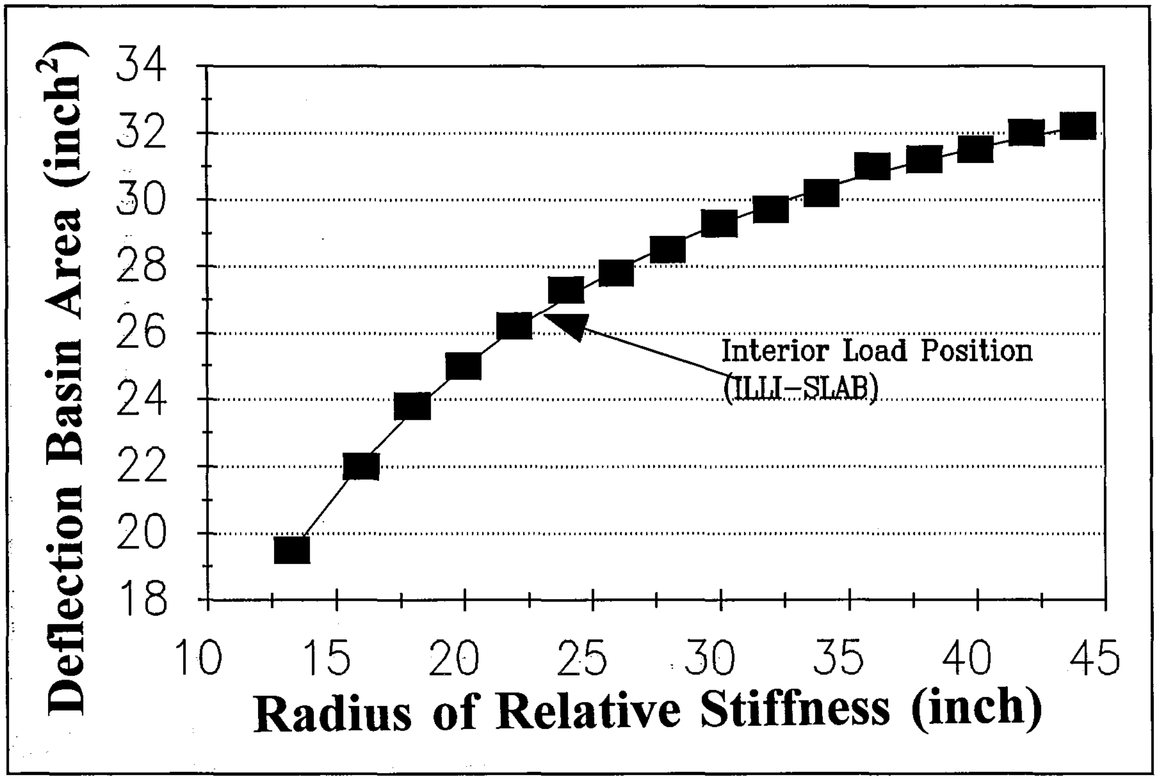

Figure 14. A Relationship Between ℓ_k and the Deflection Basin.

(LTE). This parameter is a measure of the load transfer capability of the joints and cracks in the pavement system. From the graphs provided in Appendix E (Figures E-1 through E-6), the LTE of the different type joints can be observed. Minimum values of LTE and ℓ_k can also be an indication of poor support under the pavement system. In some cases, where the LTE is an acceptable value of 90 percent, a corresponding low ℓ_k value (such as 20 inches [50.8 cm]) is a manifestation of poor joint behavior. A portion of the FT pavement constructed at Bissonet (Figure 15) was tested using the FWD. The station markers shown in this figure correspond to the station markers listed in Figures E-1 and E-2 of Appendix E. The analysis of the FWD data for this section implies that the joint system may be in poor condition. Most of the joints indicated good LTE. The construction joints at station 1 (a doweled, redwood joint) showed better behavioral characteristics than the contraction joints. Many of the recorded values for LTE and ℓ_k were below the recommended values of 90 percent and 30 inches (76.2 cm), respectively. This may be due to poor support and lack of subbase. For the Bissonet section, low values of LTE can lead to pumping and spalling (20). These joints should be monitored on a periodic basis in future investigations.

Field Maturity Testing

The maturity of concrete is a time-temperature relationship that provides an indication of the concrete strength at a particular age. The maturity method provides an uncomplicated solution to predict the complicated process of hydration and strength gain (2).

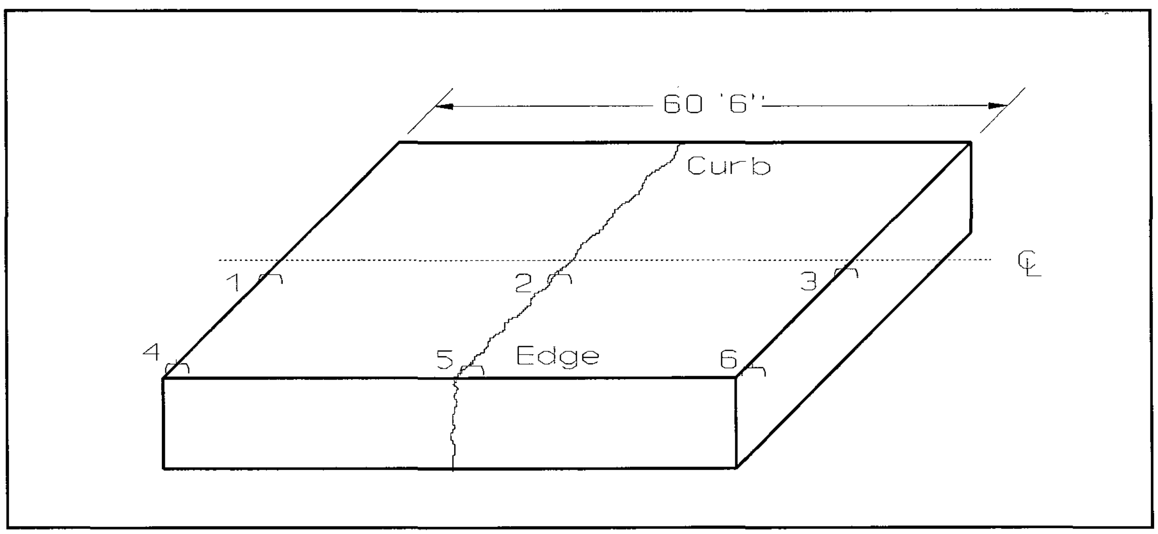

Figure 15. FWD Test Section for Bissonet Road.

The maturity method can be defined as the integral, with respect to time, of the curing temperature measured from a datum temperature (2). Maturity can be expressed as:

$$M = \int (T - T_o)\,dt$$
$$or,\ t_e = \Sigma e^{-\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_s}\right)} \Delta t \qquad \textbf{(2)}$$

M	= Maturity
t_e	= Equivalent age at a specified temperature (T_s)
T	= Temperature of the concrete
T_0	= Reference temperature
Δt,dt	= Increment in time
E	= Activating energy, J/mol
R	= Universal gas constant

The ultimate goal of measuring maturity in field is to predict the time of opening for the pavement slab without exhaustive destructive strength testing. The measurement of maturity in the field can be accomplished using either a temperature recording device or a maturity meter. Using the former, it is very important to keep accurate records of temperature and time (especially within the first 24 hours) since these are the basic inputs for maturity. The maturity meter automatically computes maturity value which can be read directly on the LCD screen (2,5).

The maturity process (in reference to the equivalent age, t_e), as applied in the field, has three components:

1. laboratory testing,
2. worksheet computation, and
3. measurement of maturity values in the field.

The first process involves the calculation of activation energy, ultimate strength, and pilot beam strength/maturity testing for the specific mix being used. This portion is discussed in greater detail later, under the section entitled "Laboratory Maturity Testing."

The second process involves using the Opening Strength Criteria Worksheet (discussed in Appendix B). Using the information from the laboratory data, the worksheet can be used to predict the time to open (Appendix C). This time is measured from the time the concrete is placed.

The third phase of this process is instrumenting the desired section with sensors to measure the maturity. The maturity of the concrete pavement can be read directly from the instruments. When the maturity of the concrete in the pavement correlates to a strength equal to or above the specified concrete strength, the pavement is ready to open to traffic.

Consistency Testing

The purpose of conducting consistency tests is to characterize the rheology or workability of the concrete mixture. The amount of time available to finish concrete is a very important factor in accelerated concrete mixes. The way to characterize these factors is through evaluating the workability of the concrete with time. The test and equipment proposed for use in the field are illustrated in Appendix F.

The consistency test is relatively new in the U.S., but is included in German Construction Specifications (DIN Standard 1048). The closest approximation (in terms of field applications) to the consistency test in the U.S. is the ASTM slump test. The primary difference between the two tests is that the German construction specification consistency test is dynamic in nature involving repeated dropping of the concrete sample, and the ASTM procedure is static in nature. The dynamic test may be a more representative measure of consistency of fresh concrete (28).

Field consistency testing using the equipment illustrated in Appendix F was conducted on fresh concrete consisting of seven bags of cement. Since a seven bag mix can hydrate at an accelerated rate, it is imperative to obtain several consistency measurements within the first hour of hydration to check for appropriate workability at the time of finishing.

The consistency test was conducted with the following parameters:

1. drop height = 1 inch (2.54 cm), and
2. flow radius varied from 10 to 18 inches (25.4 to 45.72 cm) - (which is actually user selected).

Using the same sample for each test iteration, the concrete was tested at 8 minutes (yielding 10 drops) and 20 minutes (yielding 20 drops) after placement. The decrease in workability can be easily identified by the increased drops for the concrete to flow to the 16 inch (40.64 cm) radius. For further information, refer to Appendix F.

DESCRIPTION AND PURPOSE OF LAB TESTING

Laboratory Maturity Testing

The laboratory method for the maturity (i.e. equivalent age, t_e) testing involves two procedures:

1. calculation of the activation energy (E) or reference temperature (T_o), and
2. calculation of the ultimate strength (S_∞).

Both procedures are conducted before application of the maturity testing in the field to yield constants (E or T_o and S_∞), which are used in maturity relationships that will be discussed later in this section.

A maturity relationship (i.e. equivalent age, t_e), can be developed to represent the variation of age (with respect to actual time) versus the temperature and the equivalent age of the concrete. It has been demonstrated that (2,29) the Arrhenius equation (shown in equation 5) fits this relationship best; thus, it will be the focus in this report. When using the Arrhenius equation, the activation energy (which is an integral part) must be found. The activation energy affects the shape of the age factor versus the concrete temperature. This means activation energy affects how the concrete strength varies with respect to time. Also, as the activation energy increases, the age-temperature relationship becomes increasingly non-linear.

To calculate the activation energy, the standard ASTM test C1074-89 is used. Basically, to perform the procedure, three different curing temperatures are used. Concrete mortar specimens are made and cured for each curing temperature.

After conducting cube mortar strength tests, the strength of the mortar cube can be plotted in terms of age at each curing temperature (Figure 16).

The following strength-maturity relationship can be used to determine the activation energy of a concrete mix:

$$S = S_\infty \frac{K_T t}{1 + K_T t} \qquad (3)$$

Manipulating equation (3), the following is obtained:

$$\frac{1}{S} = \frac{1}{S_\infty} + \frac{1}{K_T S_\infty t} \qquad (4)$$

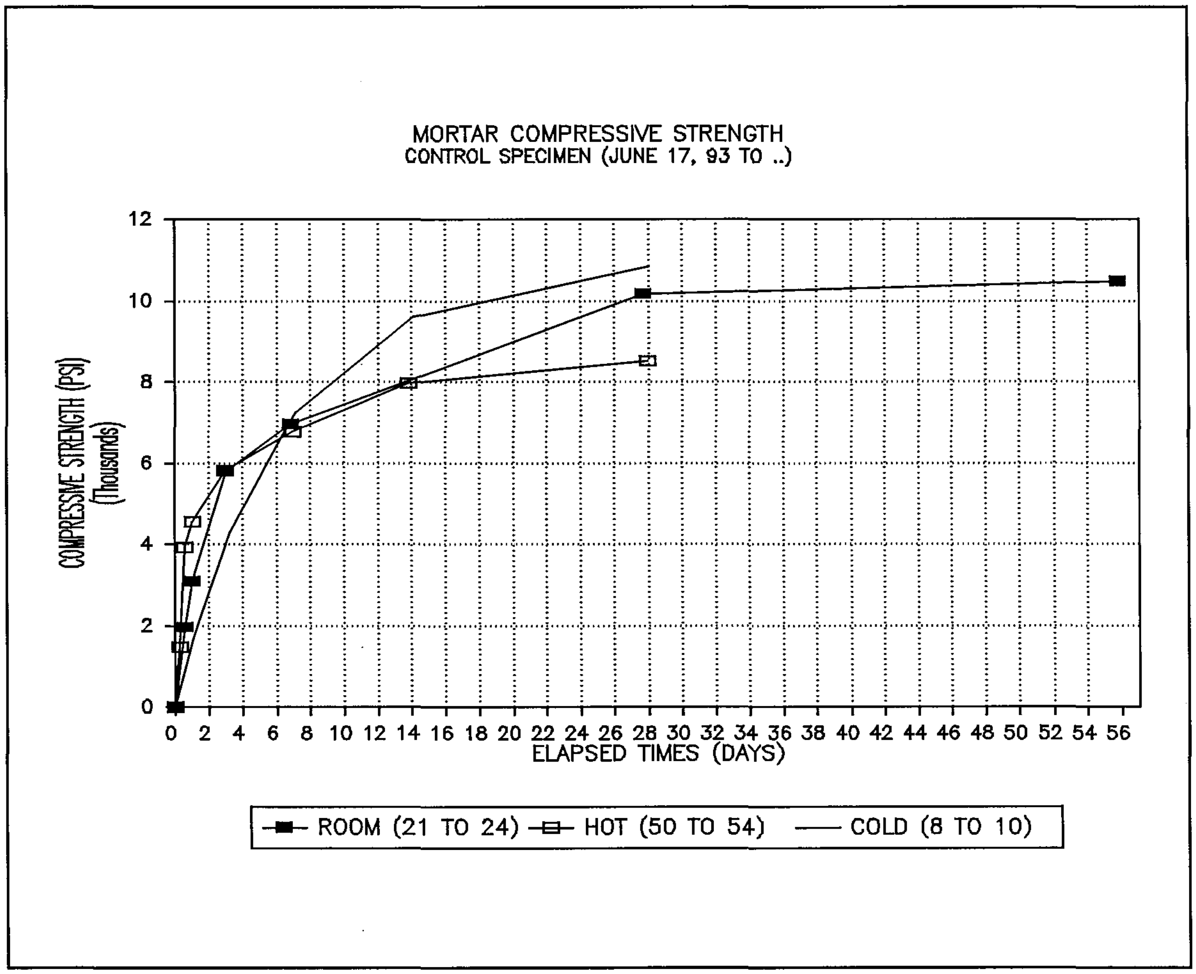

Figure 16. Mortar Strength Tests at Different Curing Temperatures.

where

S = cube mortar strength

S_∞ = limiting strength

K_T = rate constant

t = time

Figure 17 is the graph of reciprocal strength versus age of the mortar cubes. From this graph, the three rate constants for different curing temperatures can be determined by dividing intercepts of the y-axis over the slopes of the lines. The rate constant (K_T), is known to vary with the curing temperature. This variation is modeled by the Arrhenius equation:

$$K_T = Be^{-\frac{E}{R}(\frac{1}{273+T})} \quad \textbf{(5)}$$

Equation 4 can also be transformed into a linear equation as follows:

$$\ln K_T = \ln B - \frac{E}{R}\frac{1}{273+T} \quad \textbf{(6)}$$

where

B = constant

Finally, the slope of the line shown in Figure 18 represents the value of E/R (activation energy divided by the universal gas constant). The activation energy (E) can be found by multiplying E/R by the universal gas constant (R). The ultimate strength can be found from the intercept shown in Figure 17.

Setting Characteristics

The Penetration Test (ASTM C403 - 90) procedure is primarily used to measure the change of consistency of a fresh concrete mix with time. The consistency of the fresh concrete can be used to determine boundaries for the initial and final set of the concrete. This test can be used in conjunction with the maturity test in order to better evaluate the characteristics (strength and workability) of the concrete. The test is conducted with a mortar sample which is found by sieving the fresh concrete mix over the #4 sieve. The mortar is placed into a container and tested by pressing a needle into the sample and reading penetration resistance in psi.

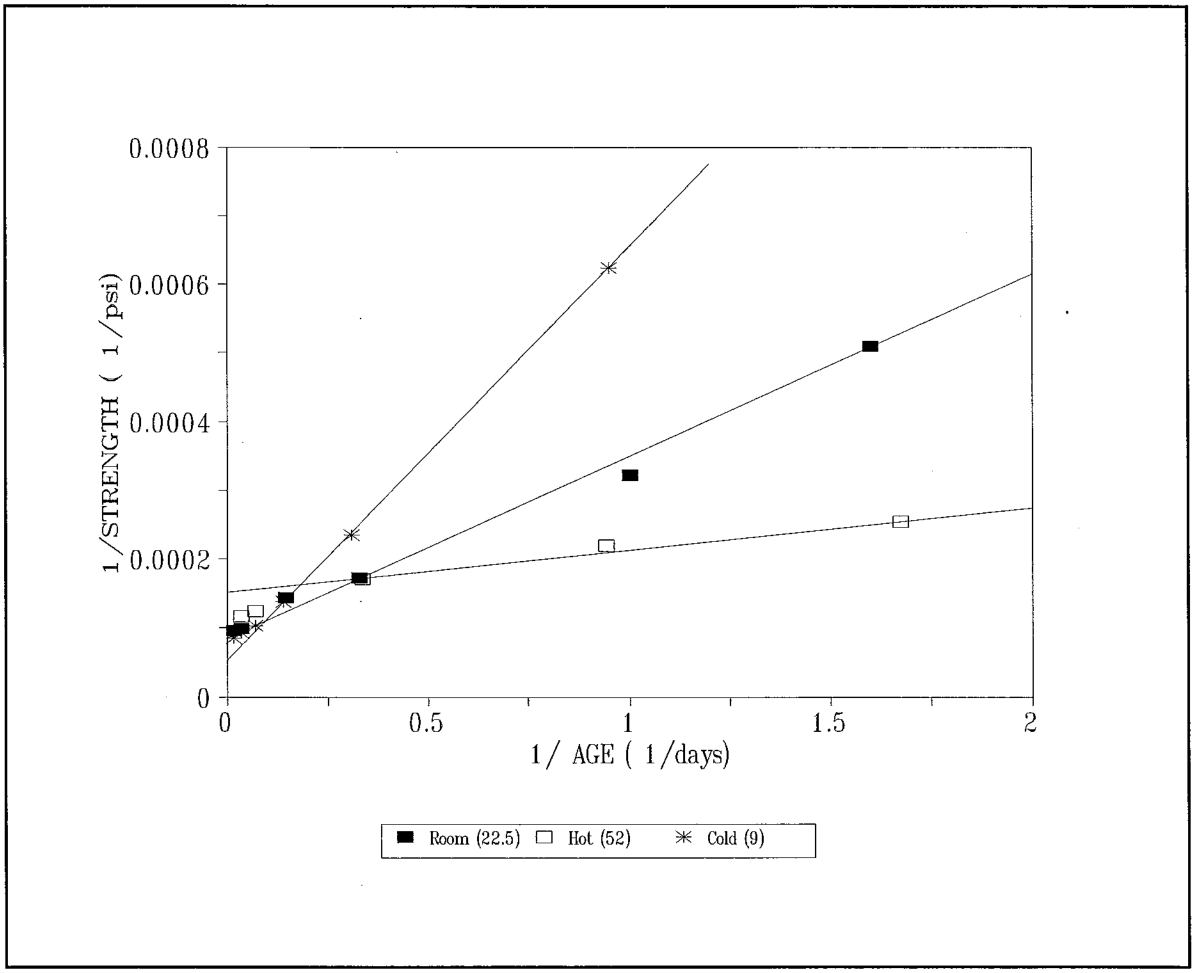

Figure 17. Different Rate Constants for Different Curing Temperatures (°C).

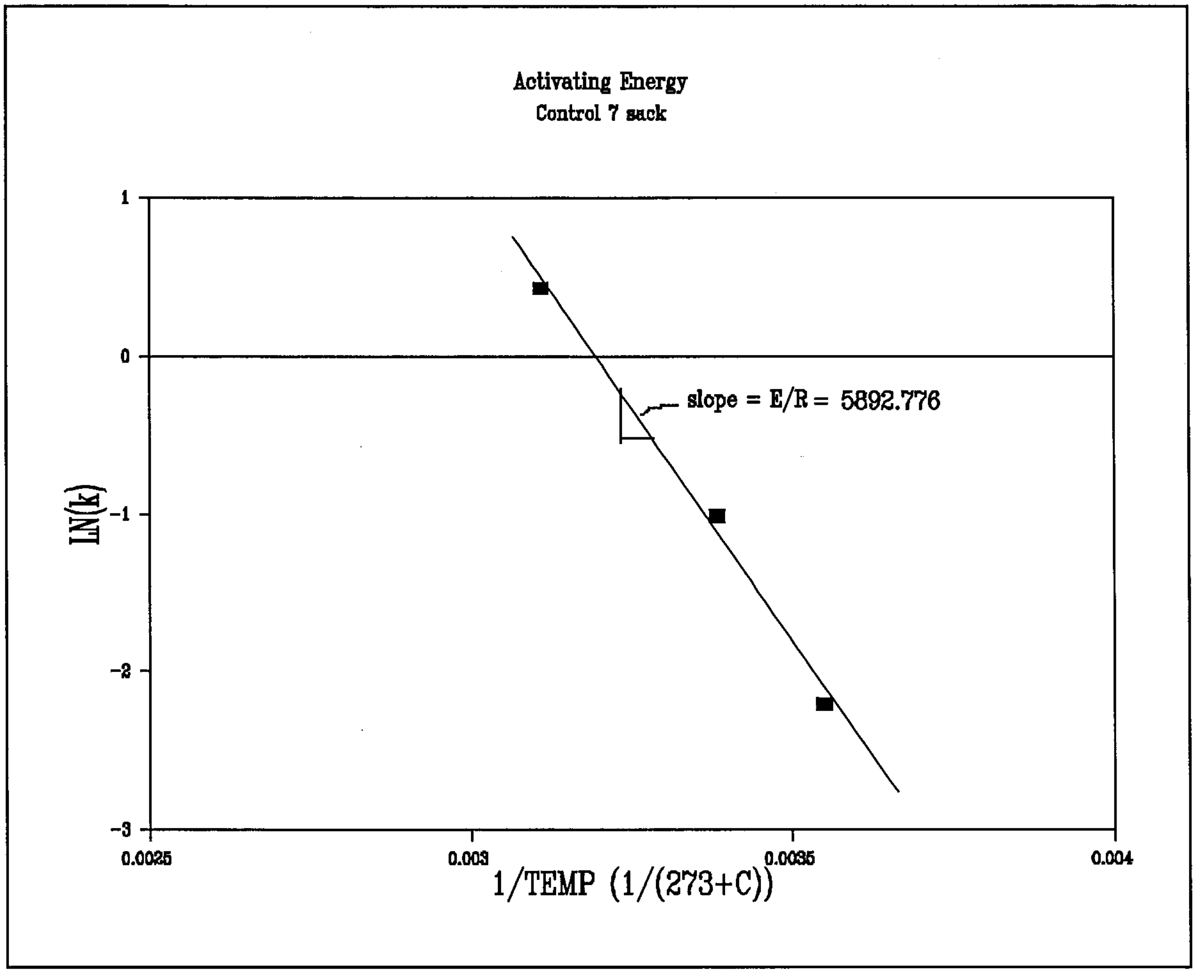

Figure 18. A Graph to Ascertain the Activation Energy.

The information this test yields is important because it gives an indication of:

1. available time to finish the concrete,
2. time frame in which to joint (sawcut) the pavement, and
3. time to open the concrete pavement to traffic.

The penetration test yields an indication of the times of initial and final set of the concrete mortar mix. The initial set is the time at which the concrete mortar begins to stiffen significantly. The final set gives evidence as to when the stiffened concrete begins to gain strength. The available time to finish concrete may be related to the amount of time before initial set occurs. The concrete must retain sufficient workability until the finishing is complete.

The time frame in which to obtain an early sawcut on the concrete pavement is confined within a certain window of time. The concrete must not be too fresh or the strength will be too low to prevent the joints from ravelling. The concrete must also not be too old or the fracture toughness will be too high to obtain cracking. To ensure cracking at the saw cut joint, the pavement must be cut after the initial set and before the final set. In accelerated construction, this window can be very small.

In laboratory testing, referred to previously, three different mixes were chosen:

1. a standard 7 bag mix design,
2. a standard 7 bag mix design with accelerator, and
3. a standard 7 bag mix design with a super plasticizer.

After conducting the penetration test, most of the expected trends were manifested by the test data (the accelerated sample hydrated the earliest while the superplasticized mix hydrated later than the control mix). As illustrated in Figure 19, the accelerated mix reached both initial and final set first, followed by the control and then the plasticized mix. Although the plasticized mix was expected to have a later initial set, the final set was expected to be closer to the control mix. However, strength testing showed that the plasticized strengths surpassed the control mix. It can also be observed from the test results (which are temperature dependent) that the parameters of finishing, jointing, and opening to traffic depend heavily on mix additives and should be considered in construction.

From Figure 19, the results of the penetration test relate to some extent to both finishing and jointing operations and the time to opening to traffic. For example, for laboratory conditions, the accelerated mix achieved initial set within 2¾ hours after mixing time which may also represent a maximum finishing time of 2¾ hours. It is important to note that the penetration test may be useful as a complement to the maturity testing, but not useful as a measure of the opening time of a pavement.

The time frame, or window, available to early sawcut the concrete pavement can be illustrated as approximately midway between the initial and final set times. From Figure 19, the time of initial set of the accelerated mix is approximately 1 hour. The penetration test may be an important indicator of when to sawcut within the acceptable time frame.

Consequently, it may be possible to estimate the abovementioned saw cutting window with the penetration test. In Figure 19, the accelerated mix reaches final set at 3¾ hours. This agrees with past fast track paving experience, where often a pavement

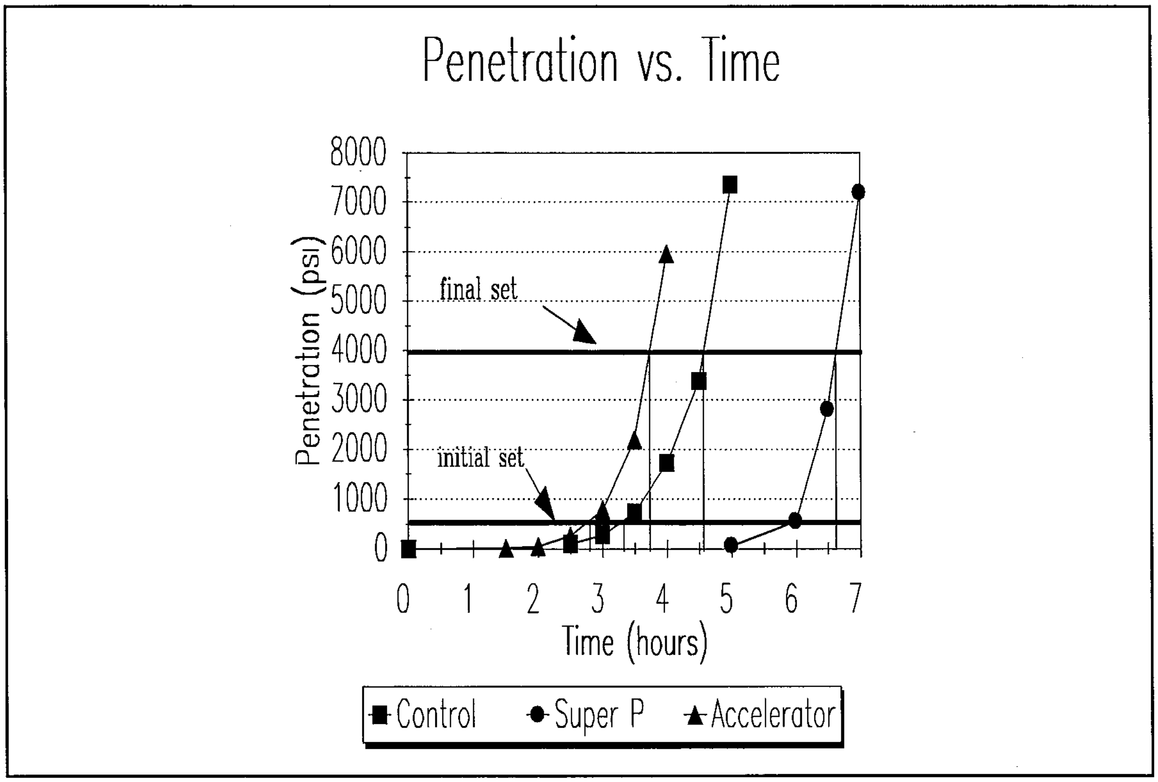

Figure 19. Lab Results of Penetration Testing.

can be sawcut in as little as four to six hours. However, ambient temperature conditions may affect this result as previously pointed out.

The initial and final set of a concrete mix may not be the determining factor in exactly when to cut, or finish a pavement. However, the setting information may provide some indication as to the behavior of a particular mix. The penetration test used in the laboratory may also provide good cross-reference with the maturity of the concrete. It is important to note that the penetration tests in the lab and the penetration tests in the field may not match exactly due to differences in paving conditions.

EVALUATION OF OPENING CRITERIA TO TRAFFIC

INTRODUCTION

The ultimate factor controlling fast track paving is when the pavement can be opened to traffic. It is recommended that this decision be based on strength and not on a time constraint (9). Strength gain is a function of the cement hydration and environment. With the flexibility of FT mix design, use of strength as the opening criteria is the most logical. Time criteria will not allow the flexibility that can be afforded by this technology. Flexural strength testing or several types of nondestructive testing are available for strength evaluation.

Determining the strength needed for opening to traffic is dependent on the construction staging plans, the rate of strength development of the mix, and/or the traffic loads that will use the pavement during the first several hours after opening. For example, the standard opening criteria could be lowered significantly if only automobile traffic were allowed onto the pavement. Examining pavement damage in a jointed concrete pavement system in relation to concrete strength at very early ages gives guidance for specifying opening strength criteria. The curves in Figure 20 were developed using the traditional Westergaard analysis for loads at the edge of a slab supported by a dense liquid subgrade. The critical load stresses under a single-wheel axle load are shown in terms of the dimensionless stress (s) and the radius of relative stiffness (ℓ_k - as previously described in equation 1):

$$\sigma_{wls} = P*s/h^2 \qquad \textbf{(7)}$$

where

h = slab thickness (in)

P = axle load/2 (lbs)

σ_{wls} = wheel load stress

A multitude of stresses for several conditions can be found from Figure 20. According to accepted pavement design practice, when the ratio of load stress (r) to modulus of rupture is limited to less than 0.5, very little damage (leading to crack formation) should develop in the concrete slab. As slab support or pavement thickness increases (or any change that causes the ℓ value to decrease), the stress level (and r) decreases (4,13,25). This variation allows different opening strength criteria to be used

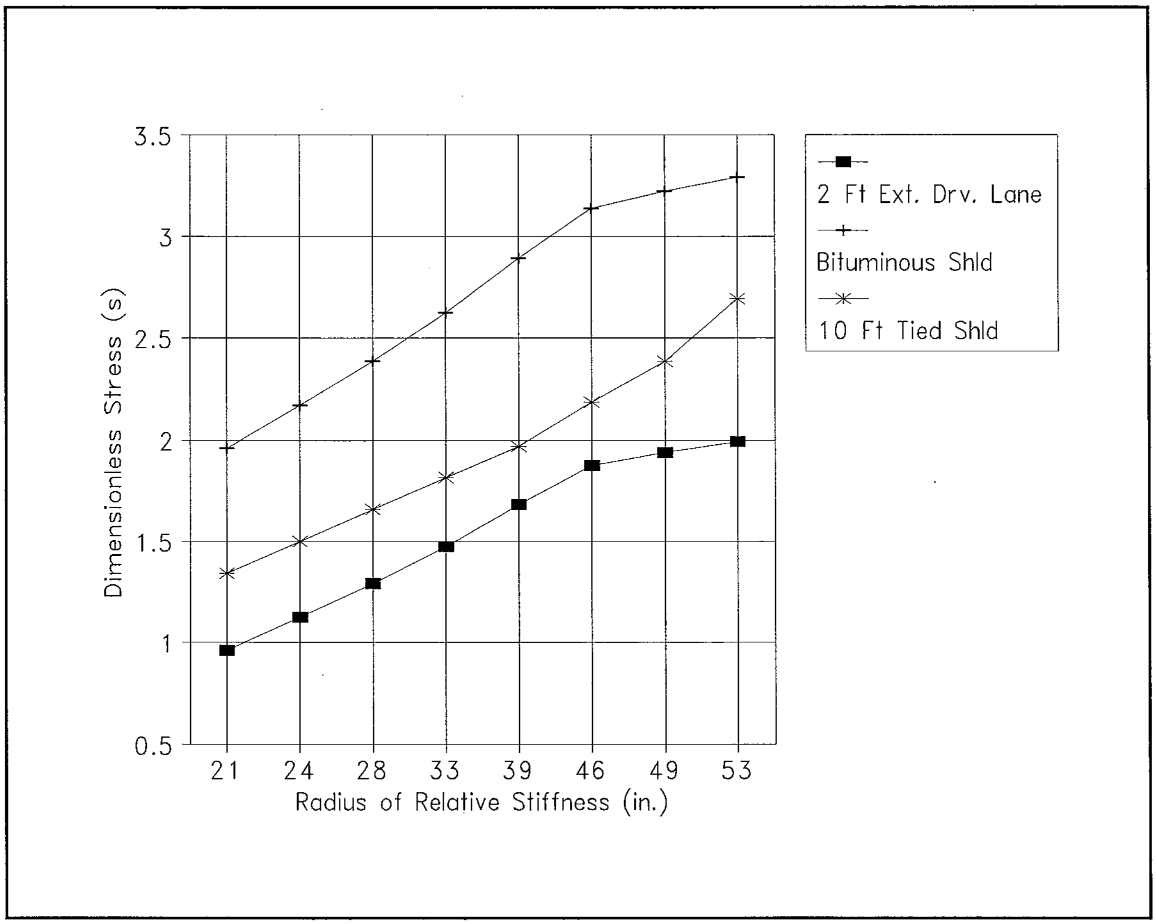

Figure 20. Load Stress in Jointed Systems.

dependent on the pavement design and the expected early loading level (see Figure 21).

For instance, if only automobiles (P = 2,000 lbs) represent the critical loading that the pavement will be subjected to at opening, perhaps an opening flexural strength of 200 psi will be sufficient according to this analysis. Elaborating further, for a pavement of 10 inches in thickness, one can calculate a value of ℓ_k equal to 37 inches. From Figure 20 for a pavement with a 10 foot tied shoulder, a value of $\ell_k = 37$ corresponds to a value of s = 1.9. From Figure 21 and for a value of s = 1.9, a stress ratio (r):

$$r = \frac{\sigma_{WLS}}{200} = \frac{2000(1.9)}{200 \cdot 10^2} = 0.19$$

results, which is well below the value of 0.5 previously noted. However, for the same conditions, if trucks are allowed (P = 9,000 lbs), opening criteria will need to be as high as 500 psi for an eight-inch pavement and about 350 psi for a ten-inch or greater slab as shown in Figure 22.

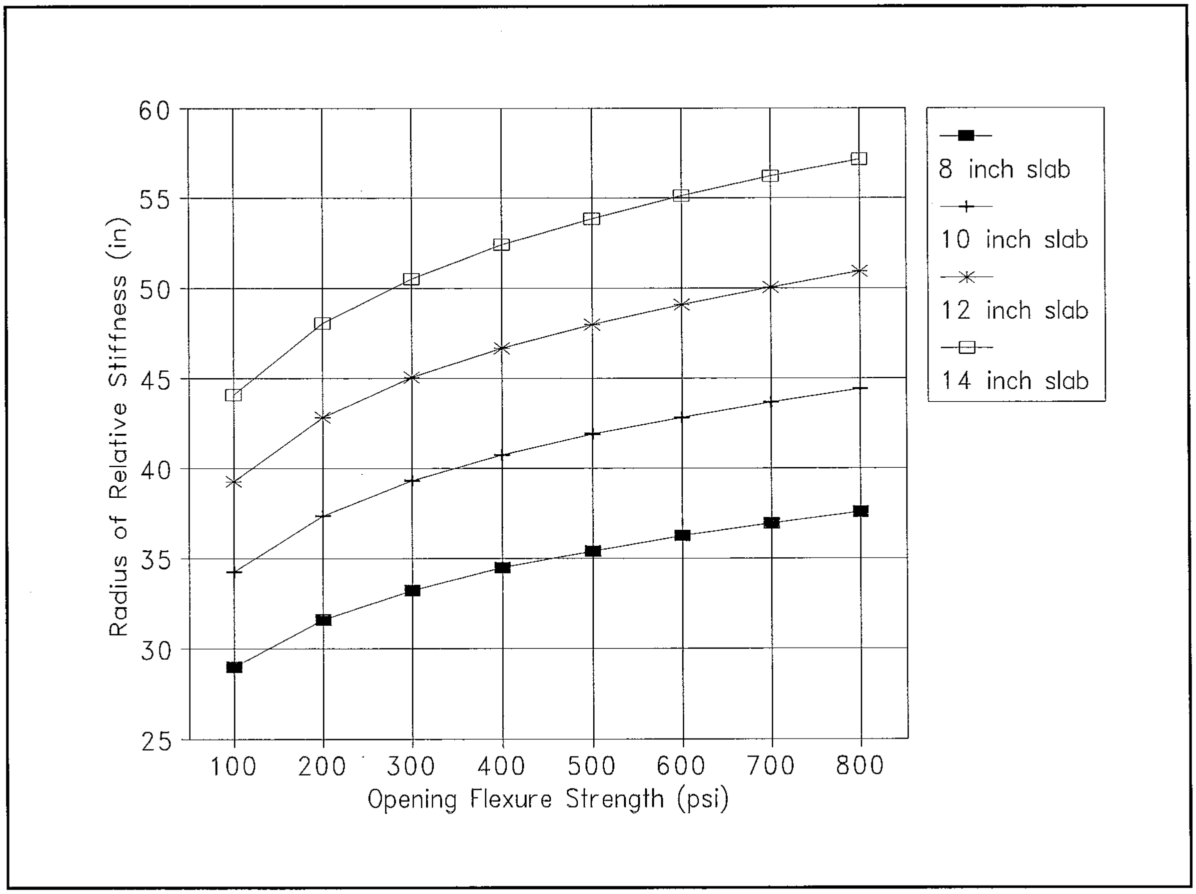

Figure 21. Jointed Pavement Design Criteria for a Ten Foot Tied Shoulder.

EARLY OPENING CRITERIA

As a means of estimating and restricting the damage done to newly-placed concrete pavements subjected to early loading, general recommendations have been developed. The amount of fatigue damage to be consumed by early construction loading may be a critical issue. This value is largely influenced by the design loadings and pavement design factors (thickness, shoulders, etc.).

The previous example depicts a recommended procedure for determining the time that the pavement can be subjected to early loading. Critical factors influencing the potential load amount of damage done to a concrete pavement are listed below:

(1) Pavement design characteristics (thickness, foundation support, load transfer),

(2) Concrete strength at the time of anticipated early loading,

(3) Rate of concrete strength gain,

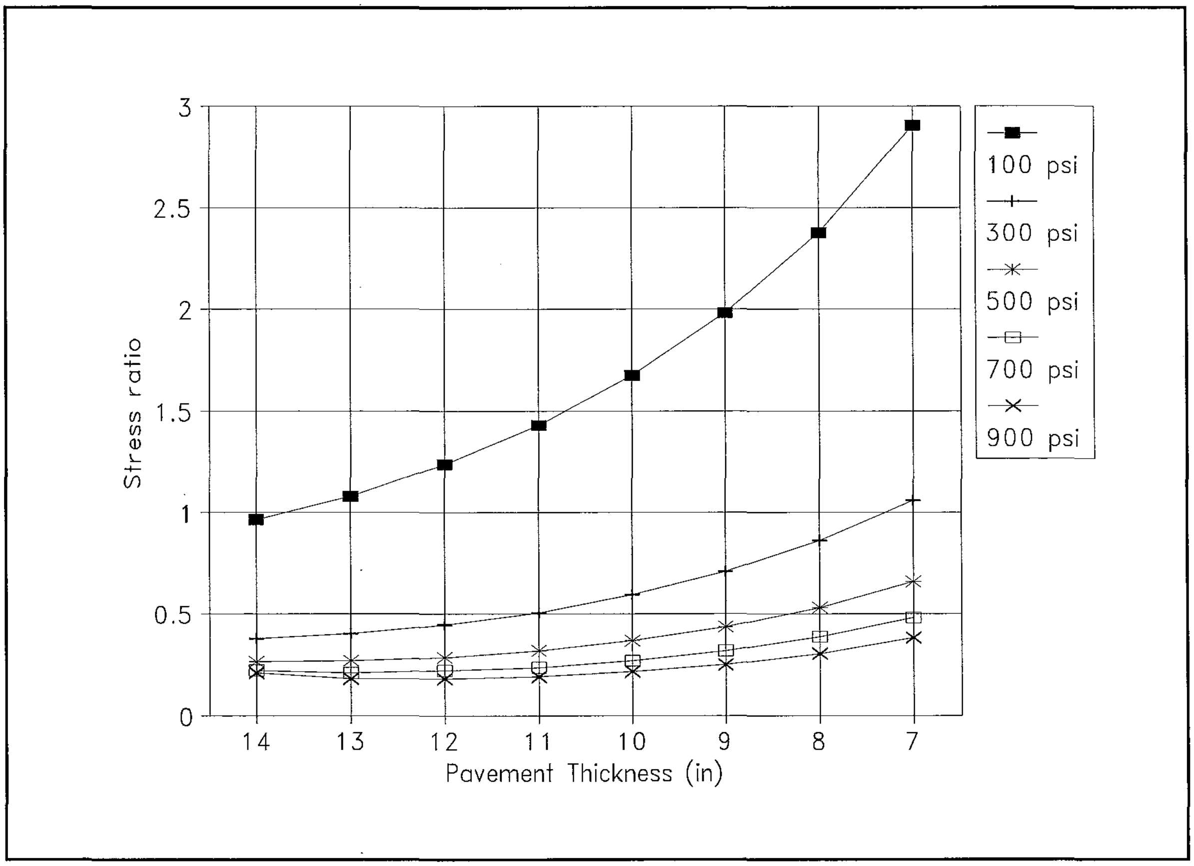

Figure 22. Opening Criteria for Jointed Pavement with Ten Foot Tied Shoulder (P = 9000 lbs.).

(4) Type of early loading construction vehicle (gross weight, axle weight, axle type, contact pressures),

(5) Pavement shoulder configuration, and

(6) Number of repetitions of early loading vehicles.

With the exception of the second and third items, all of the factors are known or can be reasonably estimated. Therefore, it is critical that there is a means to estimate the in-situ strength of the concrete slab at any time. This may be done using the maturity technique as previously discussed, or the pulse velocity method.

The pulse velocity method measures the velocity of a sound wave passing through a slab and uses the wave velocity to approximate strength. Both methods can be correlated so that the measured values can be used to estimate the in-situ compressive strength of the concrete as previously discussed (17,18).

For pavements with doweled joints, the bearing stresses exerted by the dowel on the concrete should be evaluated. To avoid possible crushing of the concrete above the dowel, a doweled slab should not be loaded until the compressive strength of the slab is larger than the bearing stress that would be developed under the anticipated traffic (17,18).

Early loading may often be controlled by the bearing stresses and not by the fatigue damage from edge loading in doweled pavements. Dowel diameter has a large effect on reducing bearing stresses in the concrete slab. Use of large diameter dowel bars allow the slab to be subjected to earlier loading than a similar slab with small diameter dowel bars. Large diameter dowels also help reduce faulting in concrete pavements (19).

EVALUATION OF CRITERIA

Restraint stresses in CRC pavements are important for the development of an adequate crack pattern to ensure the long term performance of the pavement. Special considerations are necessary where FT CRC pavements are constructed because of the rapid strength gain characteristics associated with these types of concrete mixes. Some insight into the behavioral characteristics at an early age of CRC may be achieved through analysis of the gain in strength as compared to the development of stress in a CRC pavement constructed using fast track concrete. On this basis, it is obvious that different climatic and seasonal conditions significantly affect the development of the crack pattern. The cooler the conditions under which paving is conducted, the greater will be the average crack spacing. Different mix designs may affect the average crack spacing; but coupled with the rapid gain in strength, sufficient stresses may not occur to adequately develop the crack pattern and the associated tight crack widths to ensure long term performance.

Cracking will develop when the induced concrete tensile stresses are greater than the strength of the concrete. There are several factors which contribute to the formation of transverse cracking, as explained in the section "Cracking and Coring Tests". When concrete pavement experiences a temperature and humidity drop or change, transverse cracks form due to the steel reinforcement restraining the volume changes in the concrete. This mechanism is dominant at early ages of the CRC pavement. Further cracking may be induced after opening the concrete pavement to the traffic; but most of the cracking is caused by environmental effects.

Table 4 summarizes the combinations of design conditions which were considered in the analysis of an FT CRC pavement at an early age. To develop a general idea of the effect of different FT flexural strength gain curves on the development of the crack pattern, four different kinds of concrete strength curves were used. These strength curves are representative of data obtained from actual FT mixes used in the field. The modulus of elasticity of the concrete was varied as a function of time which depended upon the compression strength of the concrete. Shrinkage strain was assumed to be uniform throughout the pavement cross-section. However, shrinkage strain is known to

Table 4. Typical Design Factors.

Design Input		Values or Conditions
Concrete	Pavement Thickness (in.)	12
	Flexural Strength at 1 day (psi)	500, 600, 700, 800
	Elastic Modulus	Depends on Strength
	Thermal Expansion Coefficient and Shrinkage Strain	Depends on Aggregate Type
Steel	Bar Size (#)	6
	Percentage Reinforcement (%) (Longitudinal)	0.5, 0.6, 0.7
Wheel Loading	Opening Time (day)	1
	Subgrade Modulus (pci)	200
Temperature	Curing Temperature (°F)	140
	Temp. Drop in 28 Days (°F)	70
	Minimum Reference Temp. (°F)	40

be non-uniform and dependent on the humidity concrete, the concrete curing temperature, and the coarse aggregate type. Above are the results of this analysis using the CRCP5 (31) program for different concrete strengths and percentages of longitudinal steel while other factors were held constant. These results are presented in Figures 23 to 26. For the analysis of different aggregate types, (limestone (LS) and siliceous river gravel (SRG)), different coefficients of thermal expansion of concrete and shrinkage strain curves over the design periods were used.

Figure 23 shows the relationship between mean crack spacing and flexural concrete strength, which contain a limestone (LS) coarse aggregate for different design steel percentages. As pointed out previously, the greater the concrete strength, the greater the mean crack spacings. The mean crack spacings for 0.7 percent of steel is shorter than that for 0.5 or 0.6 percent steel. Figure 24 shows the corresponding mean crack widths for different LS concrete strengths.

It should be pointed out that a crack width of 0.055 inches is suggested as a crack width maximum limit. Maintaining cracks below this limit helps to limit or reduce spalling potential over the life of the pavement (30). However, if the crack spacings are too large, on the average, this limit will be exceeded. Therefore, it is important to develop the crack pattern early so that crack spacings are not too far apart or too close together. Figures 23 and 25 show that a low coefficient of thermal expansion associated with a LS concrete results in larger crack spacings than a concrete containing an SRG coarse aggregate. However, as indicated by Figures 24 and 26, only a mix design which results in an opening concrete strength of 500 psi at 1 day with 0.7 percent steel is adequate for maintaining crack widths within tolerable limits. In other words, CRC pavements that are paved with an FT concrete mix and gain more than 500 psi in one day may not provide adequate performance on a long term basis unless shorter crack patterns develop over time. FT concrete mixes may require steel designs of 0.7 percent or greater since steel reinforcement lower than this tends to induce wider crack spacings and widths greater than the maximum limit. It may be possible to counter the strength gain effect by inducing the crack pattern with early-aged saw cutting which notches the pavement early enough to allow the use of normal amounts of steel reinforcement in construction; otherwise, the concrete strength may be too high to allow cracking to occur. Saw cut notches at 3 or 4 foot intervals may hold the crack tight enough to allow lower percentages of steel to be used as indicated by Figures 23 and 25.

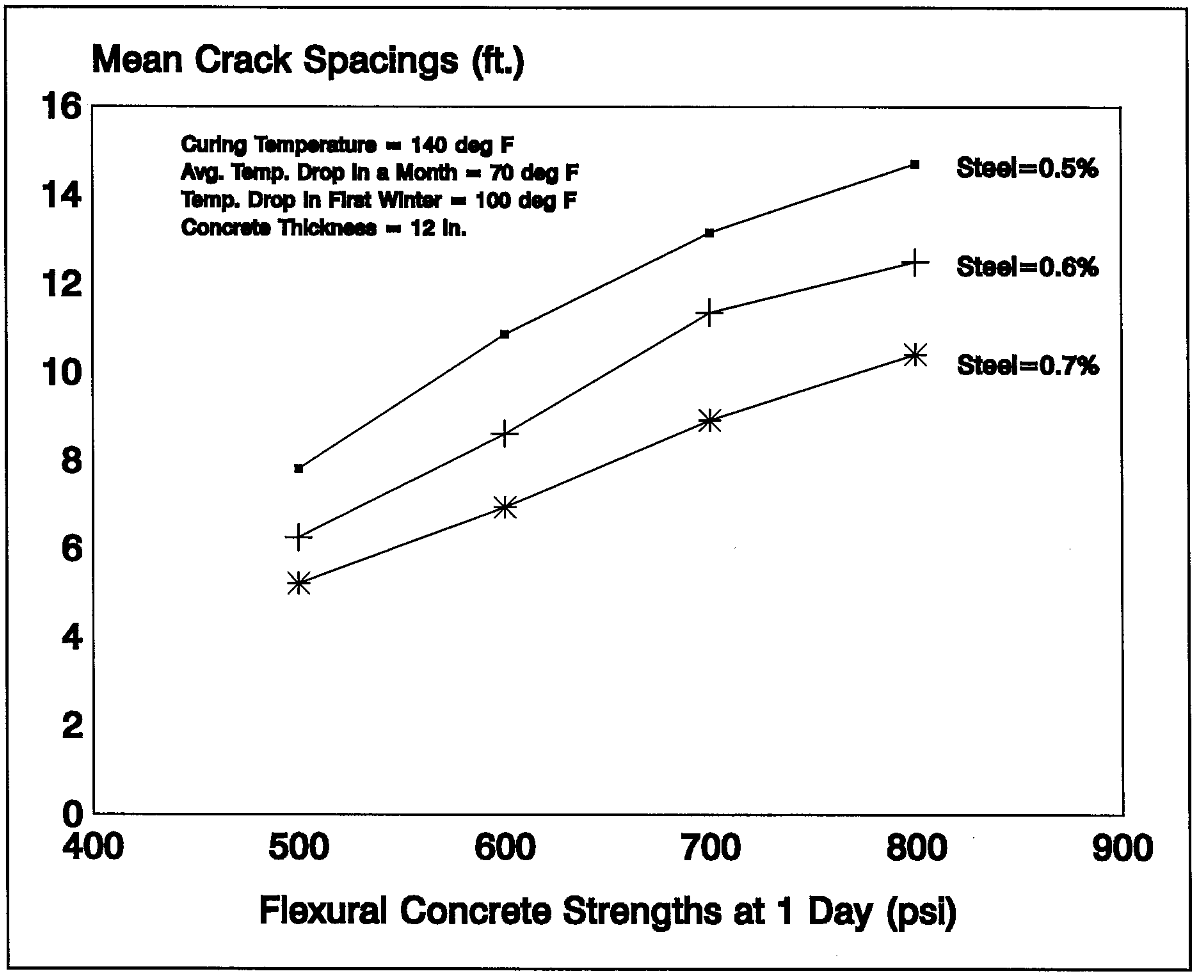

Figure 23. Mean Crack Spacing vs. Concrete Strength (LS) for Different Steel Percentage.

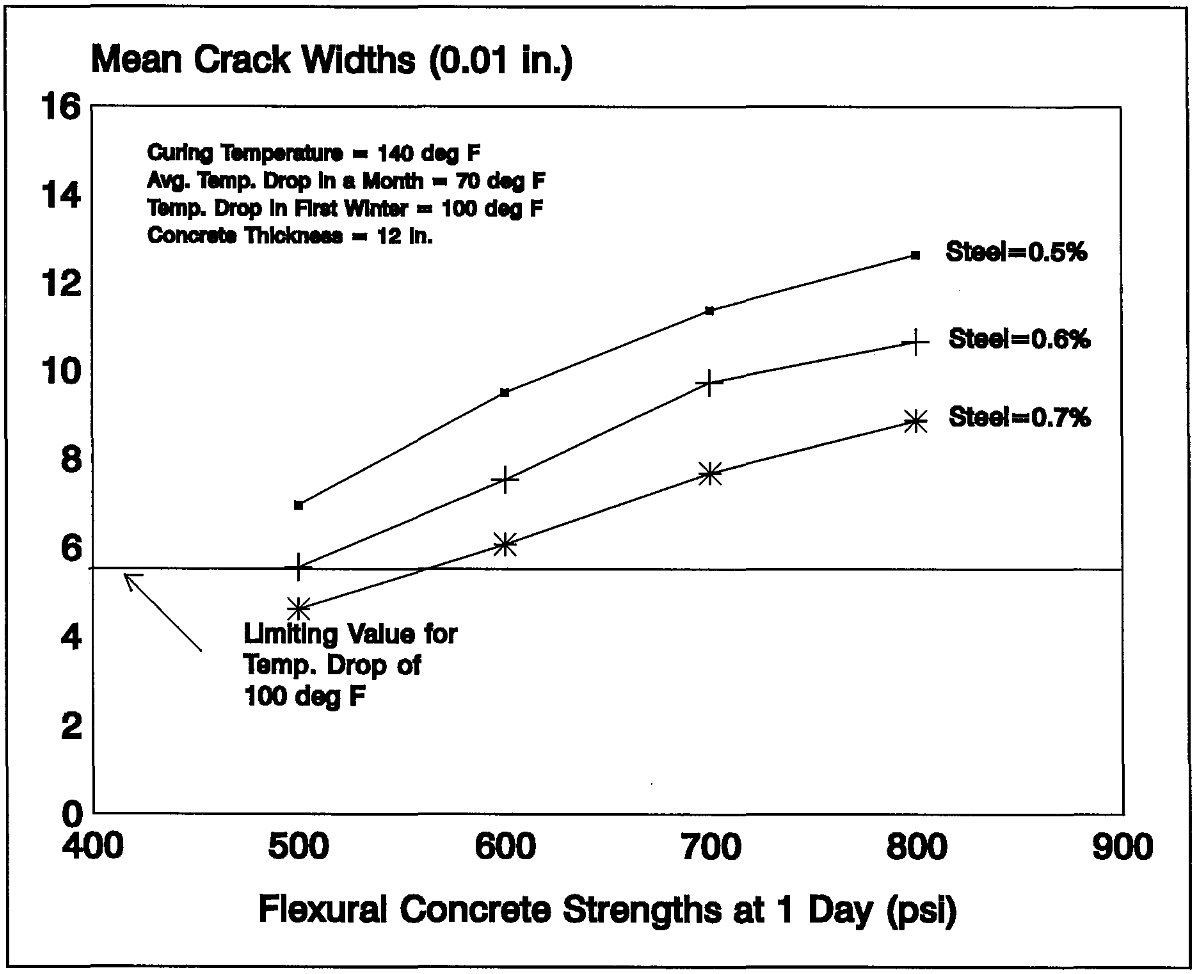

Figure 24. Mean Crack Width vs. Concrete Strength (LS) for Different Steel Percentage.

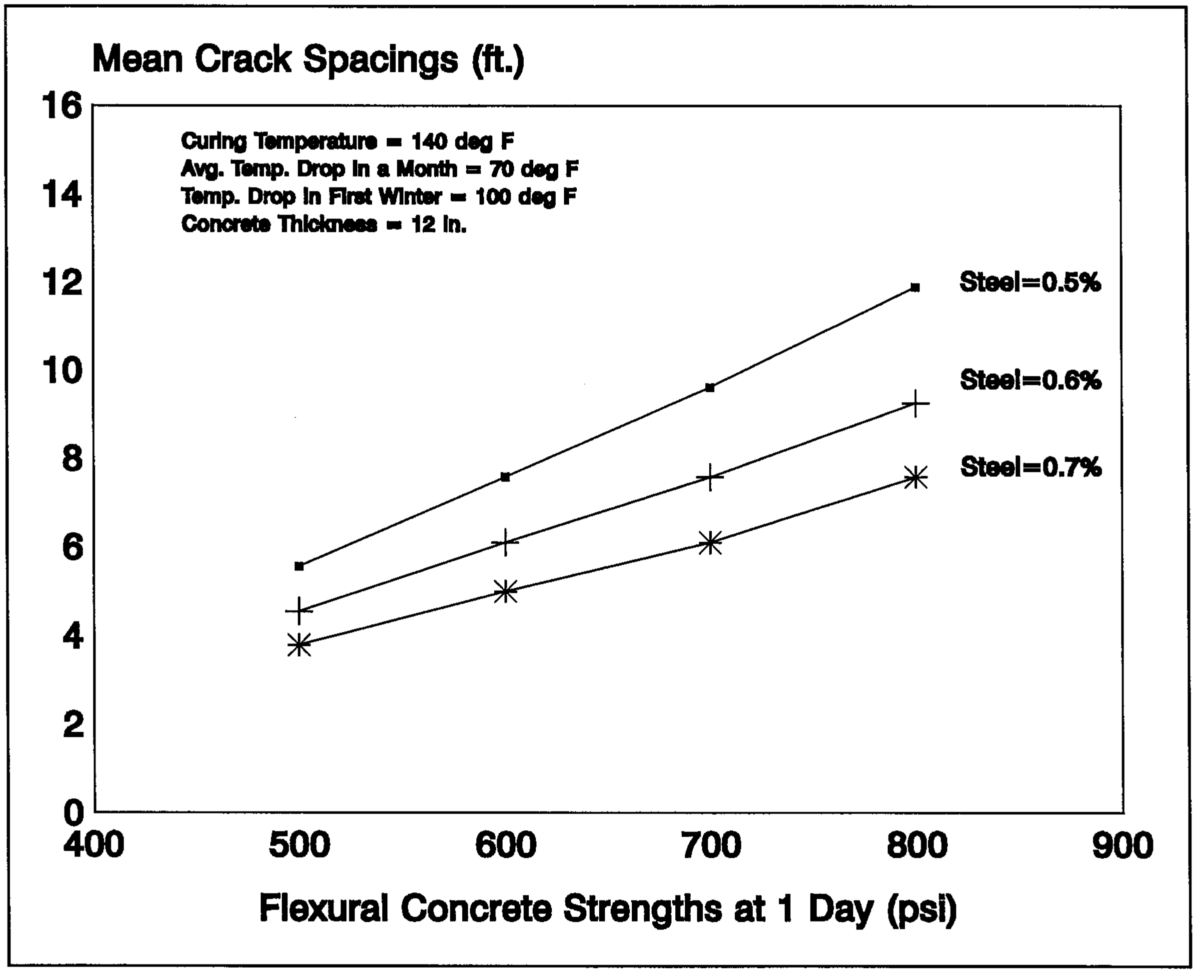

Figure 25. Mean Crack Spacing vs. Concrete Strength (SRG) for Different Steel Percentage.

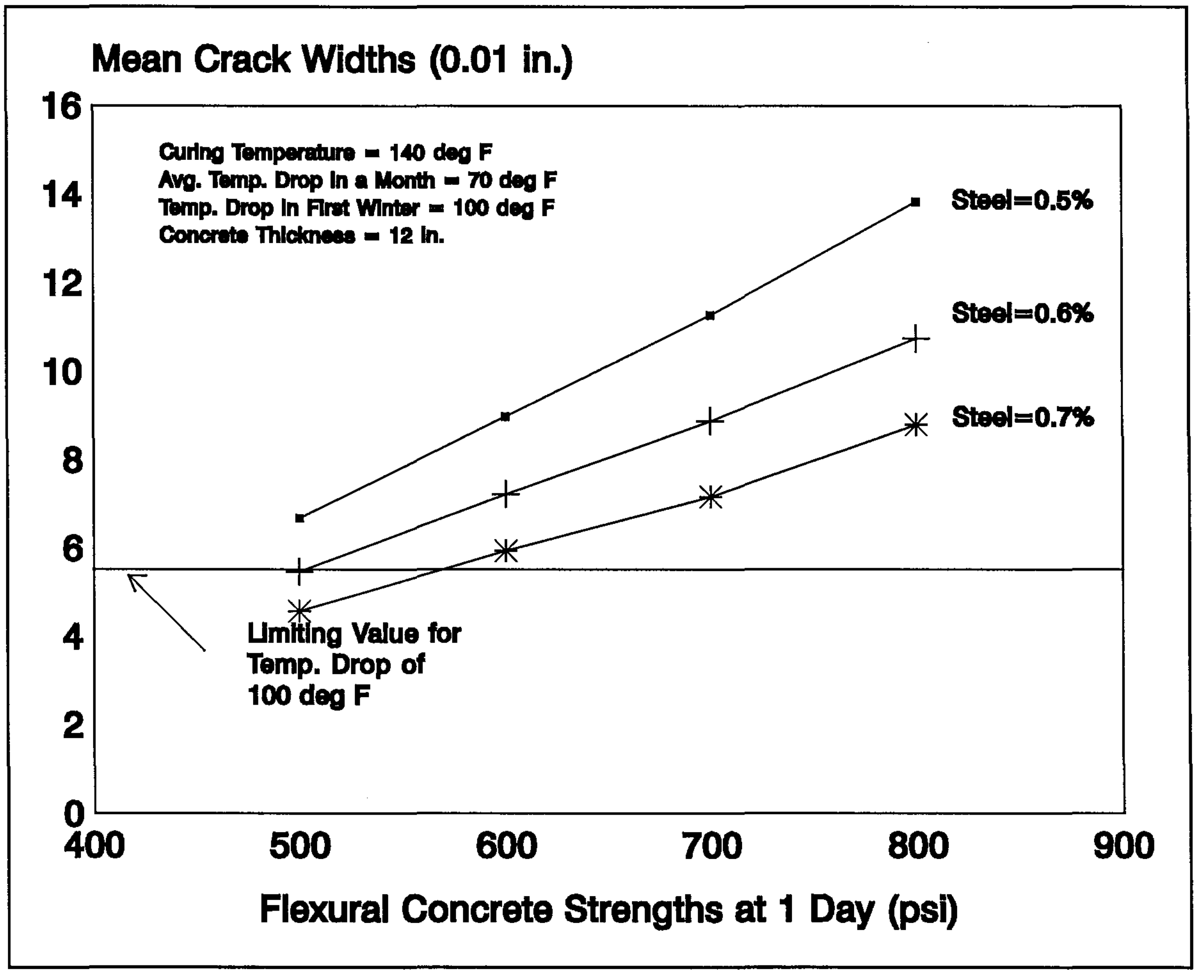

Figure 26. Mean Crack Width vs. Concrete Strength (SRG) for Different Steel Percentage.

DESIGN GUIDELINES FOR FAST TRACK PAVEMENT CONSTRUCTION

SCOPE OF GUIDELINES

Construction of fast track concrete pavements at intersections and other high-volume traffic areas has become a necessity due to the negative impact that continued lane closures at critical intersections can have upon the traveling public. Constructing an urban intersection with concrete may delay maintenance activities for many years into the future, yielding a strong and aesthetically pleasing pavement surface. However, in order to reduce the negative impact described above, past concrete paving practices must be abandoned to some extent, simply because closures at intersections cannot extend over several days before reopening. For some intersections, especially those intersections with heavy traffic volumes, a closure of even eight hours is intolerable to the traveling public.

The concept of fast track concrete paving procedures provides a solution for construction engineers and supervisors to meet the challenges of increasing traffic volumes which occur in urban areas. Fast track concrete pavement allows for the construction of a strong, durable surface with minimal closure time. Fast track concrete mix design characteristically contains high cement contents which are fundamental to accelerating the setting and strength gaining process. When using a rapid setting concrete, some additional consideration should be given for activities such as project management and construction planning to take full advantage of this characteristic. Proper construction phasing will allow the fast track concept to be fully implemented and to continue while allowing partial use of the intersection during construction. As part of the construction phasing, coordinated project management activities between the contractor and the construction supervisor will ensure the use of the fast track concept to its greatest extent throughout the construction project. Therefore, administrative measures of this nature should support and enhance a close working arrangement between the construction supervisor and the contractor. The result of this type of working arrangement should be manifest in the adoption of a set of agreed upon objectives, established during the preconstruction phase, which will begin the necessary planning activities to complete the project work to the satisfaction of the construction supervisor. Advanced planning should decrease the probability of delays during the construction of the intersection project. The fast track concrete may be able to set quickly and have a high strength gain, but without proper planning, the purpose behind the use of FT concrete will be defeated.

The implementation of fast track paving techniques should not cause major changes in design or construction procedures. However, consideration should be given to material selection and project phasing. Given the necessary planning and execution, fast track concrete can also extend to other projects, in addition to intersection construction and patching work. Fast track concrete can be applied to almost any concrete pavement type, including: bonded overlays, unbonded overlays, overlays over existing asphalt, in addition to new construction and reconstruction projects (24,25).

Innovative payment plans may also be of use to promote fast tracking in the construction process. One plan, known as cubic yard/square yard, allows the concrete material to be paid by the cubic yard and the placing, finishing, texturing, curing, and jointing to be paid by the square yard. This method of payment may be useful where variations in the grade of the base or the subgrade may exist such that variations in the surface thickness result. Therefore, the most equitable and economical basis of payment is to separate the cost of supplying the concrete and placing of the concrete.

Another payment scheme which tends to promote fast track concepts centers around the assessment of lane rental fees by the contracting agency to the contractor according to the length of time the contractor closes a particular lane to traffic. A fee schedule is provided during the bidding and letting phase of the project and varies with respect to critical times of the day, night, or weekend. By controlling the fee structure, the contracting agency can influence the time the contractor chooses to close a particular lane and the length of closure prior to re-opening.

A third option is referred to as A plus B bidding. In this instance, the contracting agency bids the project as:

A) the price or cost of constructing the FT project, and

B) the time to complete the construction.

With this type of bidding framework, the contracting agency has a choice of combinations on which to base its bid selection. In this instance, the lowest bid price may not yield the optimum combination of A plus B.

Preconstruction Planning and Phasing

Planning and construction of a FT pavement section requires the utmost in order and efficiency to obtain the best possible results. To this extent, all of the parties involved must have an understanding of what objectives are related to the construction of project and minimizing delays to the traveling public. Therefore, the overall objective of FT paving is to provide reliable pavement surface with minimal delay. Successful completion of this goal requires continuous coordination, planning, good judgement, and the overlapping of efforts by informed and qualified parties.

When constructing an intersection, the placement of small patch-like sections should be avoided. These patched sections are usually a result of inadequate planning of the intersection sequencing. These patches are most commonly placed as a fillet near the radius of a curve at intersecting roadways (Figure 27). Patched sections smaller than 100 square feet should be avoided due to the irregular shrinkage that was documented in the field surveys.

To circumvent this, a new approach to the construction procedure is required. The pavement should be designed in such a way that will not cause a delay of the construction operations. An example of such an approach is shown in Figure 28. To

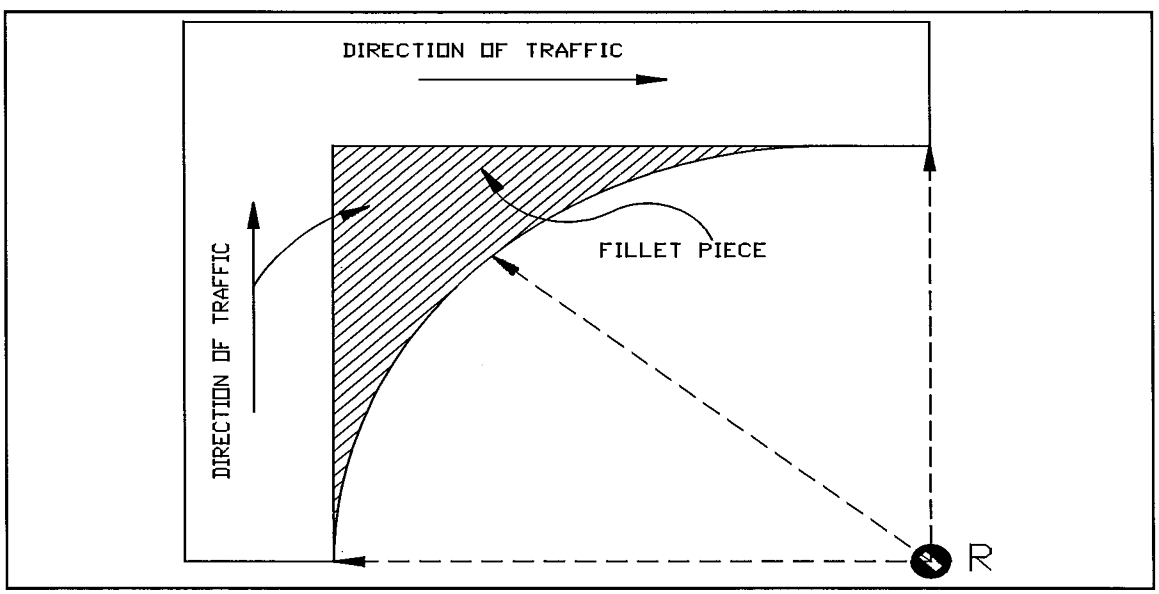

Figure 27. Example of Improper Intersection Phasing.

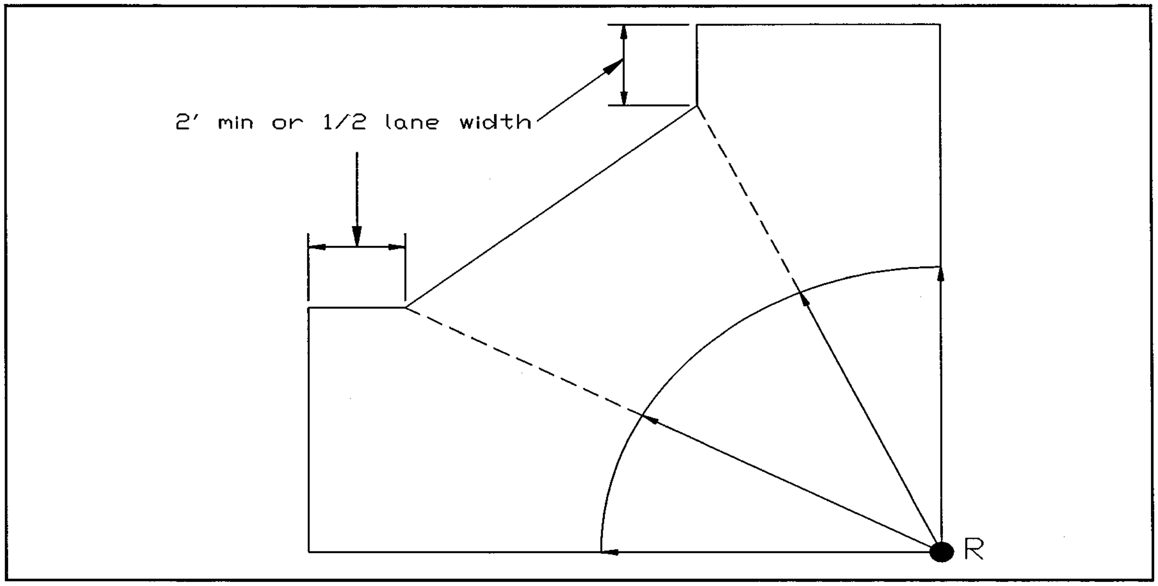

Figure 28. An Example of Intersection Phasing.

avoid a small patch section near the curve, the curve is integrated into the lanes by the addition of a slab between the intersecting lanes. The phasing portion of operations can be adjusted to allow for the new intersection design.

A working relationship between the contractor and the inspector will facilitate construction phasing and should be developed upon completion of the bidding and awarding process. This may be initiated by an initial contact between agents of the contractor and the construction supervisor. The objectives of this meeting should include the project communication during project construction, a construction timeline or schedule, and specific construction goals desired by the engineer or department, among other issues (24).

Definitions

The terms provided in Appendix G are used throughout this construction guide. Standard definitions are provided for the benefit of the reader in following and understanding the recommendation and guideline provided herein. The definitions of the terminology used in describing a transverse cross-section of a pavement system are also illustrated in Appendix G.

Subgrade Requirements

A subgrade as defined in the Texas Department of Transportation Specifications is: "the portion of the roadbed upon which the subbase, base or pavement structure is to be placed" (15). The subgrade has three basic functions:

1) to support construction equipment during pavement construction,
2) to allow a stable and uniform surface for the base or pavement slab, and
3) to provide drainage of moisture that permeates through the pavement joints.

The subgrade requires certain strength characteristics to allow for equipment loads during construction. Usually, the subgrade can be compacted to a maximum density with a optimum moisture content which leads to sufficient bearing capacity to support loads due to construction vehicles. This also reduces the shrinkage qualities of the subgrade and endows the subgrade with greater levels of strength, as previously pointed out. All subgrades vary in composition, and some are more difficult to compact. However, if time and economics permit, use of a stabilizer, such as lime, usually improves the compactibility of the subgrade.

When the subgrade is used as the underlying layer for the pavement slab, stabilization may be important. Design analysis indicates that the subgrade will not contribute significantly to the thickness design of the concrete pavement (either an increase or decrease in the pavement thickness); but inadequate subgrade preparation can be deleterious to the load carrying characteristics of a concrete pavement over a broad range of thicknesses. Another mode of failure in subgrades is from accumulated moisture in the subgrade. The TxDOT specifications suggest that drainage of the roadbed should be constantly maintained in areas where moisture accumulation may occur. Drainage may be maintained, on this basis, by including in the pavement structure subbase materials that promote the flow of free moisture away from the slab if adjacent grading is compatible with drainage from the section. Water allowed to permeate to the bottom of the pavement layer may erode the slab support under pumping action of the slab unless a drainage channel is available to remove the water from within the pavement section. Otherwise, the pavement system should be impermeable to moisture penetration, which may be the only alternative in some instances. However, pumping action tends to lead to faulting or punchouts in the pavement which constitutes failure of the pavement. Accumulated moisture can also cause a clay bearing soil to expand causing further damage to the pavement and the resulting ride. The drainage characteristics of the subgrade are indigenous to the particular subgrade material; in other words, some subgrades drain better than others. If the subgrade cannot either filter or carry away excess water, drains or other means of removing moisture may be appropriate to be included in the pavement structure. Drainage design considerations of this nature are strongly supported and encouraged by the Federal Highway Administration.

Subbase Requirements

The subbase is the pavement layer directly below the pavement structure that rests on the subgrade. The subbase is not intended to be a structural layer and, consequently, will not add any significant strength to the total pavement structure. The function of the subbase is to provide a uniform support to the pavement structure and to help prevent failures caused by the presence of moisture under the pavement system.

The first consideration for the subbase is the material composition. The material needs to be free-draining or erosion resistant. Such materials are characterized and can be located in the AASHTO Interim Guide for Design of Pavement Structures. When a drainage material is selected to allow the water to filter, the grading adjacent to the pavement should accommodate the drain for this material. Where edge grading is appropriate, it is very important that the water is removed from the pavement/subbase interface and not allowed to remain over extended periods of time. This condition can be facilitated by extending the subbase under the shoulder or by providing edge drains. Where applicable, a 6 to 8 inch subbase is recommended for FT paving, perhaps consisting of a modified flexible base material (to minimize the amount of fines) placed on a geo-fabric capped with an asphalt treated material to resist pumping action (1,6).

CONSTRUCTION CONSIDERATIONS

Fast track paving, other than the use of certain admixtures, judicious selection of aggregate proportions, and institution of some differences in quality control, does not vary greatly from conventional paving practice.

Concrete Mixing, Hauling, Placing and Finishing

Transportation of fast track concrete should be performed as expediently as possible. This usually requires good site preparation to allow the construction traffic easy access and may require a retardant to slow the rate of hydration. Due to the nature of fast track paving, some modifications need to be made with respect to the mixing, hauling, and placement of fast track concrete. Fast track concrete has been produced in central mix plants and ready-mix facilities. For transport, transit mix and agitator trucks have been used. Fast track pavements have been built successfully with both slipform and standard form procedures.

Fast track mixes, if designed properly, should not present any difficulties in workability; but, the placement must be efficiently conducted. Finishing fast track concrete should be no different than regular pavement except that the time period between placement and finishing is shorter.

As long as the paving crews are prepared to work efficiently, there are no appreciable differences in mixing, placing, and finishing FT concrete as compared to conventional concrete. All concrete mixes (whether FT or conventional) require good vibration for consolidation and ease of finishing. Therefore, when using slipform or one-pass paving, particular care should be maintained to ensure the proper number, spacing, and depth of the mechanical vibration devices.

Fast track paving requires well planned construction sequencing because the margin for error is much shorter than with conventional paving. Some initial adjustment will probably be required by the paving crew as they become accustomed to the mix characteristics. Each crew member needs to become accustomed to the increased hydration of the concrete and the impact this has on his or her duties in the fast track construction project. Test or trial pours may be helpful in familiarizing the crew with the plastic concrete characteristics before commencement of full-scale operations.

Normal finishing procedures can be used for fast track concrete. It is recommended that for high-volume primary and interstate pavements, a transverse tining texture be specified. Where minimum clearance operations do not allow for mechanical tining equipment, hand tining or transverse broom texture can be done behind the paving machine. Pavement tining is important for the facilitation of surface drainage. The tining creates small canals for the water to leave the pavement surface. The tining should be placed on the surface after the lay down process is complete and before initial set has occurred in the concrete mix. The timing of texturing the pavement surface can be critical in the case of FT concrete because of its quick set characteristics. The construction supervisor should consider the drainage grade of the pavement surface in light of the construction phasing plan when determining what direction to place the tining on the surface. In some instances, the direction of the surface tine may change within a given construction phase, depending on whether crossing traffic lanes are included in the particular phase of paving. Surface texturing is discussed further under pavement jointing and sawcutting (1,6,23).

Pavement Jointing

The jointing of fast track pavement needs to be included in the construction phasing early in the planning process. The importance of pavement jointing in design cannot be over-emphasized and is integrally related to the successful performance of the pavement. Whether the concrete pavement type is jointed or CRC, the location and positioning of longitudinal (both sawed and construction) and transverse construction joints should be given priority over the boundaries which ultimately delineate different phases of construction. With this prioritization, some additional coordination may still be necessary between construction phase lines and the position of the transverse construction joint to avoid the following undesirable conditions:

1) short and isolated CRC pavement segments,
2) irregularly shaped, jointed pavement segments,
3) CRC paving lane on which it is perpendicular to the direction of the longitudinal reinforcing steel, and
4) pavement texturing or tining parallel to the paving lane.

Paving of CRC pavement segments which fall under the description of condition 1 above tend to defeat the purpose of a CRC pavement as previously described and should be avoided in construction. Irregularly shaped jointed pavement segments are undesirable because random cracking may be difficult to control. Paving CRC pavement lanes that contain longitudinal steel reversed with the transverse steel leads to poor crack patterns and causes over-stressing in the steel reinforcement at transverse cracks and construction joints. Paving under these conditions must be avoided. Pavement texturing is normally placed perpendicular to the main or primary lane of travel; across-grade is used to facilitate surface drainage. Surface drainage factors should be the primary consideration when determining the direction to place the pavement surface texture. However, circumstances where the grain of the tined surface is parallel to the main traveled lane may need to be designated based on the judgement of the construction supervisor.

The construction of an intersection pavement may require forming against an existing concrete pavement. Questions may arise with respect to the details of a "butt" type construction joint between the existing concrete slab and the newly constructed concrete pavement. The nature of these details may become particularly confusing in cases where the steel requirements of the new pavement are different from the steel configuration of the existing pavement, or the thickness of the existing slab is not equal to the thickness of the new slab. In this circumstance, it is recommended that a transition slab be used to facilitate the transition from the existing steel configuration to the new steel configuration as shown and detailed in Appendix A. A slab of this configuration eliminates the need for bending the steel reinforcement to facilitate the transition at the construction joint. Normal practices can be used between mats of steel and along construction joints. Added reinforcement steel may also be included to enhance and maintain the load transfer across the construction joints. Reinforcement steel of this nature (#6 bars or larger) normally provides adequate "doweled" action to carry loads across the joint. The use of a transition slab provides a means to compensate for differences in steel and pavement thickness design over a recommended distance of 15 feet (14,17,20,21,25).

Construction Phasing

Construction phasing is an important process within the FT concrete paving concept. The pavement must be planned so that minimum construction time is taken in critical areas of the intersection. Construction phasing must be coordinated to allow traffic flow to continue, even if it is only in one lane of travel. An illustration of a typical, four-step diagram of construction phasing is shown in Figure 29.

The construction phasing shown in Figure 29 is established to allow continuous flow of mainstream and crossing traffic during the construction process. To meet this requirement, additional joints are used to maintain the continuity of the jointing layout throughout the intersection. It is recommended that all joints be matched that are common between neighboring construction phases. If a construction phase includes a corner of an intersection, it is recommended that a construction joint be placed to

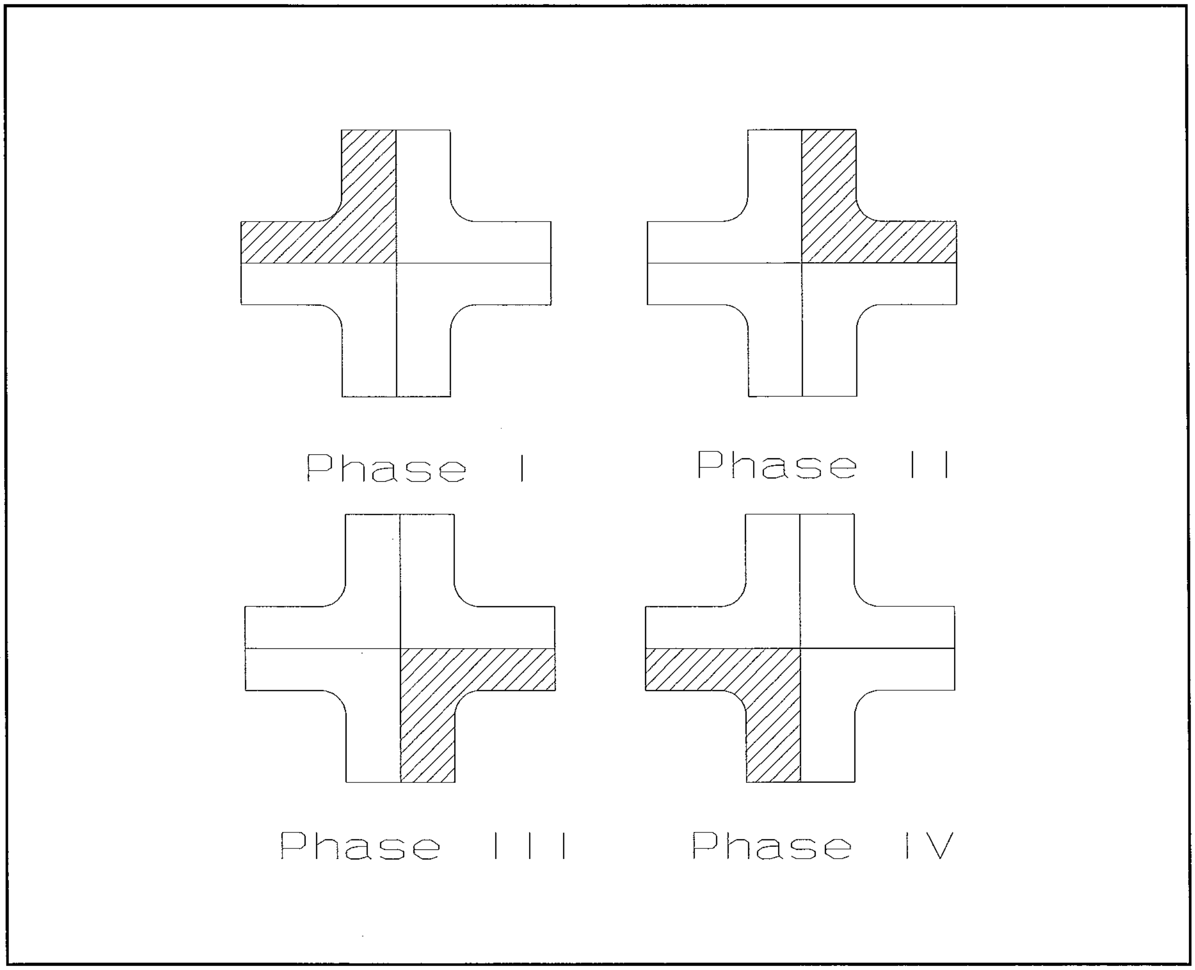

Figure 29. Typical Construction Phasing Diagram.

establish a boundary between the intersecting paving lanes in order to control the development of a stress relief crack. This is due to the tendency of the concrete material to "pull-apart" at these locations. In other words "L" shaped construction phases should be saw cut at the intersection of the "L" to avoid an unsightly random crack. Each construction phase should reflect good jointing practices that lead to matching of joints; paving construction that places concrete in the direction of the longitudinal steel; and elimination of small isolated slabs in the center of the intersection pavements.

Each phase of construction can be associated with a particular time of construction or construction objective in terms of concrete strength, saw cutting, and sealing of joints prior to opening to traffic. Each phase of work, planned in advance, should allow for efficient construction to rapidly complete the entire intersection, minimizing the impact on the public and surrounding businesses. As pointed out later, with these objectives, it is important for the construction supervisor to accurately predict the concrete strength gain as a function of traffic and climatic conditions.

Pavement Sawcutting

Sawcutting fast track pavement within a few hours after the placement of concrete is recommended as the most efficient method to control cracking in the concrete pavement. Even though the current practice is to cut the pavement to a depth of "t/3" or "t/4," saw depth of approximately 1 inch is sufficient if placed early enough to control cracking both longitudinally and transversely. Unlike the "t/4" cut, a ¾ to 1 inch cut relies on the tension created at the surface of the pavement during hydration of the concrete (and subsequent drying shrinkage) to crack the pavement full depth. When cutting the joints in the pavement, care must be taken to place sawcuts around disruptions in the pavement such as drop inlets or manholes. Experience has shown that these disruptions cause random cracking and must be controlled.

The sequencing for standard joint sawing and sealing procedures is not applicable for FT pavement construction. The delay prior to joint sealing is not consistent with the early opening or the FT concrete concept. However, some delay is needed for some currently available sealant materials because of the manufacturers recommendation that the sealant reservoir sidewalls be dry to ensure good joint sealant performance.

There are no limitations on joint sawing equipment for FT concrete pavements. Both wet-sawing, with diamond impregnated blades, and early-aged sawing (Figure 30), with silicon carbide or carborundum blades, have been used. Joints developed with either sawcutting method have performed well to date. However, late sawcuts can lead to the development of random cracking. Early-aged sawcutting was implemented originally to combat this particular problem which has a tendency to occur in hot-weather temperature conditions.

The choice of blade by the contractor primarily depends on the hardness of the aggregate in the concrete. In general, silicon carbide or carborundum blades can only be used with softer aggregates (limestones). Diamond blades can be used with all types of aggregates, and are the most effective on concretes using hard aggregates. However, dry-sawing is feasible for all aggregate types. It is always possible to saw joints sooner using the early-aged method than with the wet-sawing method.

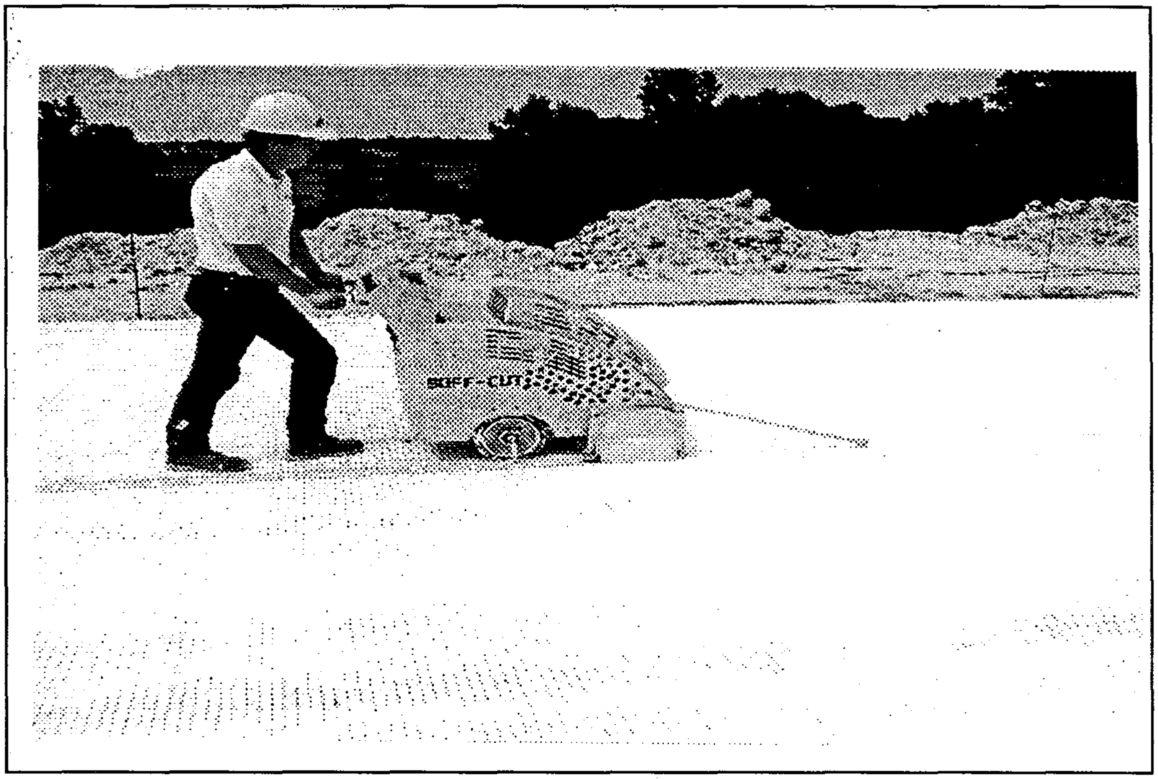

Figure 30. Soff-Cut Early Age Sawcutting Machine.

Cleaning operations vary depending on the sawing equipment. Where abrasive blades are used in dry-sawing, an airblowing procedure should follow to remove particulate residue from the joint reservoir. Water flushing is generally used after a wet-sawing procedure because the water can remove sawing slurry.

Prior to sealing, each reservoir face should be sandblasted (two passes per joint). Air blowing should follow to remove remaining sand and residue and then a backer rod installed. The following are the recommended procedures:

	WET SAWING		EARLY-AGED
1.	Water flushing	1.	Airblowing
2.	Delay period	2.	Delay period
3.	Sandblast	3.	Sandblast
4.	Airblowing	4.	Airblowing
5.	Install backer rod	5.	Install backer rod
6.	Install sealant	6.	Install sealant

Steps 3 and 4 of the early-aged sawing may be eliminated if some sealants will adhere to the sidewalls of the cracks without additional cleaning.

Guidelines for pavement sawcutting in FT paving operations can aid the construction supervisor in the decision concerning timing of installing contraction (control) and warping joints in pavements. The decision is usually concerned with two limits for the joint sawcutting window of opportunity: the near limit and the far limit (17,18). Due to the nature of concrete paving, the joints need to be sawed and sealed as early as possible, which usually means only consideration for joint spalling is necessary (this is referred to as the near limit in references 4, 17, and 18).

The near limit for the joint sawcutting window of opportunity is the earliest time sawcuts should be made if unacceptable concrete joint edge raveling is to be avoided (17). Acceptable joints are defined as those planned to have the sealant reservoir widened after initial sawcutting; whereas, good joints are defined as those judged not to have excessive raveling when no sealant widening is to be done.

Influencing factors for decisions on the near sawing limit are concrete strength gain and criteria as to what constitutes a good or acceptable joint. An acceptable joint produces 0.84 in^2 (80 mm^2) of raveling per 24 feet (17). Concrete mortar matrix strength needed to permit sawcutting in order to produce an acceptable joint edge can be measured by concrete compressive strength (or maturity) if wet sawing techniques are used. However, correlations to concrete maturity will be necessary to assess the strength of concrete in the field, based on saw cutting requirements.

A method which provides an approximation of the proper "timing" for early-aged sawcutting is to actually press a knife edge into the concrete surface, or to determine when the concrete pavement can be walked on without leaving a shoe print or mark. This criteria varies somewhat with aggregate source, cement type, cement source, admixture types, and paste volumes.

As for wet-sawing, the compressive strength of the concrete may be a good measure of saw-cut timing since the hydration of the concrete must be further developed prior to cutting than that under the early-aged cutting method. Compressive strength can be correlated with non-destructive test methods such as the pulse velocity (PV) or the maturity methods as pointed out above. The maturity method has been discussed (lab and field procedures) in great detail; but, the PV method is very adaptable to field conditions and provides rapid test results (17,18). The correlations of compressive strength, pulse velocity, and/or concrete maturity should be reaffirmed on a regular basis for project-specific concrete mix designs. For example, use of a different cement source, although the same cement type is used, can significantly alter maturity correlations.

From laboratory tests made in association with concrete mix design tests, site specific pulse velocity versus compressive strength, or maturity determination versus compressive strength correlations are established. These values can be used as criteria for timing near limit sawcutting. Observations of surface joint raveling during initial concrete placement for each project should become the basis for adjusting near limits for sawcutting (13,17,18,23).

Joint Sealing

Unless otherwise specified, joint sealing material should conform to the specifications listed under the materials section in the special specification (Item 3745). The sealing material should adhere to the sidewalls of the sawed joint and should provide an effective seal against incompressible material.

There are seven possible choices of joint sealants as shown in Table 5. The particular sealant chosen should consider the anticipated service conditions, such as applied loads, conditions of exposure, and the like. The sealant should provide a barrier to moisture infiltration and also add an aesthetic quality to the pavement surface.

The accelerated strength gain and low water-cement ratio of fast track concrete, tends to reduce excess moisture on the sidewalls of the joint reservoirs. This allows sealing earlier than with standard mix designs and pavement construction procedures. Experience has shown that low-modulus rubber sealants adhere to reservoir faces at early ages. FT pavements cut by the early-aged method have been sealed with a low modulus rubber material as early as eight hours behind the paver. A survey one year later indicates that the joints are performing well. Silicone sealants have also been used for FT operations. These sealants have provided good performance and have not indicated significant de-bonding.

Preformed neoprene compression sealants, which have not been used in conjunction with concrete pavement to-date, may be ideal. These sealants are not highly

Table 5. Pavement Joint Sealants.

Sealing Material	Composition and Use	Test Method/Specification
Class 1-a	Two Component, Synthetic Polymer, Cold-Extruded Type	Tex-525-C
Class 1-b	Two Component, Synthetic Polymer, Cold-Pourable, Self-Leveling Type	Tex-525-C
Class 2	Hot Poured Rubber	Tex-525-C
Class 3	Ready - Mixed Cold - Applied Joint and Crack Sealer	Tex-525-C
Class 4	Performed Compression Seal	ASTM D 471/ASTM D2628
Class 5	Low Modulus Silicone Sealant for Concrete Pavement	MIL-2-8802D, ASTM 2240, Tex-525-C
Class 6	Self-leveling Low Modulus Silicone Sealant for Asphaltic and Concrete Pavement Joints	Tex-525-C

sensitive to dirt or moisture and may allow sealing at an earlier age.

To gain the full potential of the FT paving concept, the joints should be sealed as soon as possible and no more than one day after paving. Sealing joints within this time frame has been used with hot pour sealants with good success. However, the sealant manufacturer's recommendations for concrete should be followed (1,6,13).

Curing

Fast track pavements require thorough curing protection. This is needed to retain moisture and heat which is necessary for high-early strengths. However, it is important that curing operations do not hamper the early sawcutting operations.

Moisture Retention

Current curing practice is to apply a membrane curing compound at 1.5 times the standard application rate, which may be nearly as efficient as using polyethylene sheeting. However, the curing system should be managed in such a manner as to impact subsequent construction operations as little as possible. The compound should be applied to the surface and exposed edges of the concrete slabs. The curing compound should retain sufficient moisture to promote early strength gain. No shrinkage cracking or other curing related cracking have been noted on existing FT pavements in which the compound was applied at the increased rate.

Heat Retention

Ensuring heat retention generally requires some form of insulation. This depends on climatic conditions. In very warm climates or during very hot summer weather, insulation may not be required. Under most normal paving operations, insulation can be accomplished by the placement of curing blankets. These blankets are placed after the application of curing compound. Blanket placement may be delayed until after sawing or blankets can be removed for sawing and replaced. It is very important to saw while the concrete temperature is rising to prevent uncontrolled cracks. Early-aged saw cutting particularly facilitates this process.

Recommended blankets consist of a layer of closed cell polystyrene foam, protected on one side by a plastic film. The blanket should have a minimum R-value rating of 0.5. The blankets are generally left on the pavement until the concrete has attained a center-point flexural strength of 400 pounds per square inch (psi), (350 psi third-point loading). The blanket material is durable and can be reused by the contractor (26).

Experience has indicated that the use of insulation blankets provides a uniform temperature environment for the pavement and improves early strength gain. Insulation blankets reduce temperature loss and dampen the effect of both ambient air temperature and solar heat on the pavement (2). Although the temperature profile is nearly uniform with depth, the blanket allows curing at a more uniform, elevated temperature. After the initial heat development from hydration, concrete allowed to cure without insulation generally follows ambient air temperature changes (1,6).

Concrete Temperature/Moisture Management

In newly cast concrete pavement, both climatic and load factors contribute to stress development. The following factors can cause concrete stresses:

1) stresses caused by wheel loading,

2) stresses caused by temperature drop or change,

3) stresses caused by moisture loss or change,

4) stresses caused by curling or warping, and

5) relieved stresses by creep of the concrete.

Concrete pavement may develop cracking when induced total concrete tensile stress is greater than the strength of the concrete.

The temperature of the concrete material has been found to be useful in predicting the strength of the concrete with respect to such activities as saw cut timing and opening to traffic. Temperature development in concrete pavements can be an indication of not only stress, but also the strength of the concrete.

The flexural strength test may be the best predictor of the actual concrete strength. This prediction of strength may also be made using the pulse velocity or maturity test results. Maturity testing for opening time of the pavement to traffic has potential for concrete pavement applications. This can be done using thermocouples (connected to a maturity meter) which are embedded in the concrete pavement. Maturity, as previously discussed in equation 2, is restated below:

$$M(t) = \Sigma (T_a - T_o)\Delta t$$

where

$M(t)$	=	Temperature time factor at age t
Δt	=	Time interval
T_a	=	Average temperature during time interval
T_o	=	Datum or reference temperature

The maturity, $M(t)$, at a certain time, t, may be summed with respect to $(T_a - T_o)$ times time interval, Δt.

The basic principle in applying the maturity method is illustrated in Figure 31. Two phases of testing are involved: (1) laboratory testing and (2) field measurement of the in-place pavement temperature history. Laboratory testing must be performed prior to establishing in-place testing. Two important results from laboratory testing are a datum or reference temperature, and the activating energy of the mix, which are subsequently explained (2).

The datum temperature is used to determine the in-place pavement maturity. This temperature represents the minimum temperature at which hydration and strength gain will occur. The maturity can be correlated to the strength of pavement after establishing a reference curve of relationship between the maturity and strength of beam specimens. The datum temperature is dependent on curing temperature, cement amount, water-

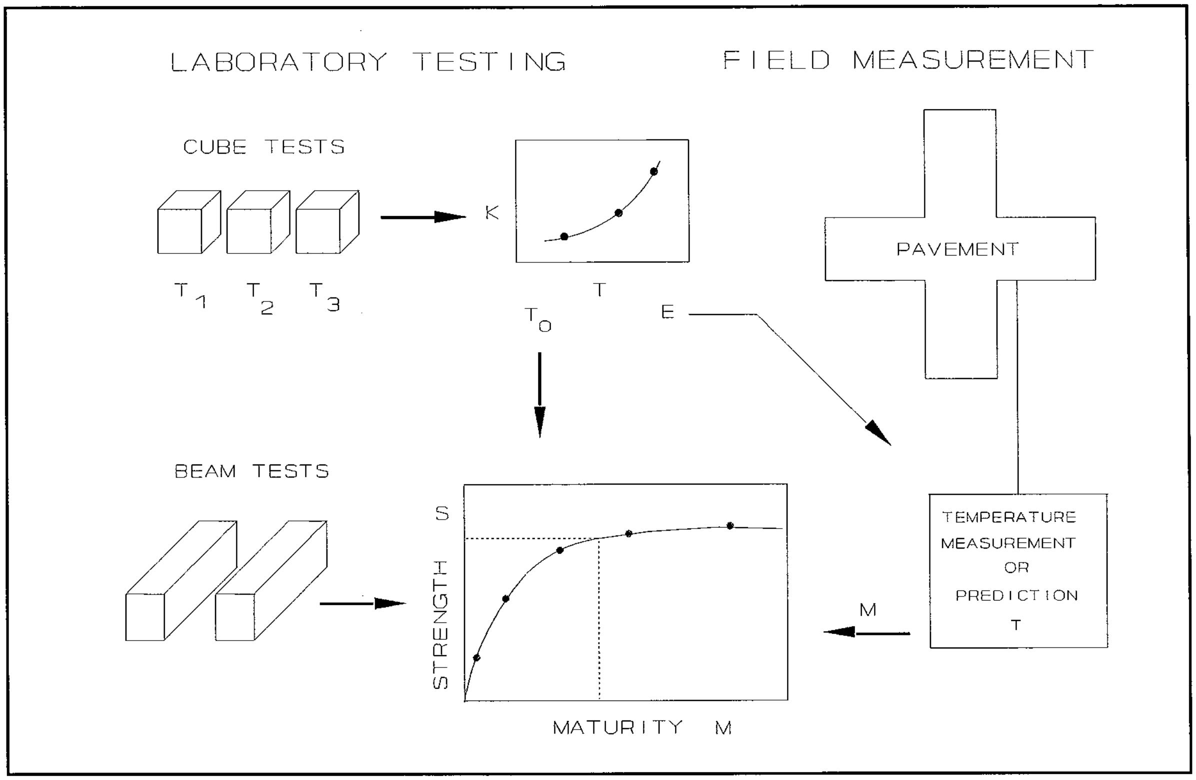

Figure 31. Maturity Procedures (2).

cement ratio, and aggregate type. The datum temperature is reported to range from 32 to 14°F, as observed from laboratory results.

Figures 32 to 37 show how to predict flexural strengths of in-place concrete pavement for any climatic condition in terms of maturity or elapsed time. First, temperatures of maturity beam specimens are recorded using the thermocouples (Figure 32). Second, flexural strengths of beam specimens are determined as a function of time (Figure 33). Third, a reference curve, which is the relationship between flexural strengths and maturity, can be obtained (Figure 34), converting temperature history of the beam specimen (Figure 32) to maturity using the maturity expression shown as equation 1. Fourth, temperatures of in-place concrete pavement are measured (Figure 35). Fifth, maturity of the pavement concrete is plotted with regard to elapsed time (Figure 36). Finally, flexural strengths of in-place concrete pavement can be predicted at a certain elapsed time (Figure 36) or maturity (Figure 37).

The other result from laboratory testing is activation energy. This value can be obtained from several regression analyses of data obtained by using ASTM C 1074. The

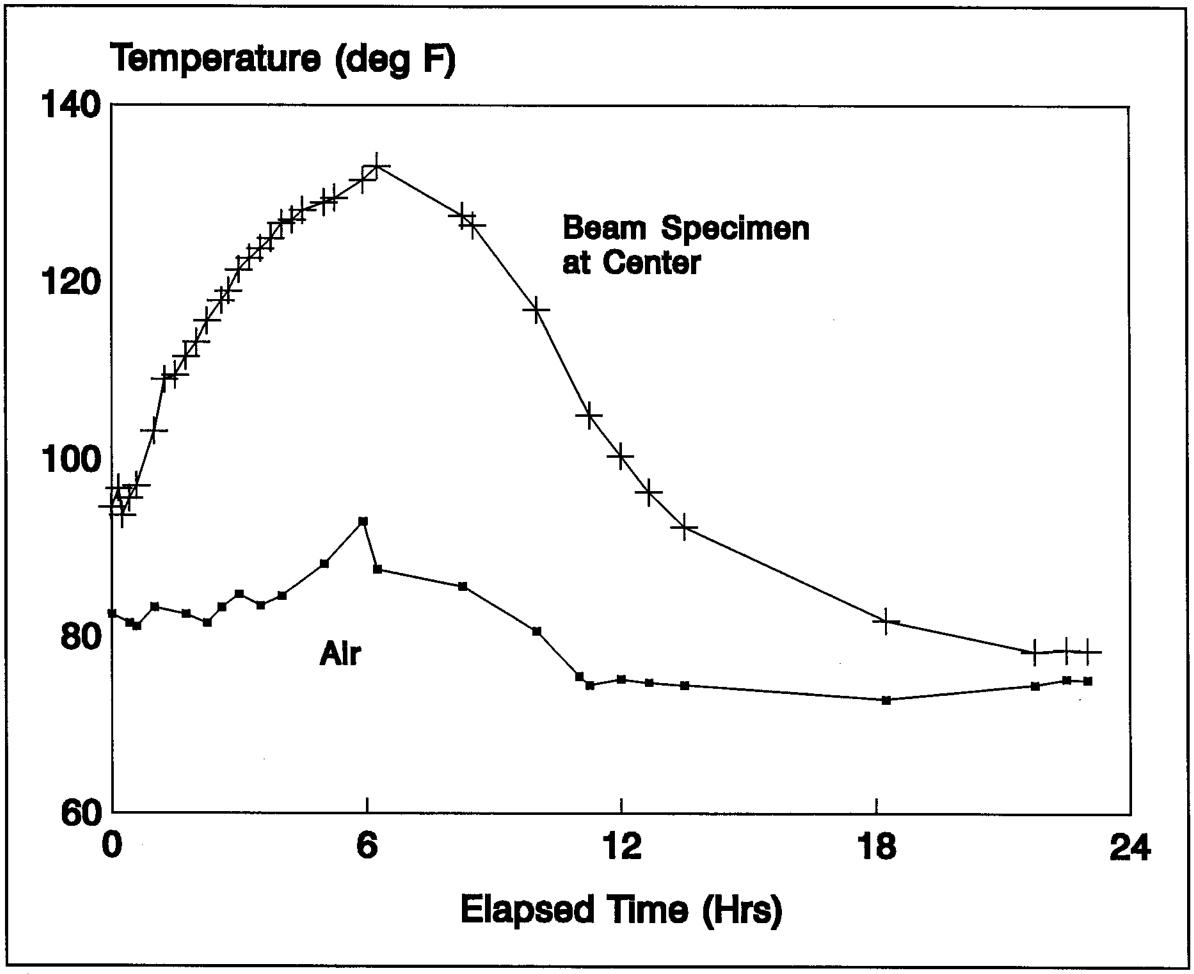

Figure 32. Temperature History of the Beam Specimen.

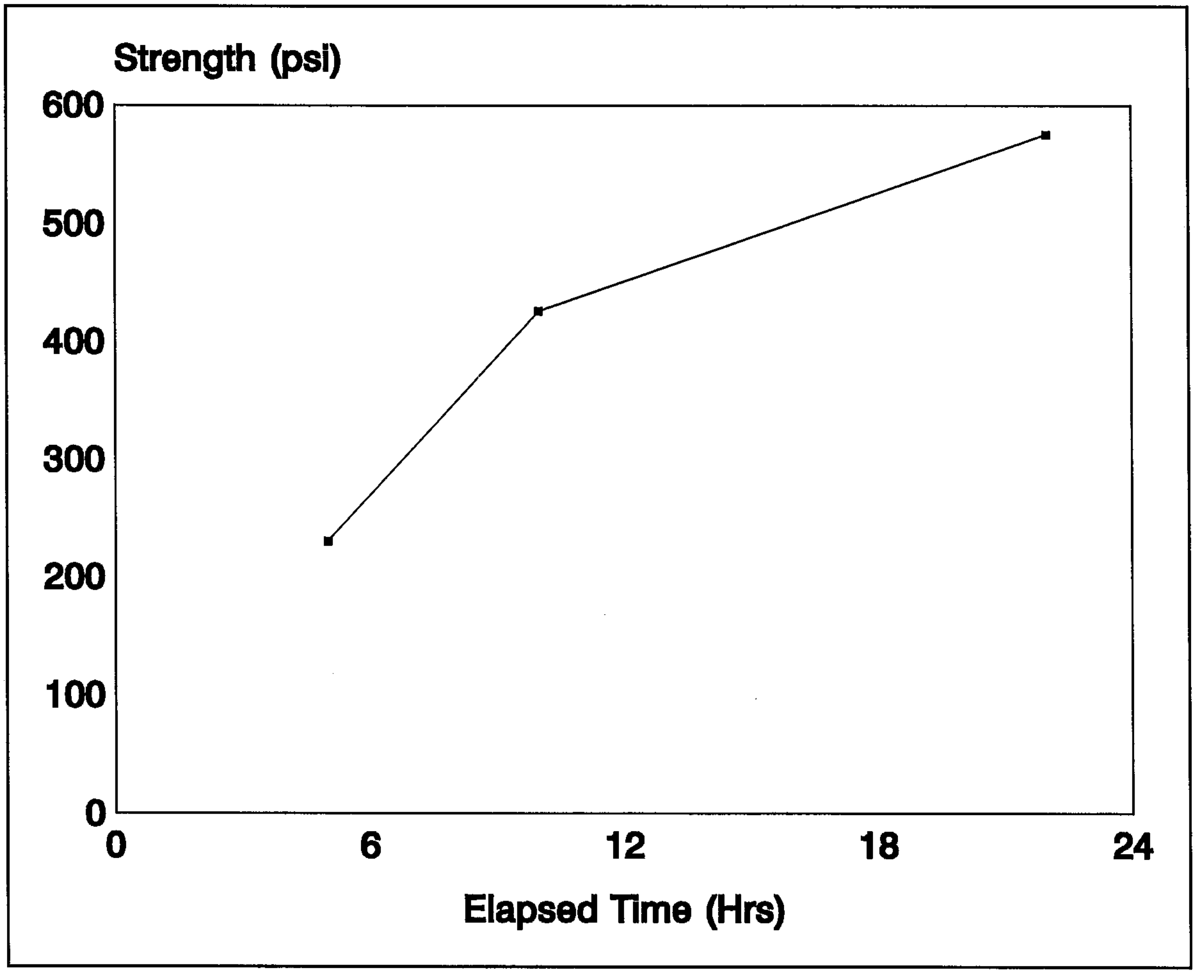

Figure 33. Flexural Strength with Time of the Beam Specimen.

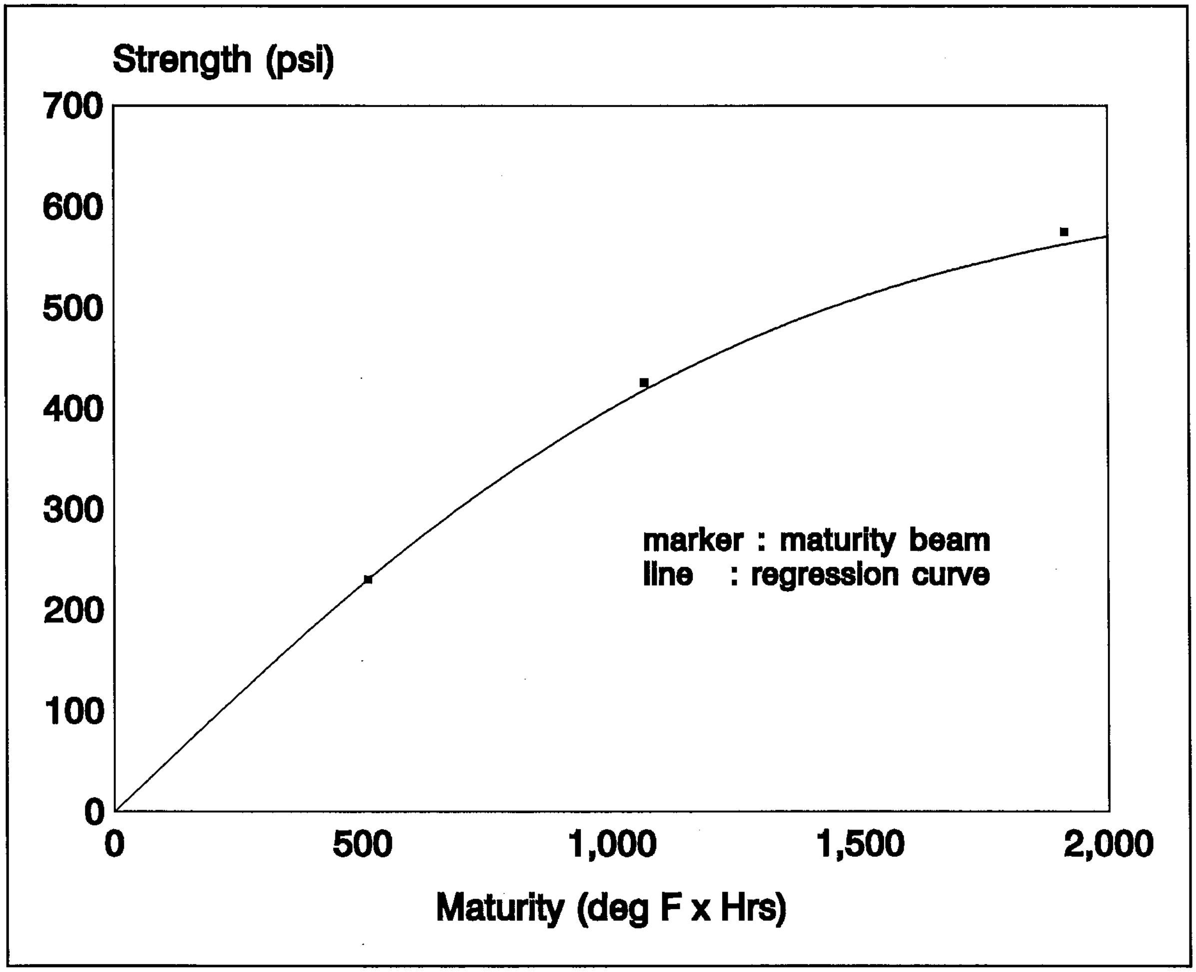

Figure 34. Strength vs. Maturity of the Beam Specimen.

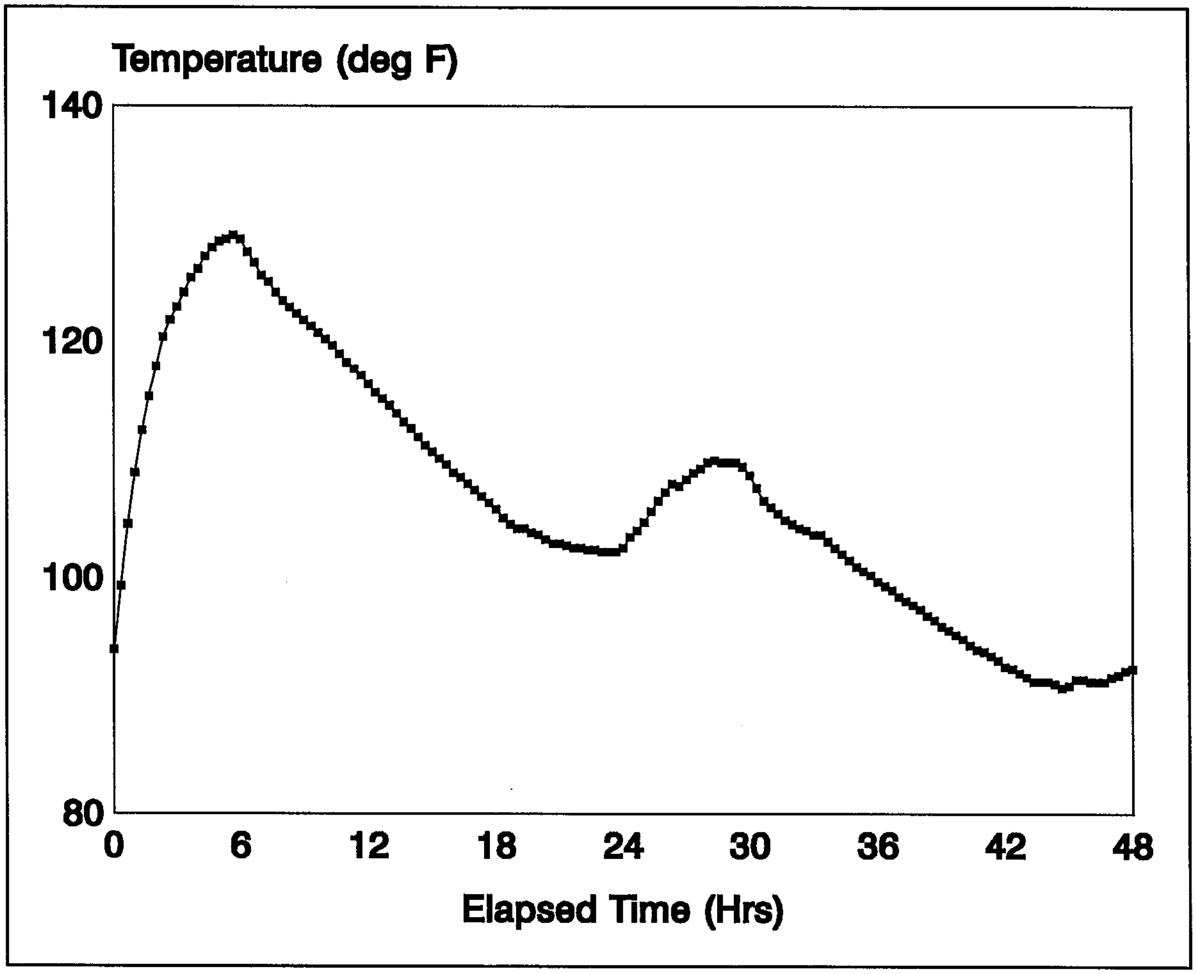

Figure 35. Temperature History of the In-Place Concrete Pavement.

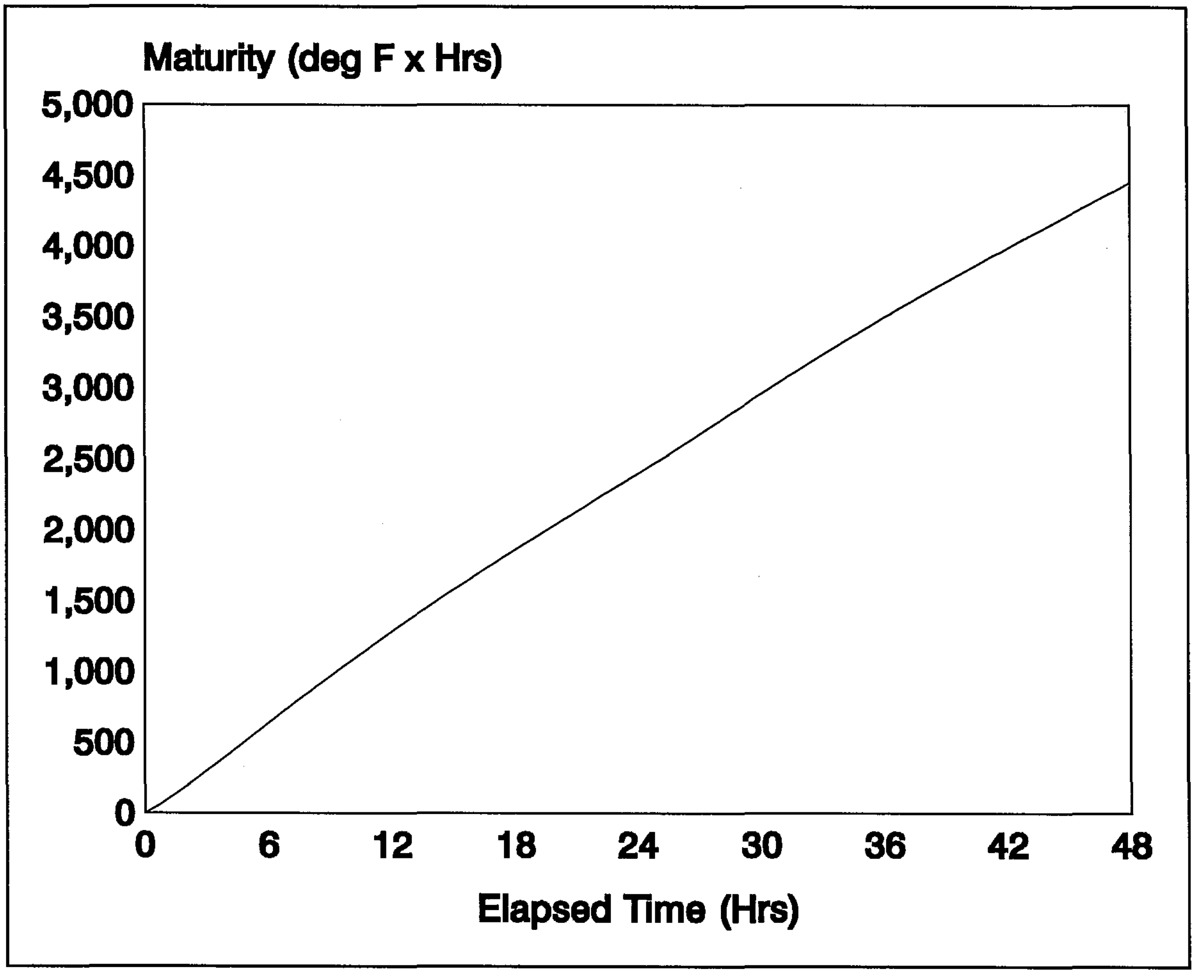

Figure 36. Maturity of the In-Place Concrete Pavement.

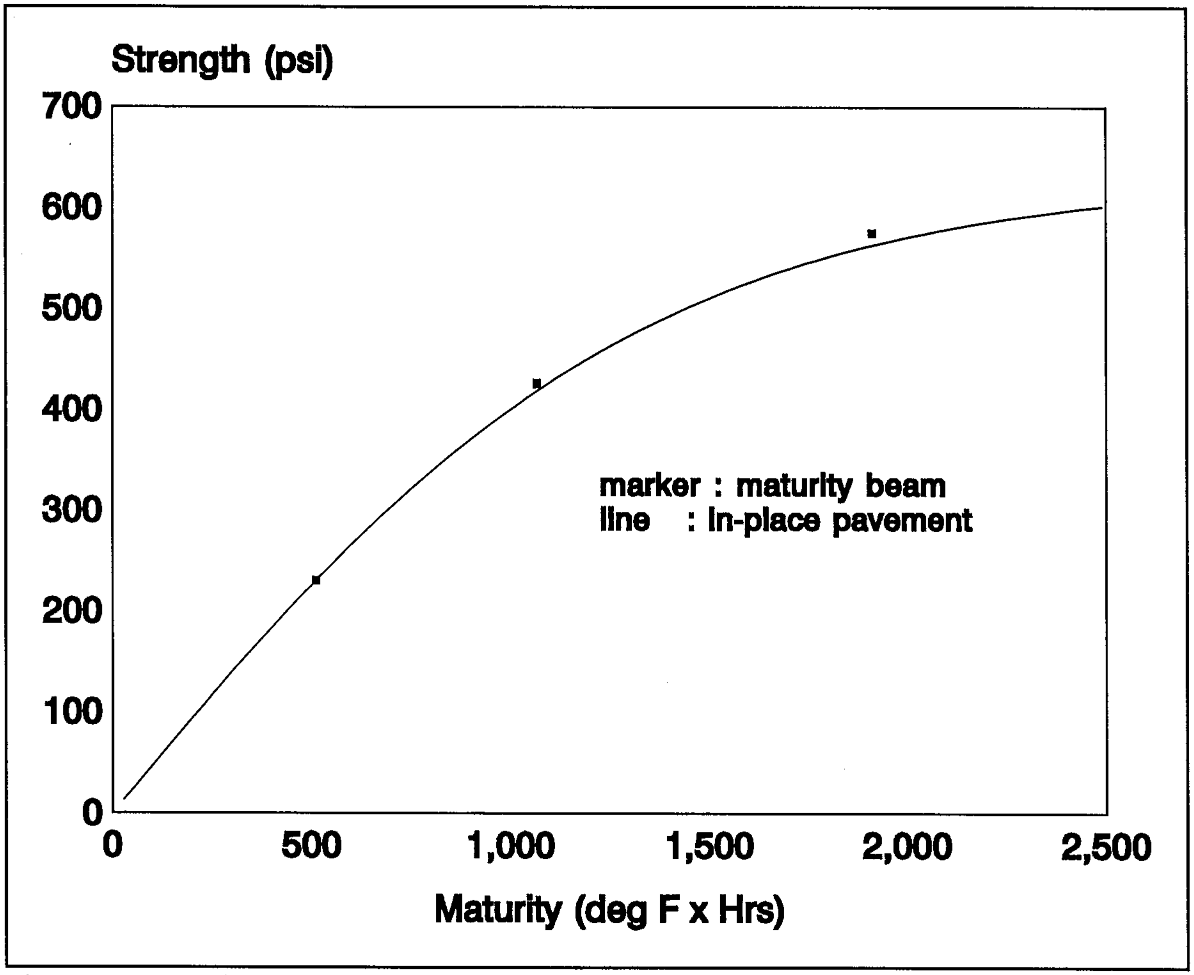

Figure 37. Predicted Strength of the In-Place Concrete Pavement.

activation energy can be related to the internal heat of generation term in the analysis of heat transfer through a given medium. If temperatures of an early-aged concrete can be determined on a theoretical basis, it may be possible to estimate the strength gain that may occur for given combination of materials and weather conditions, based on the mix reference temperature and the activation energy (Figure 31).

In general, concrete temperature is affected by mix design, curing method, and environmental conditions. Specifically, temperature measurement at the pavement mid-depth gives a general comparison between different curing methods and between different mix designs. The concrete temperature is affected by several variables, such as wind velocity, solar radiation at the top surface, and soil temperature at the pavement bottom. Concrete cured with polyethylene film tends to generate higher temperatures, compared with membrane curing. The temperature difference between both curing methods is approximately 10 to 15°F. Meanwhile, concrete cured with two coats of curing compound may attain a temperature midway between concrete cured with polyethylene film and that with only one coat of curing compound. However, different mix designs with the same curing method may produce almost identical temperature curves when the same amount of cementitious material is in each mix design. Concrete curing temperature appears to be affected more by curing methods rather than aggregate type.

At an early age, the forces tending to pull the crack faces apart develop when the slab tends to shorten as a result of a drop in temperature, concrete shrinkage, or moisture reduction. As the slab contracts, the movements are resisted by the weight of the slab and the friction of the underlying subgrade or subbase. These movements can also be restrained by reinforcing steel depending on the pavement type. As the weight of the slab tends to restrain this deformation, large stresses can be created at the surface of the interface. This condition is especially critical during the early age of the concrete (within a few hours after placement). These stresses, however, are instrumental in producing the needed stresses to control cracking. If saw cut notches are placed too late in the age of the cracking, concrete strength may be too high to cause cracking in a timely manner or random cracking may take place prematurely. Therefore, curling behavior should be considered when coordinating timely saw cutting operations.

Drying shrinkage depends on the cement, fineness of the mix, w/c ratio, and type of curing at both early and long term age. Shrinkage takes place over considerable time and the rate of increase of shrinkage decreases with time. In general, after two weeks of concrete placement, 14-34 percent of the 20 year shrinkage may occur (11).

The chief means of reducing shrinkage is to reduce the water content of the fresh concrete to the minimum compatible with the required workability. In addition, careful and prolonged curing is helpful for shrinkage control. Values of final shrinkage for ordinary concretes are generally in the range of 0.0002 to 0.0007 in./in., depending on initial water cement, ambient temperature and humidity conditions, and the nature of aggregate (1).

In summer temperature conditions, two coats of curing compound has been noted to reduce moisture loss, as has polyethylene film. However, winter placement may reduce thermal cracking because of lower drying shrinkage and relative change in ambient temperature conditions. Normally, concrete shrinks as the relative humidity drops below 100 percent (1).

SUMMARY AND RECOMMENDATIONS

The findings of this study determined that with proper procedure and evaluation criteria, fast track concrete can be used in all facets of concrete paving to construct pavements in a shorter time frame than under conventional paving procedures. Appropriate evaluation and paving methods need to be considered when implementing fast track construction techniques in order to reach the full potential of the concept.

Methods for the evaluation of fast track paving criteria have been developed to allow prediction of strength gain under in-situ climatic conditions. These methods of evaluation allow for the rapid placement and early opening that are common to fast track concrete pavement. The procedures and testing outlined below should aid in the construction and planning of fast track pavement.

RECOMMENDED FUTURE EXPERIMENTAL SECTIONS

On the basis of the results of the field surveys and discussion with construction supervisors, several recommendations can be formulated for consideration and implementation on a trial basis:

1. Consider the use of accelerating admixtures which assist in maintaining of appropriate workability and placability of the concrete material for intersection construction. This is particularly important during hot weather construction.
2. Consider the addition of a third aggregate (from 3/8 inch to #8 sieve size) to improve the overall gradation of the mix design. The addition of a third aggregate tends to improve the workability of the mix, while reducing the amount of cement paste used to fill the voids in the matrix formed by the aggregate. Consequently, this may also improve the performance of the mix with respect to shrinkage and strength characteristics.
3. Consider developing the pavement design to allow the existing longitudinal steel configuration to match the longitudinal steel configuration in the newly constructed pavement. A mismatch occurs in several instances where the FT pavement is thickened due to the elimination of subbase. The thickness of the new pavement is greater than the existing pavement thickness and, consequently, to maintain the same steel percentages in both sections

requires more steel in the fast track concrete. A proposed alternative involves the use of a transition slab to allow enough space to transition from one steel configuration to another.

4. Consider the use of early-aged sawcutting to develop satisfactory crack and jointing patterns that are not spaced too far apart or spaced too close together. Outside of other mitigating circumstances, the field surveys indicated a need to induce the crack pattern to prevent wide or irregular crack patterns.

5. Consider the impact of subgrade pumping on the performance of intersection pavements. Where is it appropriate to do so, consider the use of alternate subbase materials/types under FT pavements to provide drainage, use of standard paving thicknesses, and steel percentages which can match the existing steel configuration. The alternate subbase system can be selected in such a manner to minimize the impact upon the concept behind accelerated paving techniques.

6. Consider the adoption of non-destructive testing (NDT) techniques to monitor the strength of the pavement and to estimate the most appropriate time of sawcutting and the opening of the pavement to traffic. Methods of this nature may provide an extremely efficient means to monitor and maintain the quality of the concrete in the pavement.

7. Consider the effectiveness of different joint sealants and the impact that unsatisfactory sealing has on the life of an intersection pavement.

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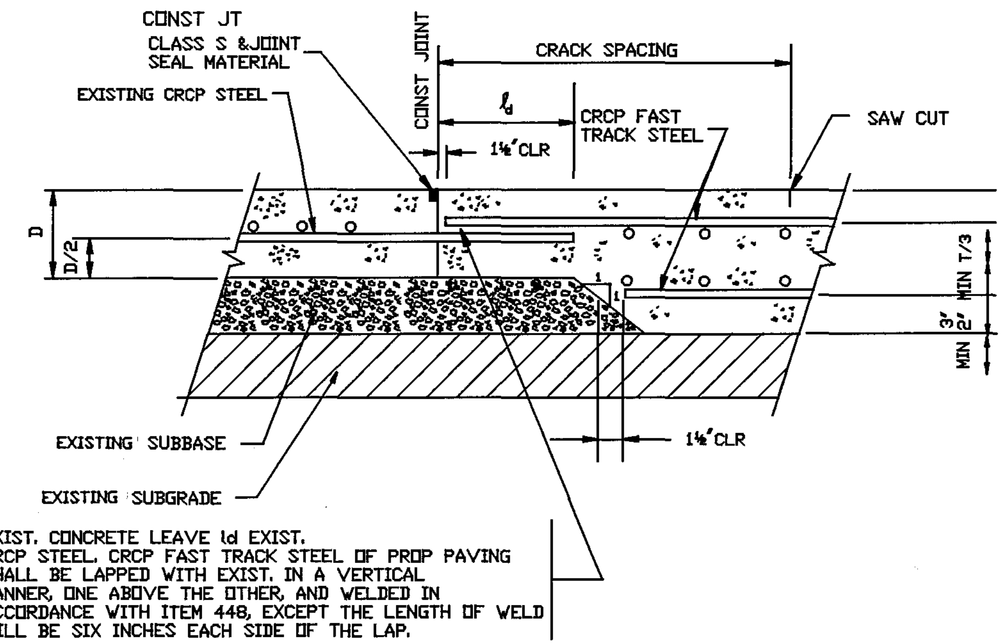
APPENDIX A
CRCP FAST TRACK JOINT DETAIL

CRCP Fast Track Joint Detail

In the construction of a concrete intersection, joint placement and joint construction is a primary consideration. Typically, in an intersection, there is a primary pavement (one with a heavier traffic load) and a secondary pavement. When both intersecting pavements are continuously reinforced, the transverse steel from the primary pavement will attempt to be tied to the longitudinal steel of the secondary pavement. Frequently, the secondary road will have a different design (different thickness, one layer of steel versus two layers, different steel diameters), which will cause the two intersecting sets of steel to align incorrectly.

One solution to this situation is to bend the steel to match the new configuration. Another approach is shown in the following two figures. What is shown is a solution for joining two layers of steel (with a greater pavement thickness) to a one layer steel system. The designs include a lapped joint (Figure A-1) and a doweled joint (Figure A-2).

When placing this type of joint the secondary intersection road will usually be cut back to expose the necessary steel. It is of utmost importance that the subbase and subbgrade are replaced adequately.



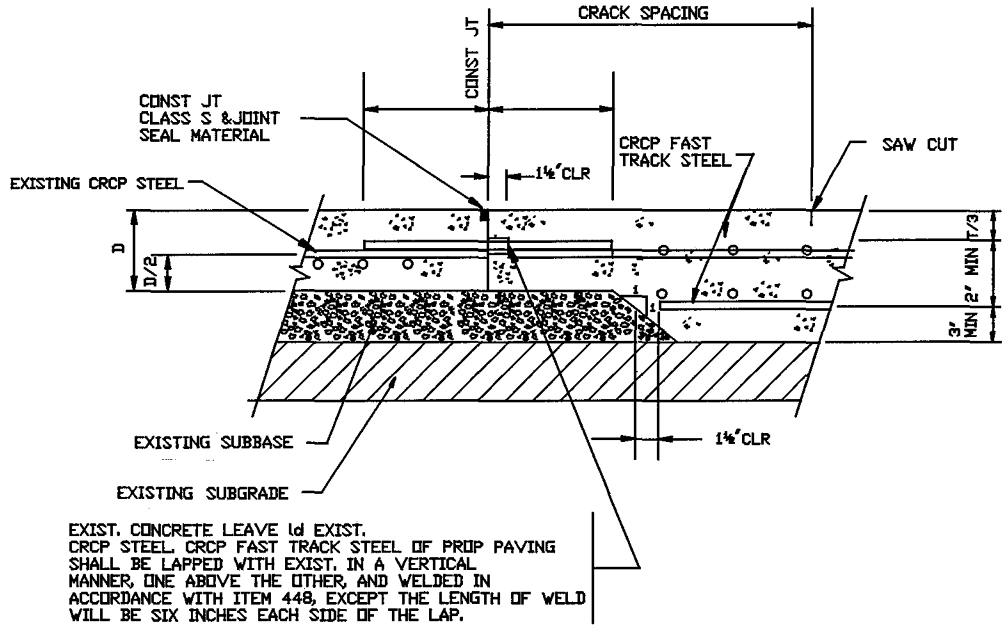
CRCP WITH CRCP FAST TRACK LAPPED JOINT

NOTES:

1. NO EXPANSION JOINTS SHALL BE USED EXCEPT AT STRUCTURE ENDS OR FIXED OBJECTS AS ELSEWHERE IN THE PLANS.
2. FOR FURTHER INFORMATION REGARDING THE PLACEMENT OF CONCRETE AND REINFORCEMENT, REFER TO THE GOVERNING SPECIFICATIONS FOR 'CONCRETE PAVEMENT'.
3. LONGITUDINAL AND TRANSVERSE STEEL WILL CONFORM TO ASTM GRADE 60 SPECIFICATIONS.
4. WHEN THE EXISTING SUBBASE LAYER IS REMOVED DURING EXCAVATION, IT SHALL BE REPLACED BY A CEMENT STABILIZED LAYER CURED AS SPECIFIED BY THE ENGINEER TO EFFECTIVELY DELAMINATE THE SUBBASE LAYER.

BAR SIZE	ld
#4	5
#5	9
#6	13

Figure A-1. CRCP Fast Track Lapped Joint.



CRCP WITH CRCP FAST TRACK
DOWEL JOINT

NOTES:

1. NO EXPANSION JOINTS SHALL BE USED EXCEPT AT STRUCTURE ENDS OR FIXED OBJECTS AS ELSEWHERE IN THE PLANS.
2. FOR FURTHER INFORMATION REGARDING THE PLACEMENT OF CONCRETE AND REINFORCEMENT, REFER TO THE GOVERNING SPECIFICATIONS FOR "CONCRETE PAVEMENT".
3. LONGITUDINAL AND TRANSVERSE STEEL WILL CONFORM TO ASTM GRADE 60 SPECIFICATIONS.
4. WHEN THE EXISTING SUBBASE LAYER IS REMOVED DURING EXCAVATION, IT SHALL BE REPLACED BY A CEMENT STABILIZED LAYER CURED AS SPECIFIED BY THE ENGINEER TO EFFECTIVELY DELAMINATE THE SUBBASE LAYER.

BAR SIZE	ld
#4	5
#5	9
#6	13

Figure A-2. CRCP Fast Track Dowel Joint.

APPENDIX B
EARLY OPENING CRITERIA WORKSHEET

Early Opening Criteria Worksheet

The purpose for the Early Opening Criteria Worksheet is to provide the field engineer a simple step by step process to evaluate the strength gain of field placed concrete and to estimate a time for opening the pavement to traffic. The data for the strength curve used in the worksheet is generated from following the laboratory procedures outlined in ASTM C 1074. These procedures should provide the following:

(1) Strength measurements at various times ranging to 28 days,

(2) Time of each strength test,

(3) Maturity at the time of each strength test,

(4) The activation energy (E) or the datum temperature (T_o) depending on whether maturity (M) or equivalent age (t_e) is being monitored in the field, and

(5) The ultimate strength (S_∞) or S_{28} (see discussion below on this topic).

With this data, the chart and graph included at the end of this appendix may be utilized to ascertain the maturity at the desired opening (or specified) strength and the time to opening for the pavement to traffic. The functional relationship between concrete strength and maturity (or equivalent age) upon which the following worksheet is based is:

$$\frac{S}{S_\infty} = e^{-\left(\frac{\tau}{M}\right)^a}$$

and transformed in a linear expression:

$$y = mx + b$$

where

y = $\text{Ln}(-\text{Ln}(S/S_\infty)$
x = Ln M
m = a (slope)
b = a Ln τ (intercept)

The constants (a and τ) can be found from the slope and the intercept of the plotted or regressed strength-maturity data. The value of S_∞ can be obtained from following the ASTM C 1074 laboratory procedure as pointed out above or from analysis of pilot beam strength data for the given concrete mixture, which may be available prior to paving, as indicated in the example calculation following this section. It should be noted that the ratio of S/S_∞ obtained under a given set of curing conditions (whether in the laboratory or the field) is generally applicable, within limits, to any other set of curing conditions. However, it should also be noted that such is not the case with the value of S_∞ since S_∞ is a function of the conditions under which the specimens were cured.

If it is determined that pilot test beam data can be made available to develop the basic strength-maturity relationship, then 5 sets of strength-maturity data (say 10 beam specimens) should be tested over a 3 day period for a fast-track mix or a 28 day period for a conventional mix. The maturity is recorded by the use of a maturity meter and is based upon either the datum temperature (T_0) or the activation energy (E) as explained in ASTM C 1074. As noted above, these are basic material properties of the cement and are determined from following laboratory procedures as outlined in ASTM C 1074. An illustrated example of a strength-maturity relationship is provided with actual pilot beam and maturity test data. The beams in this example were cast with concrete using a normal Type I cement. Also included following the illustrated example is a blank worksheet for reproduction purposes.

In light of the above discussion with regard to the determination of S_∞, a beam field strength (as a representative average beam strength $S_{b\ (field)}$) is needed during concrete placement operations , in addition to the corresponding beam maturity (M_b) of the test specimen(s), to establish the opening relative strength ratio ($S_{design}/S_{\infty(field)}$) under field conditions. This data is necessary since the ultimate strength ($S_{\infty(field)}$) attained in the field will typically be different from the ultimate strength gain (S_∞) of the mix (the mortar cubes or laboratory specimens used in ASTM 1074-89) cured in the laboratory as pointed out above. From the strength-maturity curve established from either the laboratory or pilot test beam data, the field value of $S_{\infty(field)}$ can be determined from the value of S/S_∞ associated with the corresponding beam maturity (M_b) and $S_{b\ (field)}$ as:

$$S_{\infty\ (field)} = S_{b(field)} \div \frac{S}{S_\infty}$$

Once ($S_{design}/S_{\infty(field)}$) is known, the opening value of maturity can be found as shown below.

OPENING STRENGTH CRITERIA WORKSHEET (example)

Ultimate Strength (S_∞ or S_{28}) 1250 psi

(1) Complete the table entering beam test values into the appropriate columns. Note that the value of S_∞ can be obtained from the same pilot beam test data used to develop the strength-maturity relationship as illustrated at the end of this example.

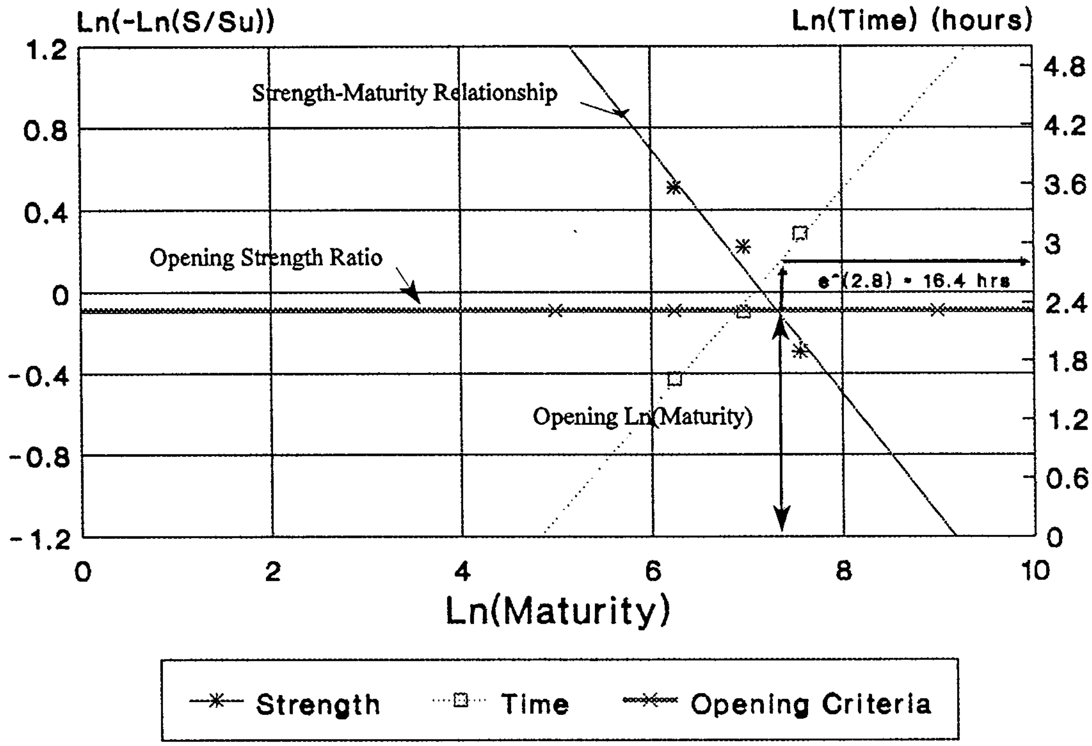
Col. A Strength (psi)	**Col. B** (Col. A) ÷ S_∞	**Col. C** Ln (Col. B)	**Col. D** Ln(-Col. C)	**Col. E** Maturity / Ln (Mat.)	**Col. F** Time/ Ln (Time) (hrs)
229	0.19	-1.66	0.51	511/ 6.24	5/1.61
349	0.29	-1.24	0.22	1067/ 6.97	10/2.30
575	0.47	-0.75	-0.29	1913/ 7.56	22/3.09

(2) Plot the values from column E and column D on the graph below; column E is the ordinate (x axis) and column D is the abscissa (y axis). Then draw a best fit line through the points. (Use conversion charts included with worksheet as necessary to determine logarithms.)

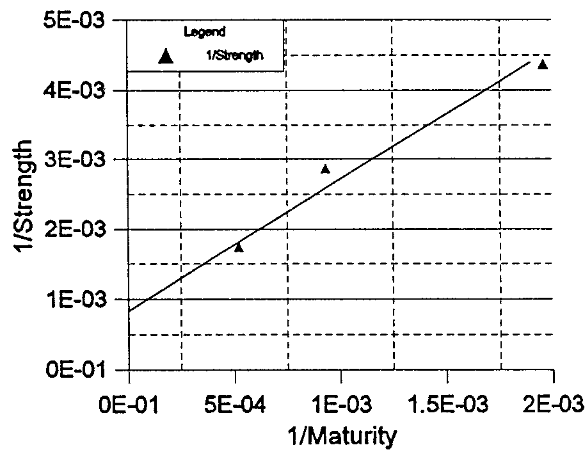
(3) Plot the values found in column F and column E. Column F will be the abscissa and column E will be the ordinate. As before, draw a best fit line through the data points.

(4) Determine the opening ($S_{design}/S_{\infty(field)}$) ratio and a corresponding horizontal line.

(5) Where the strength-maturity line in part (2) intersects the opening strength line, determine the corresponding (Ln(maturity)) on the ordinate. Use the same value of Ln(maturity) to intersect the line from part (3) to determine the time of opening on the abscissa. An example of this process is shown below (opened at 16.4 hrs).



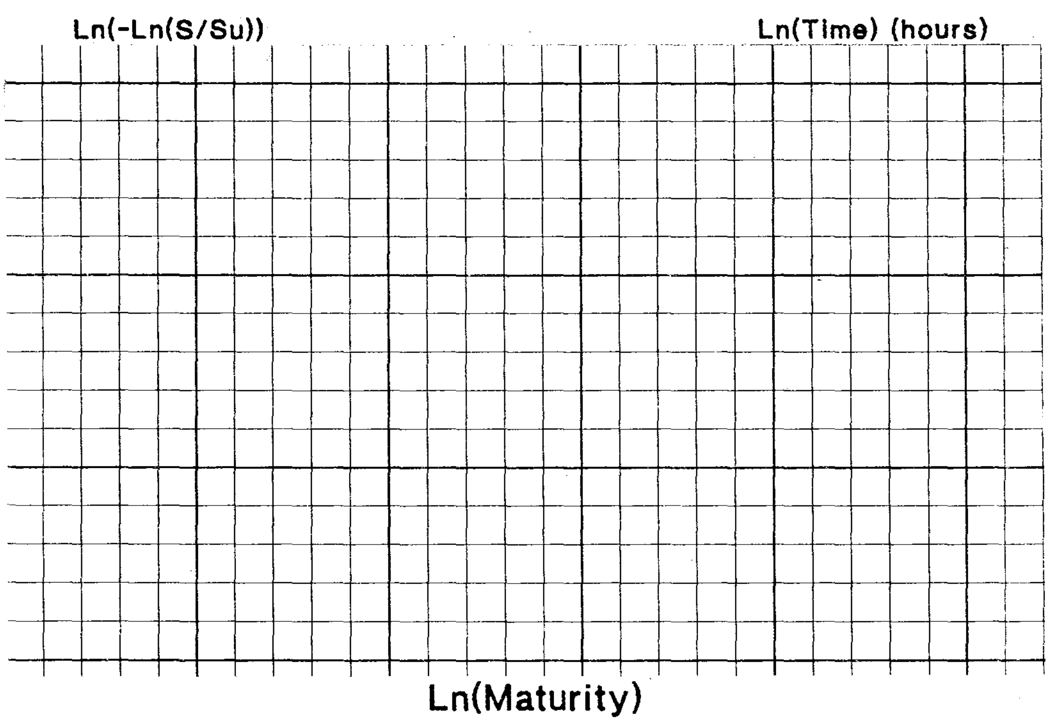
(6) The figure to the right demonstrates a method to determine S_∞ from the same beam test data used above. Note that 1/Strength = $1/S_\infty$ at a zero level of maturity.



OPENING STRENGTH CRITERIA WORKSHEET

Ultimate Strength (S_∞ or S_{28}) ________ psi

Col. A Strength (psi)	**Col. B** (Col. A) ÷ S_∞	**Col. C** Ln (Col. B)	**Col. D** Ln(-Col. C)	**Col. E** Maturity/ Ln (Mat.)	**Col. F** Time/ Ln (Time) (hrs)



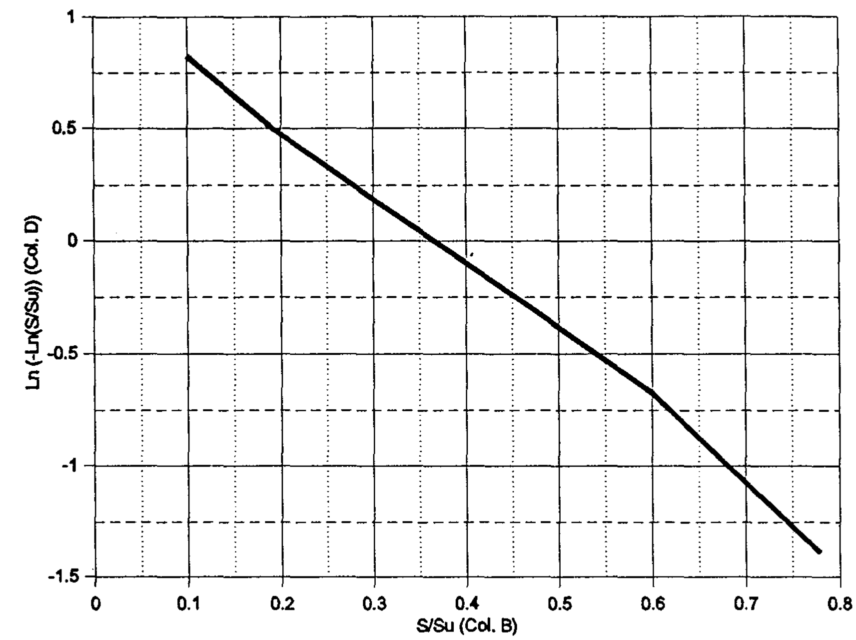


Chart to Convert Col. B Data to Col. D Data

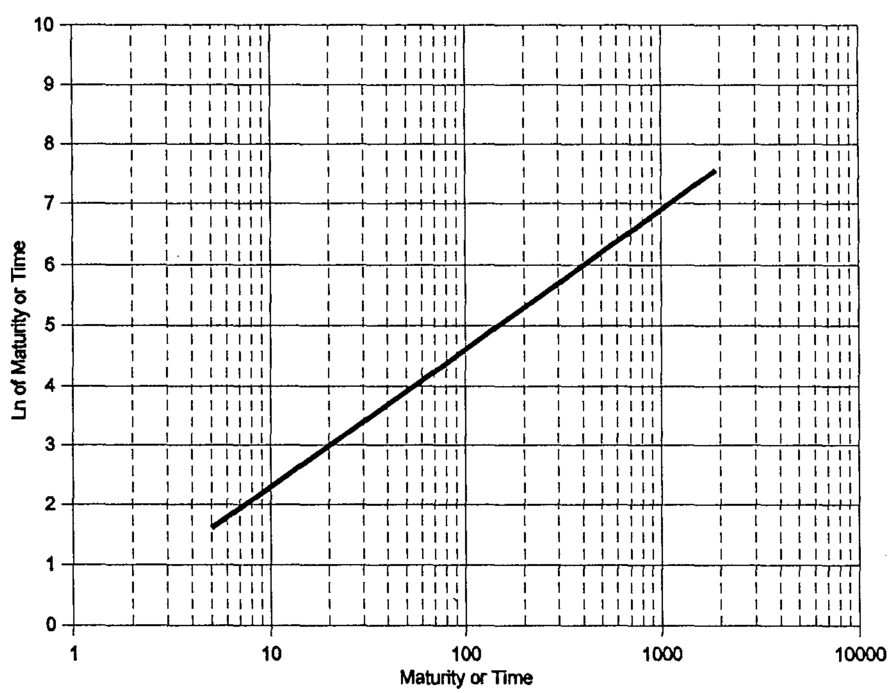
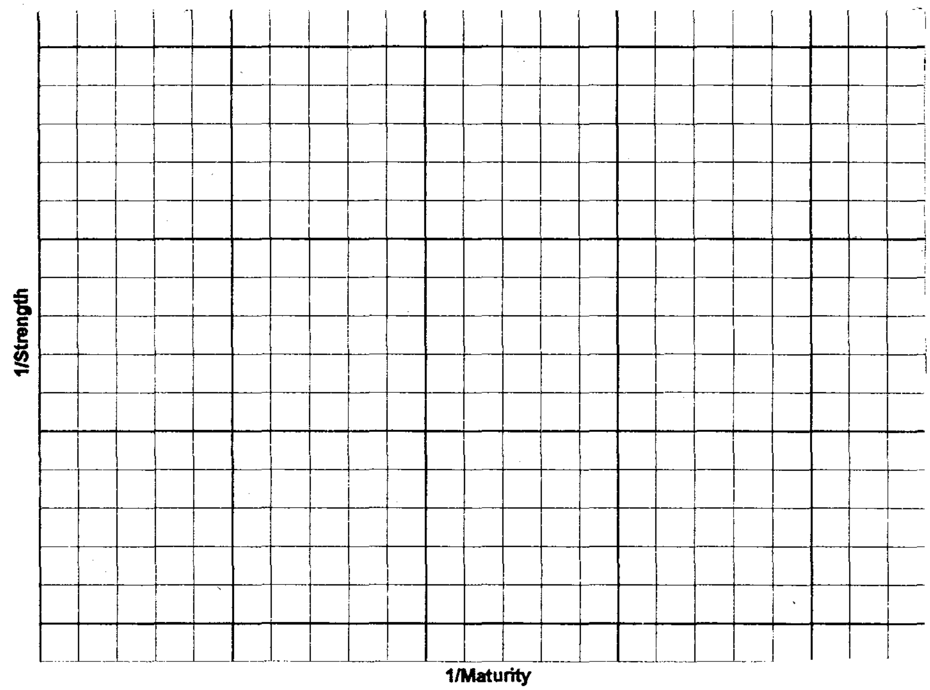


Chart to Convert Maturity or Time to Ln Value



Calculation Aid for the Determination of S_∞ (based on field data)

APPENDIX C
TEMPERATURE MODIFICATION

Temperature Modification

When paving operations are exposed to changes in temperature, it is expected that the rate of hydration of the cement will be affected and will either increase or decrease depending on the temperature change. If the concrete is exposed to cool weather conditions (winter), the concrete will hydrate at a slower rate (Figure C-1) than if it were exposed to warmer weather conditions (summer). With respect to fast track concrete, the slower rate of hydration will result in longer opening times. The opening strength worksheet will be useful in predicting the time of opening, however, under fast track conditions the time of opening that is found may not satisfy the phase requirements of a particular project.

Consequently, two alternatives may be available to the contractor to satisfy the opening criteria: (1) to open later to allow the concrete to cure completely, or (2) modify the temperature of the mixing water or the method of curing to accelerate the time of opening. To comply with the paving and early opening schedule, a change in the

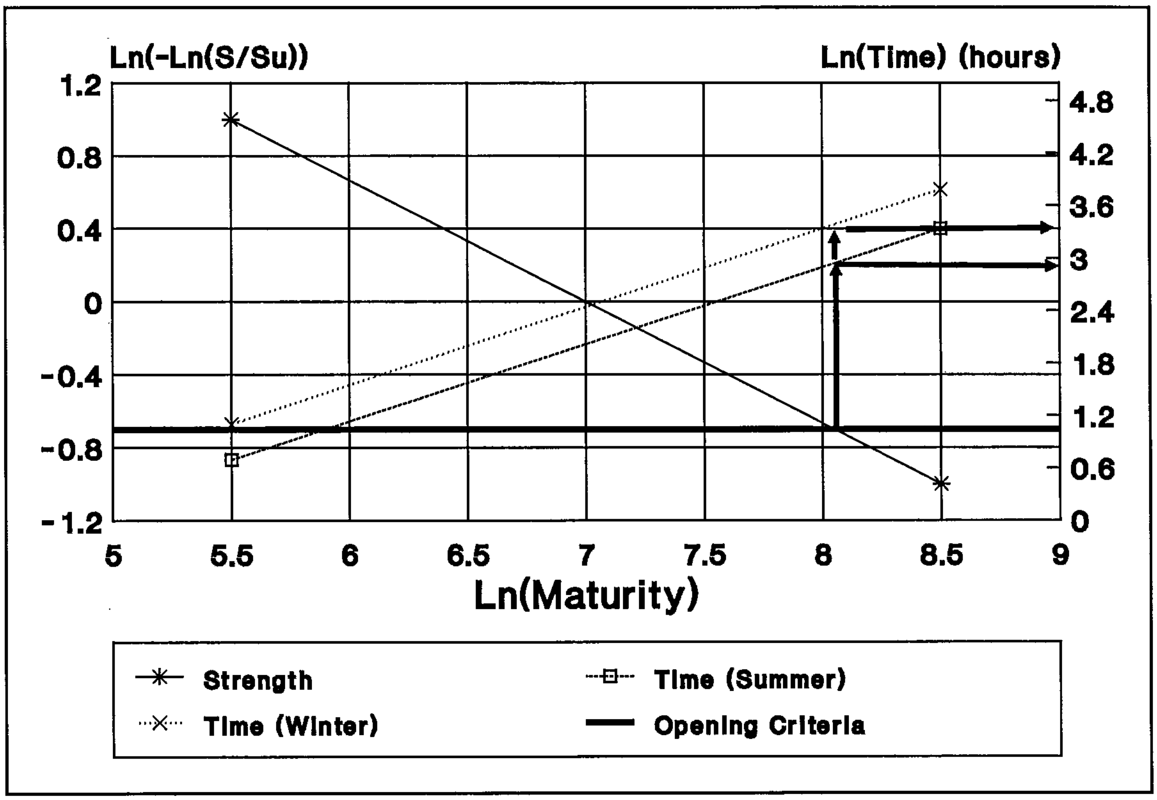


Figure C-1. The Effect of Polyethylene Curing on Opening Time Using the Maturity Worksheet.

temperature of the mixing water may be needed to modify the curing conditions to achieve a higher rate of hydration and an earlier opening time under the given temperature conditions.

Regardless of the concrete mix constituents chosen for modification, the resulting effect on the time of opening can be characterized by the activation energy (E) exhibited by a particular mix. The activation energy is a measure of how much energy is needed for a reaction (concrete hydration) to occur. For example, the activation energy of a Type III cement is lower than a Type I cement. This is because a Type I cement needs more energy than a Type III cement to complete hydration in the same amount of time. Energy can be provided to the mix by higher mixing water temperature, different curing methods, or a variation in temperature conditions. The effect of these measures will depend upon the activation energy (E) exhibited by the mix constituents. Energy exhibited by the mix constituents in combination with certain methods and conditions of curing may be useful to represent the effect on time of opening.

Using the procedures outlined for the worksheet, a comparison can be made from test data between two beams cured by different methods under summer temperature conditions. Each beam, in this instance, was cured using Type II curing compound with one beam covered with a polyethylene sheeting. The test data is shown in an opening strength criteria worksheet attached to this appendix. Polyethylene sheeting affected the time of opening by 8 hours, under the given field conditions. It is recommended that several maturity-time data points (at least 4 to 5 - with one set of data exceeding the opening t_e) be plotted to predict the time of opening. The mathematical function representing the maturity-time relation is a double integral of the equivalent age function shown in equation 2. For the conditions under which the test beams were cast and cured, the effect of the time of opening can be observed in the plotted data.

In the event of changes in the ambient temperature conditions the maturity-time relationship is expected to change and can be illustrated in the worksheet as shown in the comparsion of the two curing methods. It is recommended that additional beams be cast and cured under the changed conditions to assess the effect of different methods of curing on the time of opening. For a different set of conditions, the worksheet procedure will require data sets for the same three inputs for the test beams:

(1) Maturity,

(2) Temperature, and

(3) Time.

It should be noted that the field measurements can be made in terms of maturity (referred to as the temperature-time factor in ASTM C-1074) or as the equivalent age (t_e) at a specified temperature T_s. Depending on the method, the laboratory procedure (based on ASTM C-1074) should either provide the datum temperature or the activation energy (E). If the maturity approach is taken in the field, it may be necessary to correct the maturity readout from the instrumentation according to the guidelines given in ASTM C-1074, if an inappropriate datum temperature is employed by the maturity meter. As a matter of reference, the following activation energies are provided as determined according to ASTM C-1074.

Table C-1. The Effects of Material Modification on the Activation Energy of a Type I Mix.

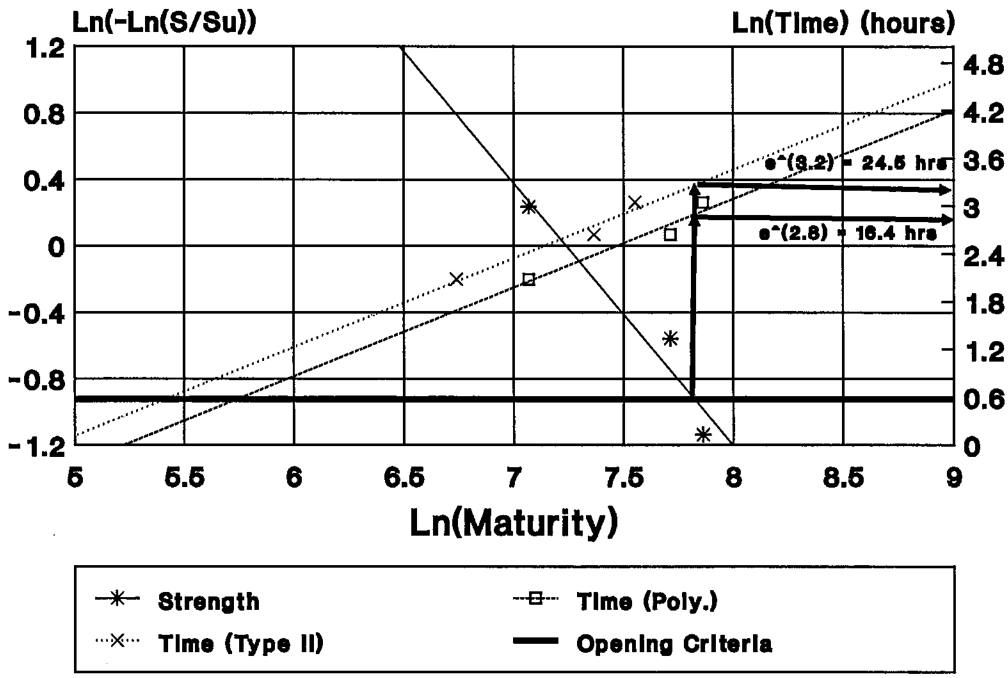
MATERIAL TYPE	ACTIVATION ENERGY (E) (KJ/mol)
Control (Regular 7 sack mix)	37.36
Accelerator + 7 sack	35.46
Plasticizer + 7 sack	32.88
FA(20%) + 7 sack	28.37

OPENING STRENGTH CRITERIA WORKSHEET

Ultimate Strength (S_∞ or S_{28}) 744 psi

Col. A Strength (psi)	Col. B (Col. A) ÷ S_∞	Col. C Ln (Col. B)	Col. D Ln(-Col. C)	Col. E Maturity/ Ln (Mat.)	Col. F Time/ Ln (Time)
210	0.282	-1.265	0.235	1174/7.07 - P 844/6.74 - T	8 8
420	0.565	-.572	-0.559	2236/7.71 - P 1576/7.36 - T	14 14
540	0.726	-0.320	-1.138	2595/7.86 - P 1902/7.55 - T	21 21

Note: $M_c = t_e(33) - (0 + 10°C)\Delta t$; $T_o = 0°C$; P = Polyethylene Sheeting; T = Type II Curing.



APPENDIX D

EXAMPLE OF FAST TRACK PAVING PROJECT

Example of Fast Track Paving Project

Superplasticizers can be useful for applications in fast track paving. Superplasticizers yield increased workability, strength and time to finish. An example of superplasticizer utilization using fast track methods was found in a project for Sysco Foods in Houston, Texas.

The Superplasticizer was used in conjunction with a mixture containing 700 pounds of Type III cement (mix design shown in Table D-1). The requirements for the project were as described below:

(1) the placement of 20 square feet square concrete slabs with dowelled joints;

(2) the concrete having enough workability to be able to be pumped;

(3) the project needed to begin at 6:00 pm Friday and to be ready for use by 12:00 pm Sunday;

(4) a required concrete compressive strength of 3000 psi (approx. 330 psi flexural strength) was desired in 6 to 8 hours; and

(5) a 7 inch slump for pumping and ease of placement.

Note in Table D-1, that six ounces of superplasticizer were used. This admixture can be added entirely at the plant or field, or part at the plant and part at the field. Experience has found that if either the workability requirements of the concrete have not been met or the placement time needs to be extended, additional plasticizer can be added directly to the concrete in the mixing truck to increase the workability at the time of placement.

The paving operations were conducted at night. The resulting strengths received through tests were above the design recommendations (shown in Figure D-1). From Figure D-1, the trend of the graph indicates that the superplasticizer has a beneficial effect on the strength gain achieving compressive strengths in excess of 4900 psi (flexural 530 psi).

Table D-1. Mix Design for Sysco Foods in Houston, Texas.

Material	Type	Quantity
Cement	III	700 lbs.
Fly Ash	-	0
Coarse Aggregate	1" L.S.	1,800 lbs.
Fine Aggregate	Concrete Sand	1,173 lbs.
Admixture	Super-6	6 ozs.
AEA	-	2.5 ozs.
Total Water	-	225 lbs

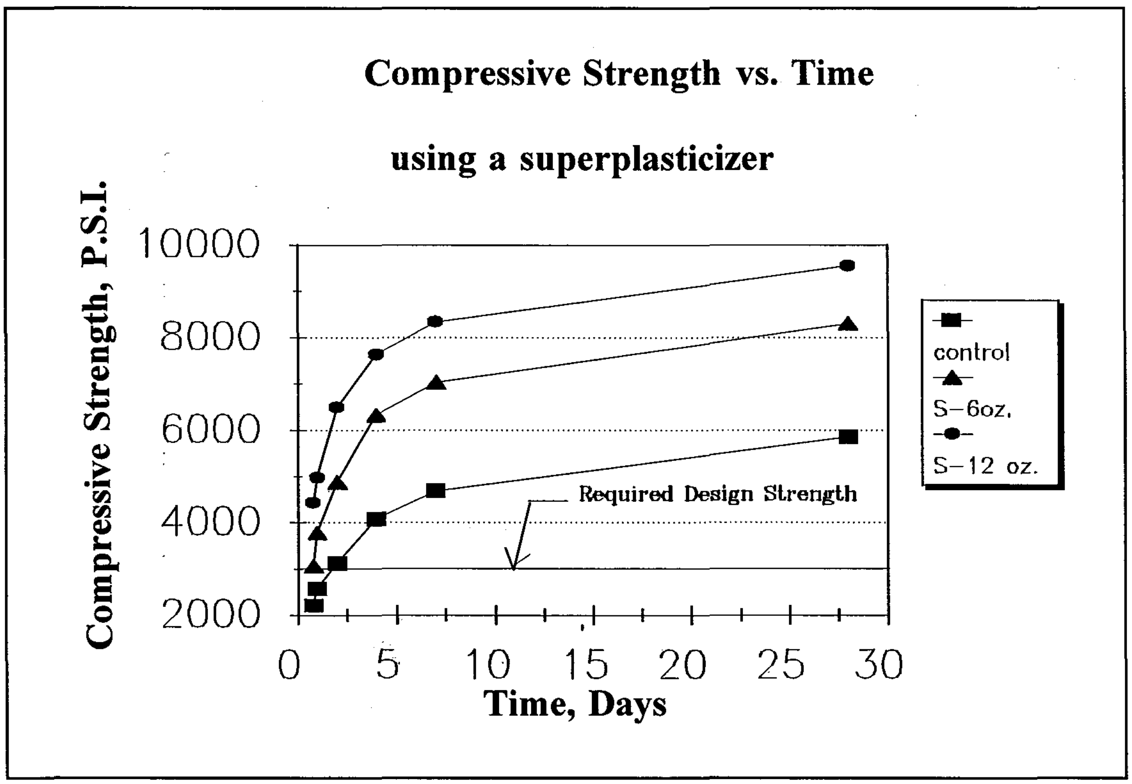


Figure D-1. The Effects of a Superplasticizer on Compressive Strength.

APPENDIX E
FWD DATA AND ANALYSIS

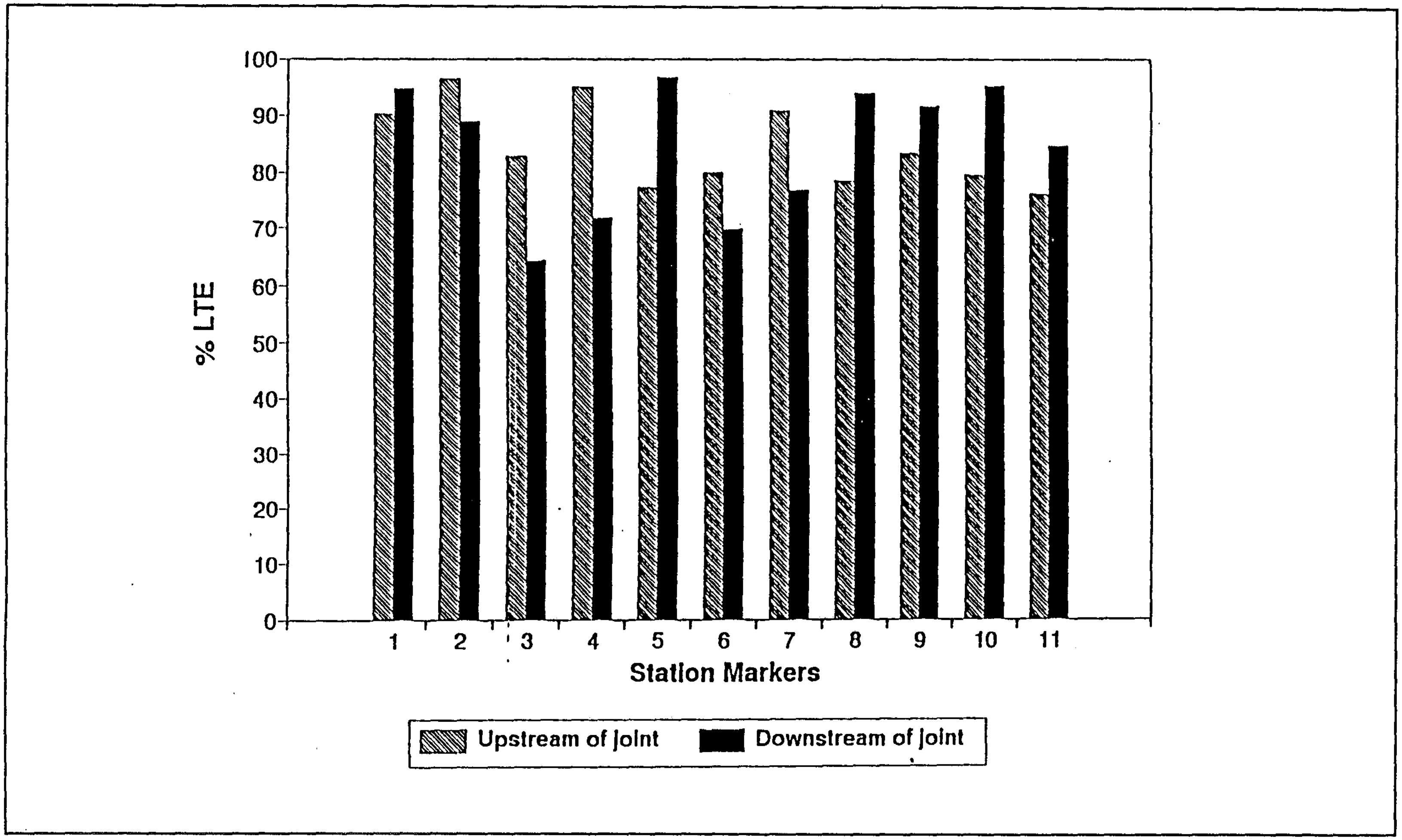


Figure E-1. LTE vs. Station: US-59.

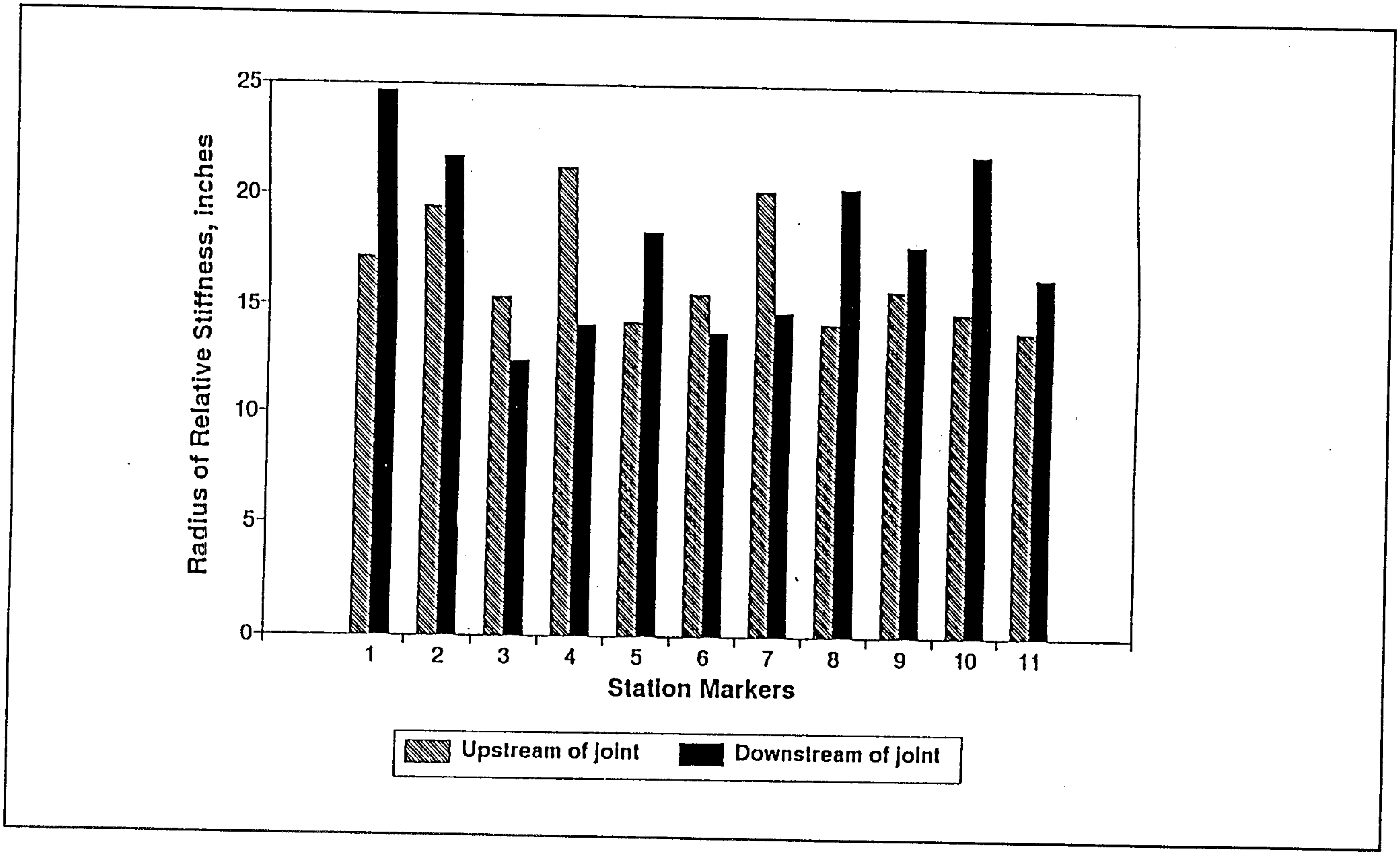


Figure E-2. Radius of Relative Stiffness vs. Station: US-59.

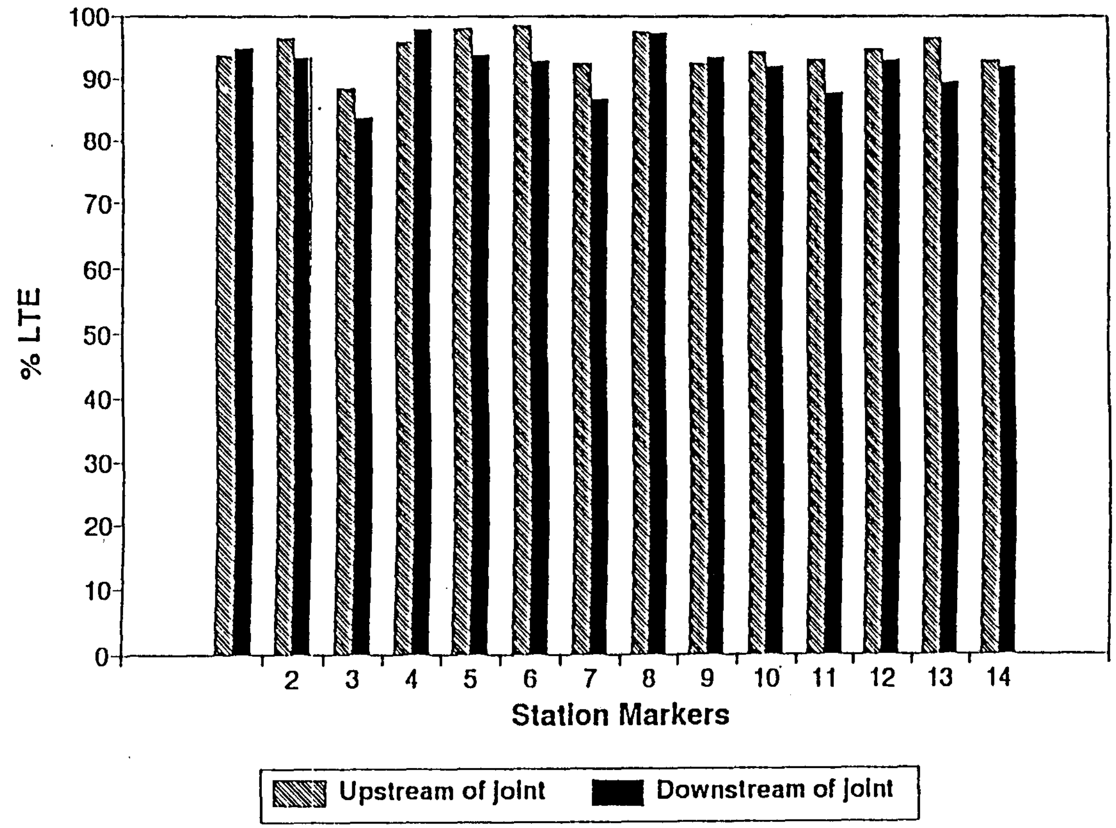


Figure E-3. LTE vs. Station: I-45 Rayford.

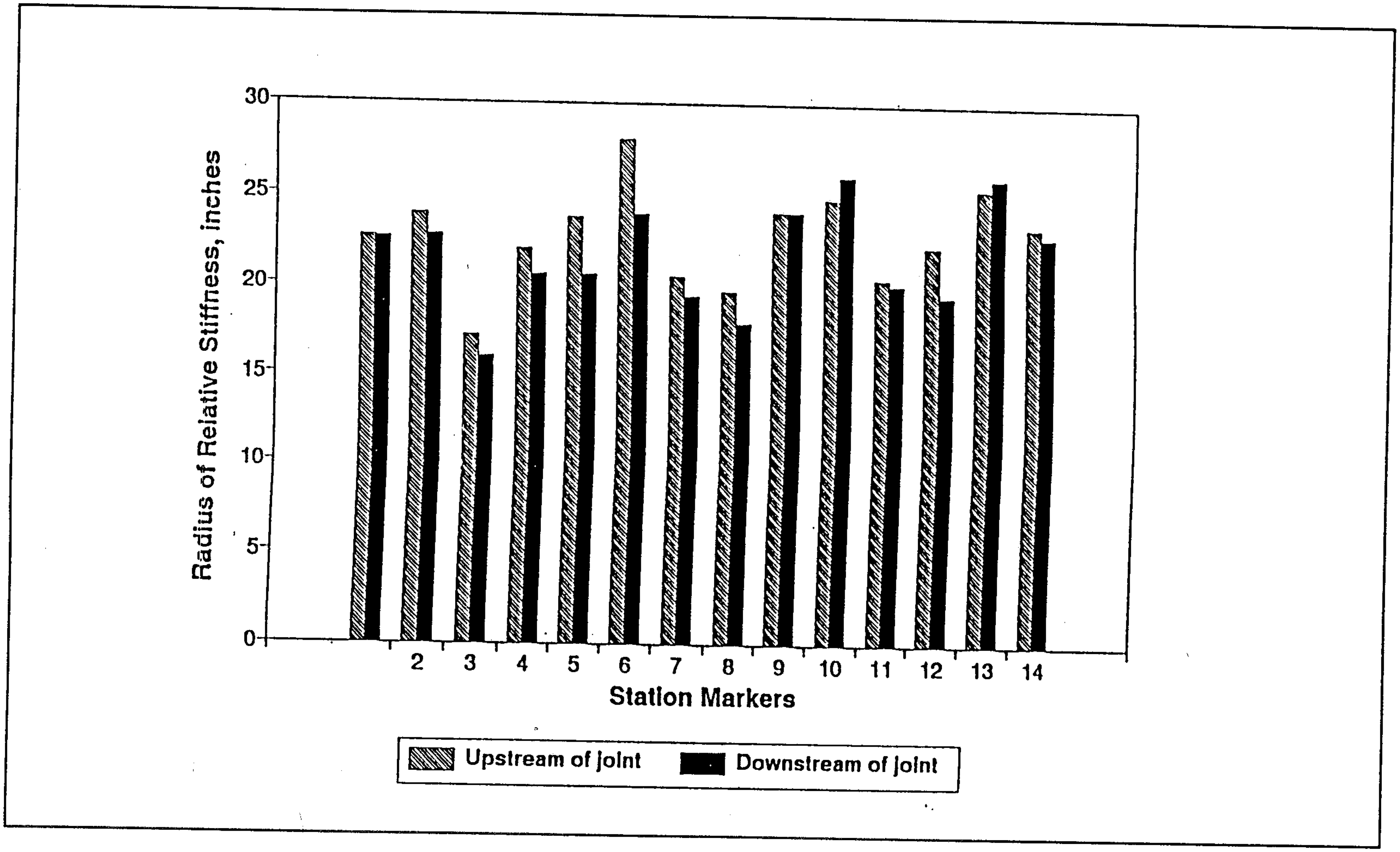


Figure E-4. Radius of Relative Stiffness vs. Station: I-45 Rayford.

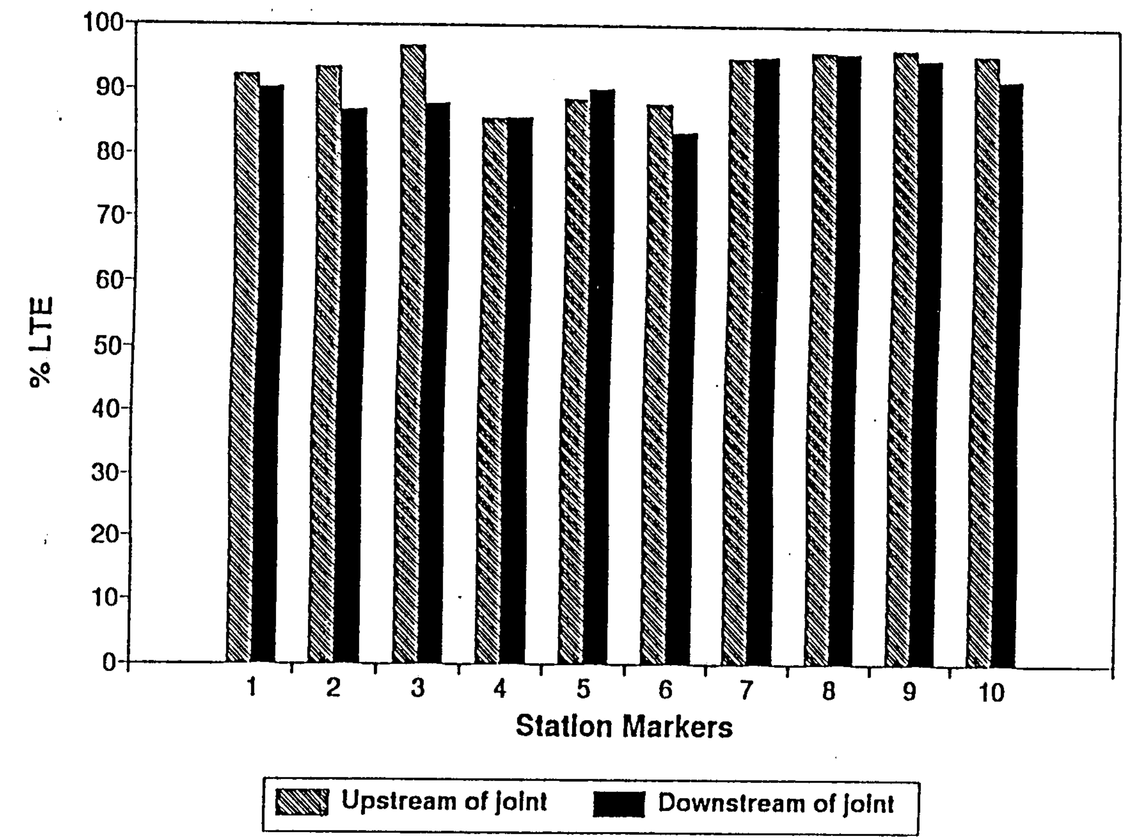


Figure E-5. LTE vs. Station: I-45 Sawdust.

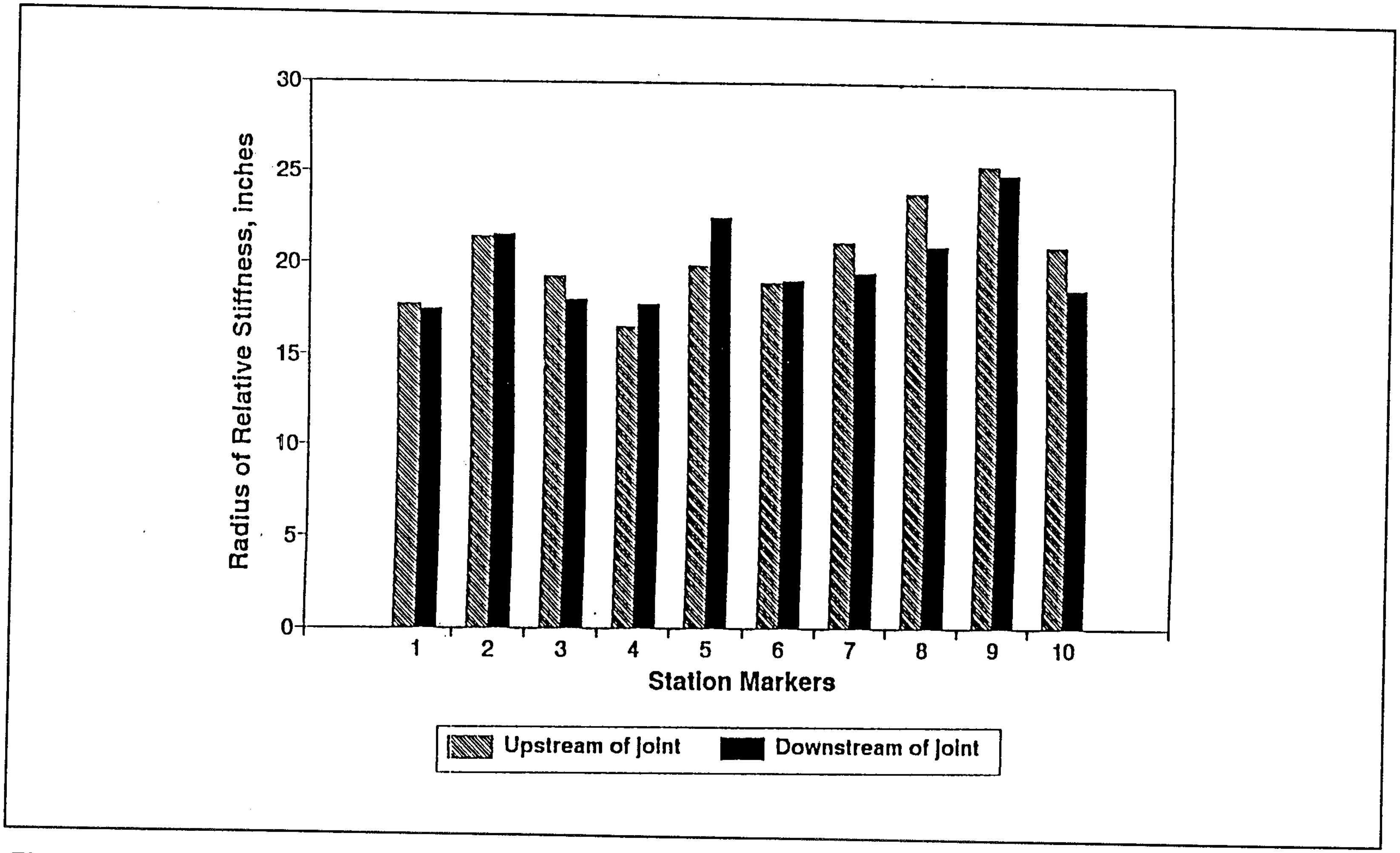


Figure E-6. Radius of Relative Stiffness vs. Station: I-45 Sawdust.

APPENDIX F

CONSISTENCY TEST GUIDELINES

Consistency Test Guidelines

The purpose of a consistency test is to characterize the rheology or workability in a concrete mixture. A consistency test can serve as an important indicator for determining if the mix workability is appropriate for a given construction application. Consistency also is an indicator of:

(1) initial set of concrete, and

(2) finishability.

The primary manner in which consistency is currently measured in the field is with the standard slump test. However, it has been shown (The Standard Practice for Selecting Proportions for No Slump Concrete, ACI (211.3-75) Reported by ACI Committee 211) that the workability of concrete is greatly affected by the type of compaction or vibration used to place the concrete. Vibratory energy transferred to a concrete mass can serve as a measure of workability.

Past efforts to measure the consistency of fresh concrete have focused on methods that use compactive or vibratory type energy. These methods include the:

(1) Vebe Test,

(2) Thaulow Drop Test, and

(3) the German DIN 1048 Test.

It is important to obtain consistency measurements in the field to test the actual concrete that is being placed. To test the consistency in the field, the instrumentation should be simple, durable yet effective. The first two methods (the Vebe test and the Thaulow Drop Test) are primarily used in laboratory conditions due to the equipment needed to perform the tests. The equipment for the DIN 1048 (shown in Figure F-1) is smaller and does not require a generator and is relatively easy and inexpensive to fabricate.

The design suggested for implementation can be smaller than the flow table shown in Figure F-1 (DIN 1048 specification). The procedure may also use the standard ASTM slump cone and the ASTM compacting rod in addition to the flow table being modified to use a metallic surface on the top.

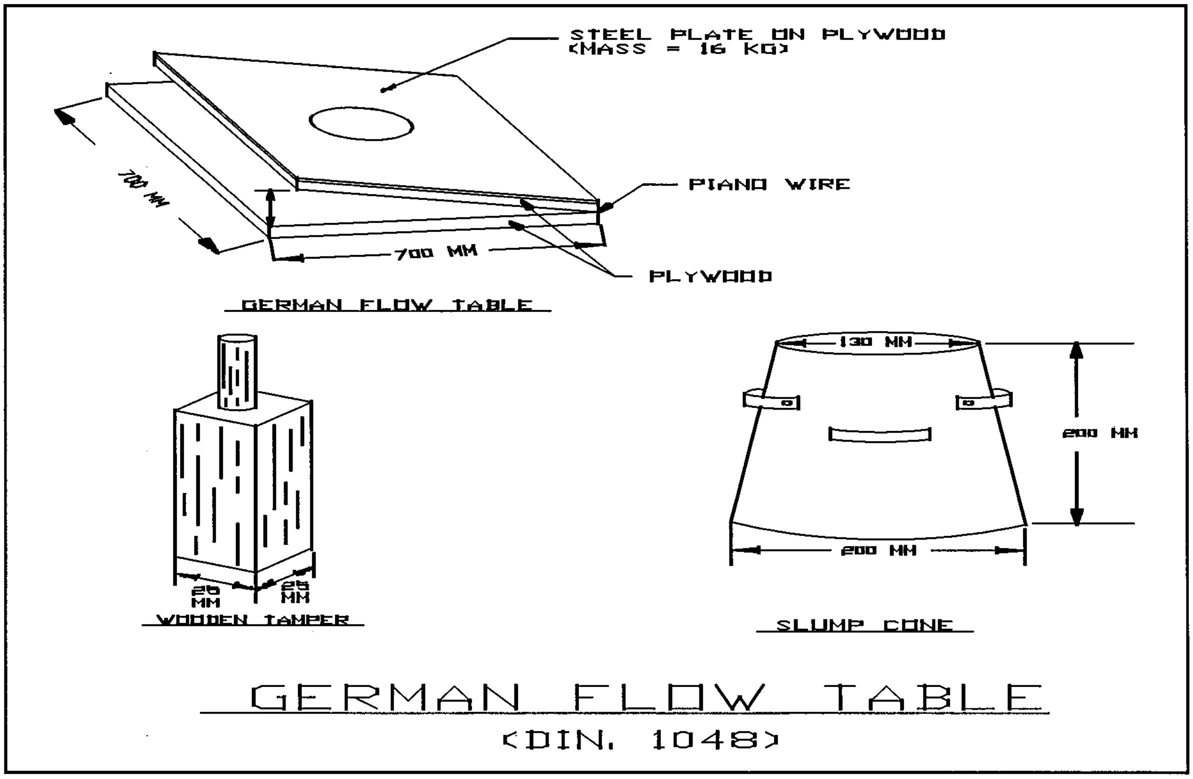


Figure F-1. The German Consistency Test, DIN 1048.

The basic steps to perform the consistency test are as follows:

(1) using ASTM methods place slump cone directly on the circle traced for the slump cone;

(2) remove the steel cone and measure the slump;

(3) based on the type of mix design a perimeter is chosen (10, 12, 14 or 16 inch);

(4) the platform is raised and dropped 1 inch until any portion of the concrete crosses the chosen perimeter; and

(5) the number of drops is recorded to reach the specified perimeter.

For fast track paving mixes, due to the earlier setting of the concrete, the test is run a number of times within the first hour of the placement to obtain a measure consistency before the concrete reaches initial set.

A sample data sheet is provided on the following page to record the number of drops to obtain an indication of the consistency of the concrete. It is recommended that the number of drops be recorded at a selected diameter for the particular mix being tested. Conducting this test repeatedly, will allow a trend to be established for a given diameter circle (on the flow table) as a function of time to represent the consistency of the particular concrete mix being tested.

A Suggested Data Sheet for Consistency Tests

Time	Flow Table Diameters (inches)						
min.	10	12	14	16	18	20	22
5							
10							
20							
30							
45							
60							

APPENDIX G
DEFINITIONS

Definitions

Activation Energy — The activation energy, often represented by (E), relates the heat of hydration to a cement mix to the amount of strength gain achieved in a specific time period.

Aggregate Interlock — The random projections of aggregate across a crack in concrete which carry shear forces imposed by passing wheel loads.

Construction Joint — A joint made necessary by a prolonged interruption in the placing of concrete (6); whereby fresh concrete is placed in contact with hardened concrete. Construction joints may be formed in the transverse or longitudinal direction. Often, the joints may include a redwood separator.

Contraction Joint — A joint designed primarily to allow horizontal movement to relieve strains from shrinkage and contraction due to changes in temperature. This may also be a doweled or hinged joint (6).

Crack — A permanent fissure or open seam within a concrete pavement at which tensile stress in the concrete has exceeded the tensile strength of the concrete. This crack can be naturally occurring (the relief of pavement stresses) or induced by sawcutting the pavement. (1)

Deformed Bar — A ribbed steel reinforcing bar meeting the requirements for deformed bars as specified in ASTM A615, Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement; A616, Specification for Rail Steel Deformed and Plain Bars for Concrete Reinforcement; or, A617, Specification for Axle-Steel Deformed and Plain Bars for Concrete Reinforcement.

Dowel — A smooth steel bar embedded in concrete to provide shear resistance for wheel loads placed near a joint, and to help prevent faulting, while allowing the slab to move freely in the direction of the dowel axis.

Drainage — The movement or accumulation of moisture and water in, or over, the land. "Pavement drainage" refers to the prevention of water accumulations through the controlled movements of water in, and over the pavement structure so as to obtain the desired pavement performance.

Expansion Joint — A joint located to provide for expansion of a rigid slab, without damage to itself, adjacent slabs, or structures. Expansion joints are often used next to bridge structures (6).

Fatigue Damage — The cumulative damage to the pavement after the fatigue life of that particular pavement has been exceeded.

Fatigue Life — The time it takes for a certain number of continuous traffic loads to fail the pavement through fatigue.

Faulting — Differential vertical displacement of rigid slabs at a joint or crack (1); usually creating a small step downward in the direction in which the traffic moves.

Joint — A designed vertical plane of separation or weakness (6); intended to aid concrete placement, control crack formation, or to accommodate length changes of the concrete.

Load Transfer Device — A mechanical means designed to carry wheel loads across a joint (6), normally consisting of concrete aggregate interlock, dowels, or dowel-type devices.

Maturity — The relation of strength gain to the time-temperature product. The maturity helps determine a prediction of the probable strength gain characteristics of a particular mix

Modulus of Rupture — A measure of the ultimate strength of a concrete beam and sometimes called "rupture modulus" or "rupture strength." It is calculated for apparent tensile stress in the extreme fiber of test specimens under a load which produces rupture. It provides an indication of the ultimate flexural strength of a slab. Various tests have been standardized for measuring the modulus of rupture and correlations have been established with other strength measurements.

Modulus of Subgrade Reaction (k) A measure of the supporting capability of the foundation medium; obtained by measuring the penetration of a loaded, large diameter plate (30 inches); expressed in terms of the load in pounds per square inch divided by the inches of penetration. Procedures for measuring have been standardized (TxDOT 360.4) and correlations have been established with other measures.

Pavement Structure A combination of subbase, rigid slab, and other layers designed to work together to provide uniform, lasting support for the traffic load, and to distribute the load to the subgrade.

Permeability With respect to pavements, this is the rate of moisture movement through a subbase material.

Plastic Index (PI) also called plasticity The range in the water content through which a soil remains plastic and the numerical difference between liquid limit and plastic limit, as calculated according to ASTM D 4318.

Pulse Velocity The generation of waves (pulses) through the concrete to determine qualities such as: uniformity of the concrete, estimation of concrete strength, and the determination of saw-cut times.

Pumping The ejection of foundation material, either wet or dry, through joints, cracks, or along edges of rigid slabs due to vertical movements of the slab under traffic (6).

Reinforcing Steel Steel embedded in a rigid slab to resist tensile strain and the detrimental opening of cracks (1); thereby ensuring close contact between the faces of the fracture so that vertical shear transfer across the crack is preserved.

Rigid Pavement A pavement structure which distributes loads to the subgrade through a portland cement concrete slab of relatively high bending resistance (6).

Shoulder The portion of the roadway contiguous and parallel with the traveled way for accommodating stopped or errant vehicles; for maintenance or emergency use; for providing lateral support of the slab; some edge support; and for aiding surface drainage and moisture control of the underlying material.

Stabilization The modification of soils or aggregate by incorporating materials that will increase load bearing capacity, firmness, and resistance to weathering or displacement (6).

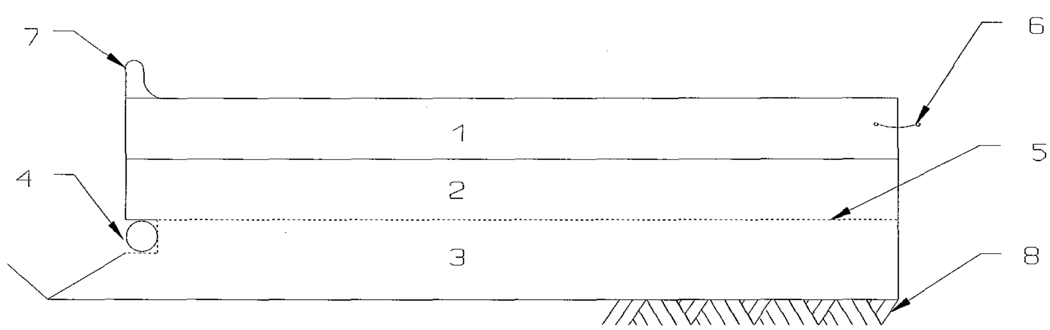
Standard Density Maximum density at optimum moisture according to ASTM D 698.

Subbase The layer or layers of specified or selected material, of designed thickness, placed on the subgrade to provide uniform support for the concrete slabs; to protect the slabs from disruptive movements of the underlying soils; and to improve drainage. The function of the subbase is elaborated in section 1.6. Use of a subbase for these purposes is highly recommended by the Federal Highway Administration.

Subgrade The top surface of a roadbed upon which the pavement structure and shoulders are constructed. The function of the subgrade is elaborated in section 1.5 (6).

Tie Bar A deformed steel bar or connector imbedded in the concrete pavement across a longitudinal joint to prevent separation of abutting slabs (6). Various proprietary devices which serve the same purpose are available, such as tie bolts or hook bolts. The tie bar should conform to the properties specified for Grade 60 in ASTM standard A 615.

Warping or Hinged Joint A transverse joint in which flexure is permitted without applicable horizontal or warping stresses movement (in relief of curling). These joints are used on pavements to control cracking at sawed locations and normally have extra reinforcing steel to promote load transfer at the joints. These joints may be alternated with the doweled joints.



1. Pavement Surface
2. Subbase
3. (Treated/Untreated) Subgrade
4. Drain
5. Geotech Fabric
6. Neoprene Joint Seal
7. Curb
8. Original Ground

Figure G-1. Proposed Typical Section for Rigid Pavement Structure.