

An **IPRF** Research Report
Innovative Pavement Research Foundation
Airport Concrete Pavement Technology Program

Report IPRF-01-G-002-03-6

Using Maturity Testing for Airfield Concrete Pavement Construction and Repair



Programs Management Office
5420 Old Orchard Road
Skokie, IL 60077

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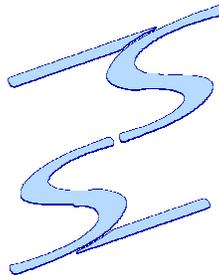
**Using Maturity Testing for
Airfield Concrete Pavement
Construction and Repair**

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March 2006

This report has been prepared by the Innovative Pavement Research Foundation under the Airport Concrete Pavement Technology Program. Funding is provided by the Federal Aviation Administration under Cooperative Agreement Number 01-G-002. Dr. Satish Agrawal is the Manager of the FAA Airport Technology R&D Branch and the Technical Manager of the Cooperative Agreement. Mr. Jim Lafrenz, P.E. is the Program Director for the IPRF.

The Innovative Pavement Research Foundation and the Federal Aviation Administration thanks the Technical Panel that willingly gave of their expertise and time for the development of this report. They were responsible for the oversight and the technical direction. The names of those individuals on the Technical Panel follow.

Mr. Robert “Murphy” Flynn
Mr. Michael Shayeson
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Dr. Bruce Brummel, P.E.

Federal Aviation Administration
The Harper Company
Cement Association of Canada
Rose Paving
FH Paschen, Inc.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Aviation Administration. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

This handbook was prepared by the following project team members:

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The project team would like to acknowledge the invaluable insights and guidance of the IPRF Program Manager, Mr. Jim Lafrenz, P.E. and the members of the Technical Panel.

The authors would like to thank Ms. Vické Adams, independent consultant, who provided exceptional assistance in the form of technical editing, proofreading, graphic design, and document formatting.

In addition, the following individuals provided insightful user-review comments that greatly improved the practicality, clarity, and quality of this handbook:

- Mr. Paul Corr, Fred Weber, Inc.
- Mr. Gary Fuselier, Metropolitan Washington Airports Authority
- Ms. Renita Mollman, P.E., Burns & McDonnell, Inc.
- Ms. Marie Torres, MRM Construction Services, LLC

The project team would also like to thank Lafarge North America Inc. for providing Type III cement and The Dolese Brothers Co. for providing concrete aggregates for the laboratory portion of this project.

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1. Executive Summary

Concrete maturity testing provides numerous benefits to airport administrators, engineers, paving contractors, and testing laboratories.. The primary benefits include:

- Better decision-making,
- Reduced runway and taxiway closure times,
- Faster construction,
- Fewer beam specimens, and
- Improved concrete quality control.

Concrete maturity enables *better decision-making* with respect to open-to-traffic decisions. This occurs because concrete maturity enables real-time, in-place flexural strength measurements that are more accurate and more cost-effective than field-cast beam specimens. The improved open-to-traffic decision-making applies not only to aircraft traffic but also to construction-vehicle traffic.

Concrete maturity results in *shorter runway and taxiway closures* as a direct result of the improved open-to-traffic decision-making. Rather than having to wait for field-cast beam specimens to reach the required strength (and the guesswork associated with when to break them), the pavement can be opened to traffic at the earliest possible moment because the in-place flexural strength can be obtained instantaneously.

Faster construction also directly results from the improved open-to-traffic decision-making. This is due to the benefits of allowing staged open-to-traffic criteria rather than the standard “14-day or 550-psi” requirements.¹ With staged open-to-traffic, the pavement can be monitored in real-time until the required flexural-strength threshold is reached for each major type of construction equipment. As such, lighter vehicles can be allowed on the pavement soon after placement, with heavier equipment being allowed somewhat later, but typically much sooner than the wait period based on conventional methods.

Concrete maturity testing can result in *fewer beam specimens* required on a project, particularly the number of field-cast beams. This is because a single maturity sensor can provide an infinite number of in-place flexural strength measurements at a given location. As such, multiple sets of beams to support open-to-traffic decisions are no longer required. In addition, alternative methods of field verification, such as splitting tensile, direct tension, or compressive strength testing can be used to further reduce the need for field-cast beams.

¹ The 2/17/89 version of Item P-501 *PORTLAND CEMENT CONCRETE PAVEMENT* (in section 501-3.21) states “The pavement will not be opened to traffic until test specimens molded and cured in accordance with ASTM C31 have attained a flexural strength of 550 pounds per square inch (3792 kPa) when tested in accordance with ASTM C78. If such tests are not conducted, the pavement shall not be opened to traffic until 14 days after the concrete was placed.”

With respect to quality, the concrete maturity method, when used as a mix-verification tool, provides the framework for an extremely effective and robust concrete quality control plan that can result in *improved concrete quality control*. This benefit is the direct result of the mix-specific nature of the method. The strength-maturity relationship for a given concrete mix is unique to that mix design. As such, the maturity method is extremely sensitive to any changes that affect the rate of strength gain or the ultimate strength of the concrete mix, such as the quality or proportioning of the raw materials. This sensitivity enables a maturity-based quality control plan to catch mix-related or batching-related errors in a matter of days or even hours rather than weeks.

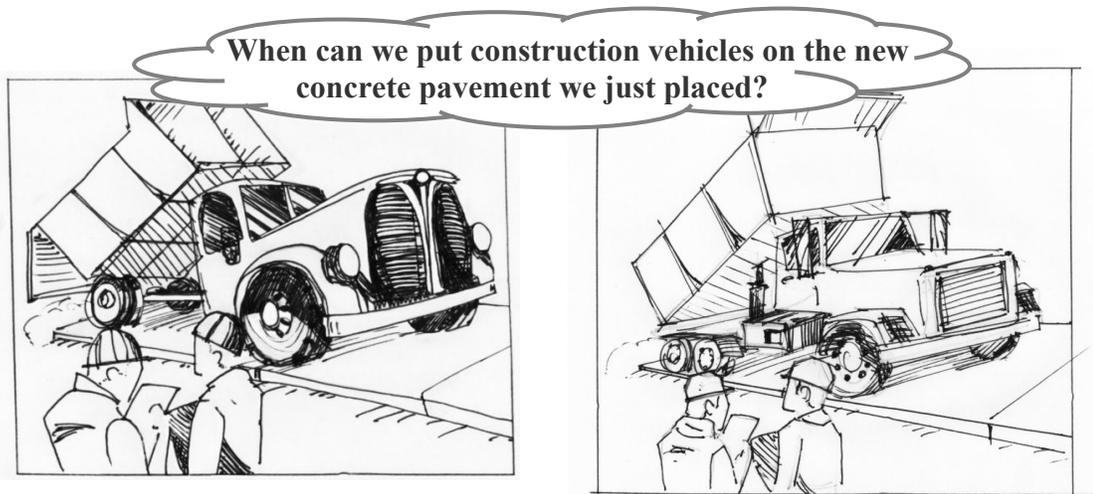
To summarize the benefits, concrete maturity empowers the field engineer and the contractor to make critical decisions based on the actual *in-place* strength of the pavement using *real-time* measurements that take into account the physical properties, dimensions, and curing conditions of the pavement structure. Figure 1.1 graphically demonstrates some of these benefits.

The maturity method is typically implemented as a four-step process.

1. An initial laboratory “calibration” to establish the unique strength-maturity relationship of each mix design,
2. Daily mix verification (which also serves as a robust quality control tool),
3. Anytime, *real-time* field measurements of actual in-place flexural strength, and
4. Monthly validation of the strength-maturity relationship (and subsequent “recalibration” whenever significant mix changes occur).

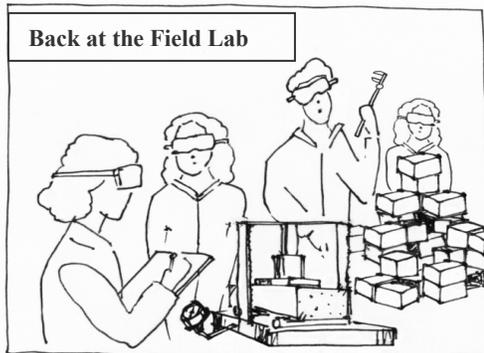
In addition to demonstrating the benefits of concrete maturity for use on airfield projects, this handbook provides:

- A brief history and overview of concrete maturity methods,
- Guidelines to help specification writers and contractors choose maturity methods and techniques for a project,
- Protocols and process flowcharts to guide new users through each step of implementation,
- Informative discussion and practical suggestions to help field personnel understand and reduce or eliminate potential sources of error associated with concrete maturity methods,
- An example case study project to clearly demonstrate the “how-to” aspects of maturity, and
- A sample guide specification to facilitate swift, yet thorough adoption of concrete maturity testing into concrete pavement contracts.

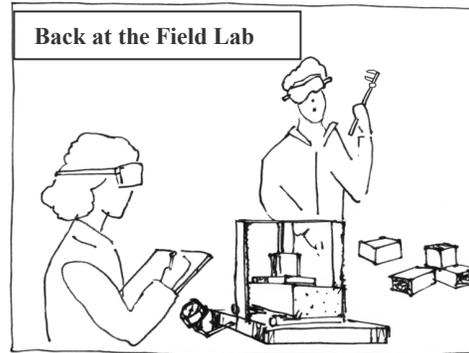


“Same as it has been since the 1950s, we have to either wait 14 days or wait until those beam specimens at the field lab reach 550 psi flexural strength.”

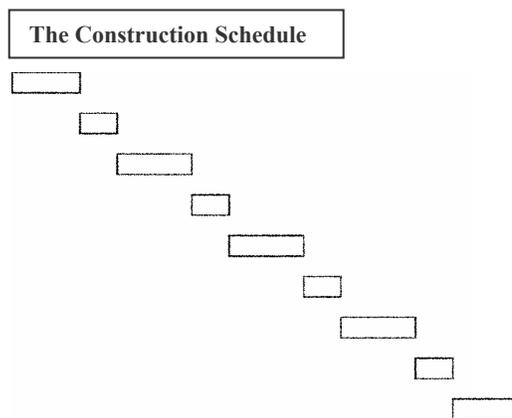
“Since we’re using maturity on this project, as soon as the in-place flexural strengths equal 117 psi for pickup trucks, 230 psi for the concrete trucks, and 397 psi for the paving equipment.”



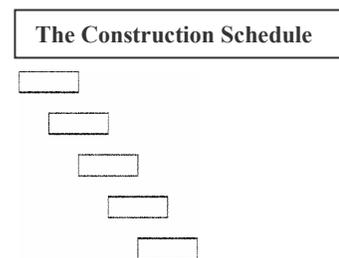
“This sure is back-breaking work. I wish there was a way to reduce the number of beam specimens we have to cast and break each day.”



“Now that we’re using maturity, we don’t have to cast or break as many beam specimens as we used to.”



“I sure wish there was a way we could speed up this construction project.”



“Maturity definitely helps our airfield construction projects proceed more quickly!”

Figure 1.1 – Benefits of using Maturity to Make Meaningful Open-to-Traffic Decisions

2. Introduction

The maturity method for determining in-place concrete strengths, when properly implemented, is a powerful tool for expediting construction and improving the quality of concrete airfield construction and repair projects. As such, maturity testing is well-suited for fast-track runway and taxiway construction, full panel replacement projects, and even “normal” airfield pavement construction. This handbook has been purposefully written to educate airport stakeholders concerning the benefits and limitations of concrete maturity methods as applied to airfield pavement projects.

2.1. *Intended Audience*

This handbook has been tailored for use by engineers, contractors, testing laboratories, and airport administrators. In particular, this document is aimed at personnel having limited experience with concrete maturity methods. As such, the manual focuses on general concepts, provides step-by-step implementation protocols, and includes a complete hypothetical “case study” example. In addition, for individuals desiring more in-depth discussion of the concepts of concrete maturity, the Appendices provide additional technical information, including a comprehensive sample guide specification.

2.2. *Purpose of the Handbook*

This handbook has been created to provide practical information regarding the application of concrete maturity methods to airfield pavement construction and repair projects, with particular emphasis on the benefits, limitations, and potential sources of error. The primary benefits include:

- Quicker opening to construction-vehicle traffic,
- Quicker opening to aircraft, and
- Improved quality control.

The purpose of this document is:

- To enable airport planners to make informed decisions about whether to use maturity on specific airfield construction projects by enabling them to more fully understand and appreciate the method, its benefits, and its limitations;
- To assist engineers, contractors, and testing laboratories in effectively implementing maturity to expedite construction and improve quality on airfield projects; and
- To provide general and specific guidance regarding how to achieve reliable and predictable results using concrete maturity methods.

2.3. *Benefits*

The primary benefits of using concrete maturity on airfield pavement projects are three-fold – opening to construction traffic, opening to aircraft, and quality control. Although these benefits can apply to all projects that implement maturity, the relative impact of each benefit will vary from project to project based on the project’s size, type, and time sensitivity. Table 2.1 provides a matrix for qualitatively comparing the benefits of

maturity with respect to the three project criteria of size, type, and time sensitivity. The comparisons are qualitative rather than quantitative and may vary depending upon an individual’s chosen definitions of “high” versus “low” payback.

With respect to project size, two categories are shown in Table 2.1 – [1] small or short-duration projects and [2] medium or large projects. With respect to project type, two categories are compared – [1] patching or single-lane slipform and [2] multi-lane slipform. Concerning time sensitivity, three levels are compared – low, medium, and high. The following subsections discuss the impact of these three project criteria on the relative magnitude of each of the three primary benefits. To facilitate cross-comparisons, each subsection includes a table similar to Table 2.1 that is tailored to specifically present the relationships between each primary benefit and the three project criteria.

Table 2.1 – Framework for Evaluating the Benefits of Maturity for Airfield Projects

		Time Sensitivity of the Project		
		Low	Medium	High
Small or Short-Duration Projects	Patching or Single-Lane Slipform			
	Mult-Lane Slipform			
Medium or Large Projects	Patching or Single-Lane Slipform			
	Mult-Lane Slipform			

Basically, concrete maturity provides the contractor and field engineer the ability to make critical decisions based on the strength of the actual *in-place* pavement based on *real-time* measurements that take into account the physical properties, dimensions, and curing conditions of the pavement structure. As such, maturity provides a simpler and more robust in-place strength measurement than conventional tests which rely upon surrogate samples that are subject to errors due to sampling, testing, handling, and differential curing conditions.

2.3.1. Opening to Construction Traffic using Maturity

On projects requiring multi-lane slipform paving, the benefits of using maturity for early and/or staged *opening to construction traffic* can be tremendous. By contrast, airfield patching and single-lane slipform paving projects using maturity for open-to-construction-traffic decisions may yield only minimal benefits. This is due to the fact that they do not usually pose a logistical problem for construction vehicle access. These tradeoffs are demonstrated in Table 2.2, which shows that the majority of the benefits derived from using maturity as an “open-to-construction-traffic” tool occurs with multi-

lane slipform projects. And, with those projects, the higher the time sensitivity of the project, the higher the payback. Table 2.2 also highlights the fact that the open-to-construction-traffic benefits of maturity apply equally well to small and/or short-duration projects as they do to medium and large projects.

Table 2.2 –The “Opening to Construction Traffic” Benefits of Maturity

		Time Sensitivity of the Project		
		Low	Medium	High
Small or Short-Duration Projects	Patching or Single-Lane Slipform	Low		
	Mult-Lane Slipform	Moderate	High to Very High	
Medium or Large Projects	Patching or Single-Lane Slipform	Low		
	Mult-Lane Slipform	Moderate	High to Very High	

2.3.2. Opening to Aircraft using Maturity

The magnitude of the benefit of using concrete maturity for *open-to-aircraft* decisions is directly related to the time-sensitivity of the project, with highly time-sensitive projects deriving the greatest benefit. This effect is depicted in **Error! Not a valid bookmark self-reference.** In general, the size and type of the project play a subdued role in terms of the benefits derived from the use of maturity for open-to-aircraft decisions. However, the size and type of a given project may play a role in determining the time sensitivity of the project. For instance, many patching projects require temporarily closing active runways and taxiways. Such closures tend to be highly time sensitive. However, this is not always the case. There could be instances where patching is being performed as part of a larger project such that the patching work is not on the critical path for the closure. In that instance, the use of maturity solely to determine when to open the pavement to aircraft may not be highly beneficial.

2.3.3. Quality Control Benefits of Maturity

The quality control benefits of maturity are available to every project, even if improving quality control is not the primary motivation for using maturity. The quality-control benefits of maturity stem from the method’s ability to quickly detect changes to the concrete mix constituents or the batching process, small or short-duration projects tend to benefit substantially less than medium or large projects. This is due to two factors. First, small or short-duration projects, by virtue of being small or short in duration, are much less likely to experience significant raw material or process changes. Second, the up-front costs (and time) associated with calibrating each mix design may not be cost-

effective for small or short-duration projects *if quality control is the sole reason for using maturity*. However, if one of the other benefits of maturity makes its use cost-effective, even on a small or short-duration project, then the quality-control benefits of the method will certainly apply.

The concrete maturity method can be used to improve quality by virtue of its extreme sensitivity to changes in the relative proportions of the mixture components and/or the quality characteristics of the raw materials (including adverse chemical interactions). As such, this sensitivity can be beneficially used as a process- and mix-verification tool to quickly flag any such changes and thus alert the contractor or field engineer concerning those changes.

Table 2.4 demonstrates the sensitivity of this benefit to project size (as explained above) and the fact that the quality-control benefits are equally advantageous regardless of project type or time sensitivity.

NOTE: Whereas the mix-verification capabilities of concrete maturity make it suitable *only when used in conjunction with companion physical strength testing*. CONCRETE MATURITY METHODS SHOULD NEVER BE RELIED UPON FOR ACCEPTANCE WITHOUT COMPANION PHYSICAL STRENGTH TESTING, such as flexural beams, compressive cylinders, or split-tensile cylinders.

Table 2.3 –The “Opening to Aircraft” Benefits of Maturity

		Time Sensitivity of the Project		
		Low	Medium	High
Small or Short-Duration Projects	Patching or Single-Lane Slipform	Low	Moderate	High to Very High
	Mult-Lane Slipform			
Medium or Large Projects	Patching or Single-Lane Slipform			
	Mult-Lane Slipform			

2.3.4. Summary of the Benefits

To summarize, the primary benefits of concrete maturity for airfield projects are threefold:

- Improving decisions regarding opening to construction traffic,
- Improving decisions regarding opening to aircraft, and
- Enhancing quality control.

Tables 2.2 – 2.4 compared the relative magnitudes of these benefits with respect to the three project criteria of size, type, and time sensitivity. Table 2.5 merges these comparisons into a single table. As such, Table 2.5 is intended to be a quick reference to help airport planners swiftly assess the relative potential benefits of using maturity on a given project.

Table 2.4 –The Quality-Control Benefits of Maturity

		Time Sensitivity of the Project		
		Low	Medium	High
Small or Short-Duration Projects	Patching or Single-Lane Slipform	Low		
	Mult-Lane Slipform			
Medium or Large Projects	Patching or Single-Lane Slipform	High to Very High		
	Mult-Lane Slipform			

Table 2.5 – Potential Payback from using Concrete Maturity for: Quality Control / Opening to Construction Traffic / Opening to Aircraft

		Time Sensitivity of the Project		
		Low	Medium	High
Small or Short-Duration Projects	Patching or Single-Lane Slipform	Quality Control Construction Aircraft	Quality Control Construction Aircraft	Quality Control Construction Aircraft
	Mult-Lane Slipform	Quality Control Construction Aircraft	Quality Control Construction Aircraft	Quality Control Construction Aircraft
Medium or Large Projects	Patching or Single-Lane Slipform	Quality Control Construction Aircraft	Quality Control Construction Aircraft	Quality Control Construction Aircraft
	Mult-Lane Slipform	Quality Control Construction Aircraft	Quality Control Construction Aircraft	Quality Control Construction Aircraft

Payback Legend: **High to Very High**
 Moderate
 Low

3. History / Overview of the Maturity Method

3.1. History of Concrete Maturity in the United States

The maturity method for measuring concrete strength was demonstrated in Europe as early as 1949 (Nurse 1949) and made its way to United States quite some time later, eventually becoming a standard practice of the American Society for Testing and Materials (ASTM) in 1987 (ASTM C1074). The heart of the method is based on the fundamental relationship between chemical reaction rates and the energy (i.e. temperature) of the molecules involved in the reaction (because chemical reactions proceed more quickly at elevated temperatures). The application of this law to the complex chemical reactions in concrete has been demonstrated time and again both in the laboratory and the field over many decades.

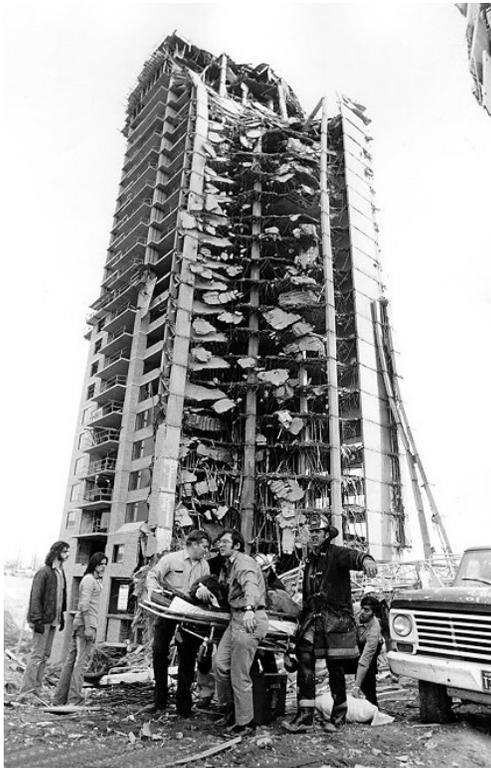


Figure 3.1: Skyline Towers Collapse, Fairfax County, Virginia (source: <http://www.fairfaxcounty.gov/fr/deptinfo/history.htm>)

A tragic display of this phenomenon occurred in 1973 in Fairfax County, Virginia when a multi-story building collapsed during construction (Figure 3.1), killing fourteen and injuring 34. The National Bureau of Standards (NBS) investigated the accident at the request of the Occupational Safety and Health Administration (OSHA). NBS investigators identified a four-day-old floor slab, which had been subjected to an average ambient temperature of only 7 °C as the most likely cause of the accident (Carino and Lew 2001). This disastrous result of the temperature-dependence of concrete strength gain and a similar accident during the construction of a nuclear power plant at Willow Island, West Virginia in 1978 (Figures 3.2 and 3.3) sparked serious examination of available methods for estimating the in-place strength of concrete during construction. As a result, the NBS identified the maturity method as a viable means for estimating the strength of concrete subjected to different curing temperatures (Carino 1984; Carino and Lew 2001). This,

in turn, led to the establishment of the world's first standard (ASTM C1074) for estimating concrete strength via the maturity method (Carino and Lew 2001).

As a part of the Strategic Highway Research Program (SHRP) in the mid-1990s, the Federal Highway Administration (FHWA) recommended maturity as an available technology for estimating in-place concrete strength development in highway structures (Carino and Lew 2001). The FHWA now routinely demonstrates the application of the

concrete maturity method to interested federal, state, and local transportation personnel via their Mobile Concrete Laboratory.

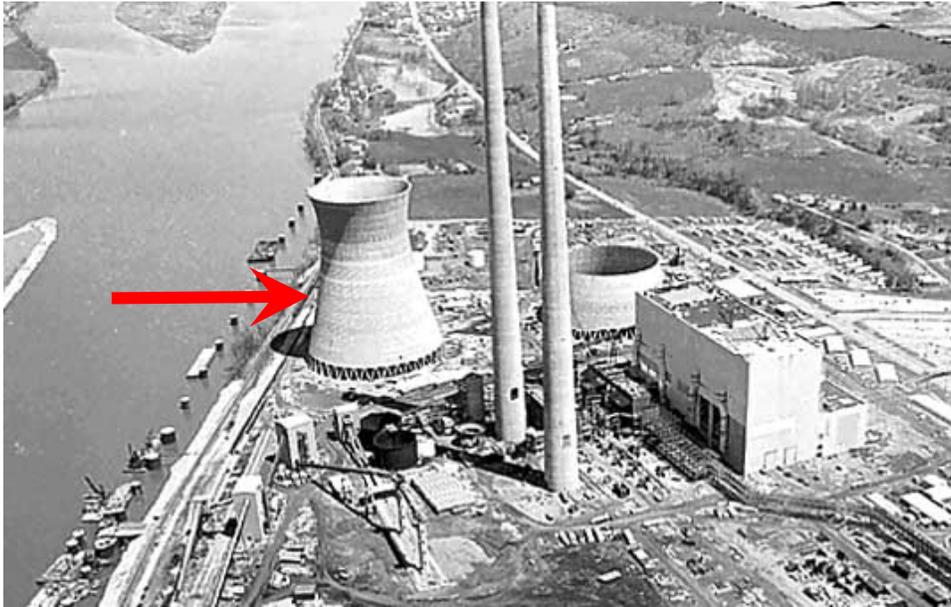


Figure 3.2 – Willow Island Collapse (Tower-1 Completed / Tower-2 under Construction, Prior to Collapse) (source: <http://www.geocities.com/pburgwva2001/willow1.html>).

(The arrow adjacent to Tower-1 shows the level that had been reached on Tower-2 when the scaffold collapsed and killed 51 workers in April 1978.)



Figure 3.3 – Portion of the Willow Island Cooling Tower Collapse (source: <http://www.geocities.com/pburgwva2001/willow1.html>)

3.2. The Theoretical Basis for Maturity

Concrete gains strength gradually over time as a result of multiple exothermic chemical reactions between water and the various cementitious and pozzolanic materials in the mix, such as Portland cement (a poly-phase cementitious material), fly ash (a pozzolanic byproduct of coal-fired power plants), blast-furnace slag (a cementitious and pozzolanic byproduct of steel production), and silica fume (a pozzolanic byproduct from the manufacture of silicon). Over time, various chemical and physical processes take place allowing these hydration reactions to occur, wherein the cementitious materials (including the pozzolanic materials) combine with water molecules to produce a complex crystalline matrix (resulting in the stiffening and hardening of the concrete). Figure 3.4 shows a magnified view of the crystalline structure of hardened cement paste.

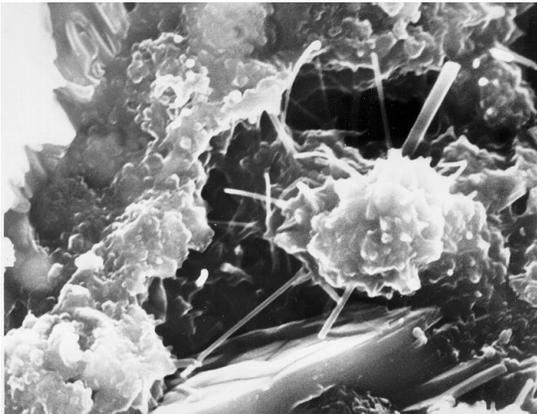


Figure 3.4 – Hardened Cement Paste (source: <http://www.abdn.ac.uk/chemistry/research/cement/>)

For a specific concrete mixture, strength at any age is related to the combined degree of hydration of the cementitious materials in the mix. The degree of hydration of cementitious materials can be measured directly by determining the degree of hydration of each individual reactive component within the mix, or indirectly by measuring a property of the concrete product as a whole (e.g. strength).

Because the rate at which hydration occurs is greatly dependent upon temperature and whereas the individual hydration reactions are exothermic, one indirect method of determining the degree of hydration is by measuring heat generation (through a process known as “calorimetry”). Also, because the rate of hydration is temperature dependent, the rate of strength development for a given concrete mixture will be a function of the internal concrete temperature. Thus, the strength of concrete depends on its time-temperature history assuming that sufficient moisture is present to feed the hydration reactions. Insufficient moisture within the concrete matrix will cause the hydration reactions and the concomitant strength development to cease (thus emphasizing the importance of timely and adequate application of “curing” compound).

The maturity concept is based on the fact that strength development, as well as all other properties that depend upon degree of hydration, can be represented by a function of the internal temperature of the curing concrete over time (Carino 1984). As such, the concept of maturity provides a method wherein the in-place strength of the concrete can be instantaneously determined without conducting physical and destructive tests (Mindess and Young 1981).

4. Calculating Maturity

Before any use of the maturity concept can be applied to a particular situation, a mathematical function that can accurately relate time and temperature to strength must be adopted and implemented. Such mathematical functions are commonly referred to as maturity functions. Numerous maturity functions have been formulated over the past several decades.

In 1987, the American Society for Testing and Materials (now ASTM International) published a standard practice for determining the strength of concrete using maturity methods (ASTM C1074). The practice requires a calibration procedure to establish the unique strength-maturity relationship for a given concrete mix. The resultant strength-maturity relationship can then be used in conjunction with field maturity values to determine in-place concrete strength. The maturity values are derived from periodic temperature measurements of the in-place concrete. As a part of the ASTM C1074 standard practice, ASTM recognizes two different maturity functions—Nurse-Saul and Arrhenius.

The Nurse-Saul maturity function (Equation 4.1) assumes the chemical reaction rate in concrete increases linearly with temperature. By contrast, the Arrhenius method expresses this relationship as an exponential function (Equation 12.1). Whereas real-world chemical reactions do in fact follow an exponential rate law, the Arrhenius method is considered theoretically more “correct” than Nurse-Saul. However, the exponential nature of the Arrhenius equation can cause extreme overpredictions of concrete strength under certain unpredictable and uncontrollable conditions. Detailed discussion of the Arrhenius maturity function is beyond the scope of this manual.

The Nurse-Saul method can also exhibit overpredictions under certain conditions. However, when using Nurse-Saul, these conditions can be controlled so as to virtually eliminate this occurrence. More detailed discussion of this can be found in the discussion on datum temperature contained in Appendix B.

4.1. The Nurse-Saul Maturity Function

In 1949, R. W. Nurse proposed a method to estimate the strength gain of concrete based on a linear equation relating hydration rate to temperature. In 1951, A. G. A. Saul linked this maturity function to compressive strength in what he called the law of gain of strength with maturity:

Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make that maturity.

In recognition of the early work of these pioneers, Equation 4.1 is commonly referred to as the Nurse-Saul maturity function.

$$M = \sum_0^t [\max[0, (T - T_o)]] \cdot \Delta t \quad \text{Equation 4.1}$$

where:

M = maturity index, °C-hours,

T = average concrete temperature, °C, during the time interval Δt ,

T_o = datum temperature, °C,

t = elapsed time, hours, and

Δt = time interval, hours.

The index computed by Equation 4.1 is known by many different terms, such as the maturity index value; the temperature-time factor (TTF), or simply the “maturity” of the concrete. Equation 4.1 is based on the assumption that the initial rate of strength gain (during the acceleratory period that follows setting) is a linear function of temperature (Carino 1984, 1991). The net effect of Equation 4.1 is that the maturity, or TTF, for the in-place concrete is the area under the curve (down to the datum temperature) when internal concrete temperature is plotted versus time (with temperature along the y-axis and time on the x-axis). Figure 4.1 shows this graphically.

Throughout this handbook, maturity will only be referenced in the metric units of °C-hours (sometimes shown by the shorthand notation “CH”). The rationale for this decision is as follows:

1. °C-hours has become the defacto standard throughout much of the concrete construction industry,
2. The use of different units, such as °F-hours, can lead to significant and dangerous errors if the units are inadvertently switched between calibration and field measurements, and
3. Whereas the units of “temperature times time” have no real physical meaning (other than the area on a time-temperature chart), conversion to another system of units provides no substantial benefit.

4.2. Datum Temperature

The theoretical explanation of datum temperature is “the temperature for a given concrete mix below which all hydration reactions cease.” In theory, when the temperature of the concrete falls below the datum temperature, no additional strength gain occurs and, therefore, no net gain in maturity is recorded by Equation 4.1. While other datum temperatures have been proposed, the following is recommended:

- Use a 5 °C datum temperature, and
- Cure standard maturity calibration specimens in accordance with ASTM C192 (i.e. at 23 ± 2 °C).

The justification for this recommendation is described in the discussion on datum temperature contained in Appendix B.

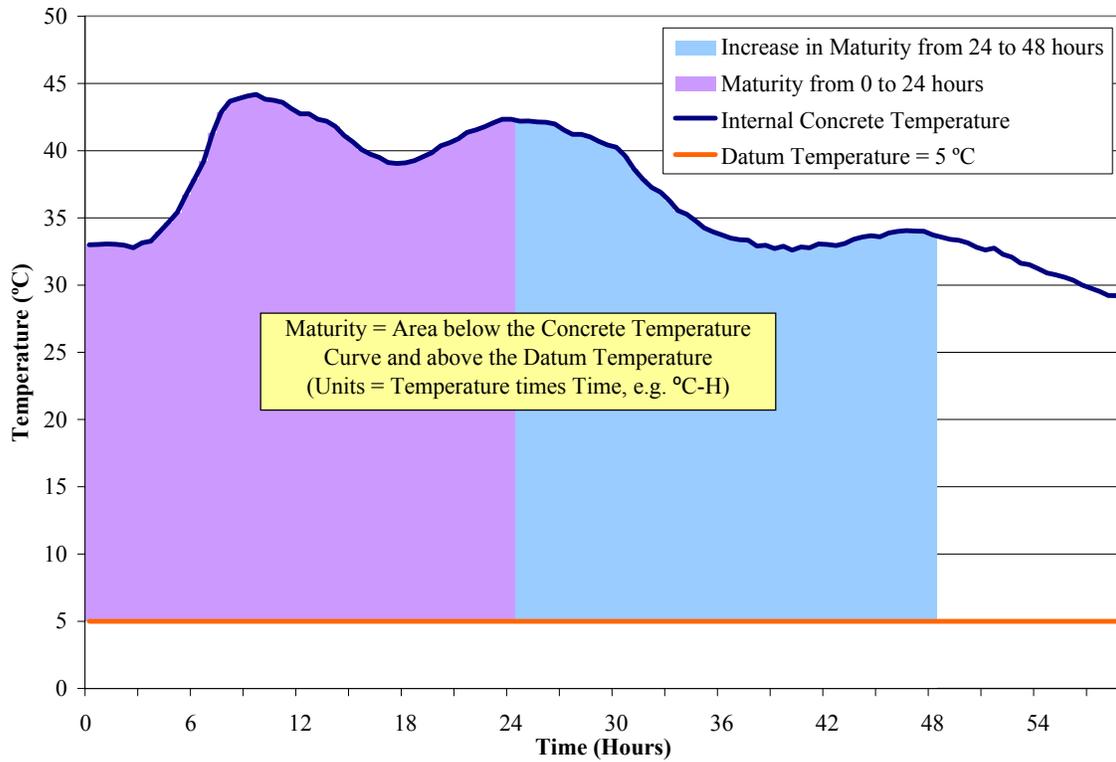


Figure 4.1 – Example Concrete Temperature Profile to Graphically Demonstrate Nurse-Saul Maturity Calculations

5. Maturity Measurement Equipment

Maturity measurement equipment has evolved from simple manual systems to complex electronic systems to advanced micro-electronic systems. A variety of systems currently exist, providing varying degrees of accuracy, automation, security, and data-integrity. Following a description of the basic components that make up all maturity systems, several different “types” of systems are discussed. The systems are categorized into two distinct “generations”. The distinction between first and second generation systems lies in the data recording and storage technology. More specifically, the distinction lies in the *location* where the data are recorded and stored. All first-generation systems store their data external to the concrete pavement or structure they are monitoring. Second-generation systems, on the other hand, all store temperature and/or maturity data within the concrete itself, thus protecting both data and equipment from external hazards.

5.1. Maturity System Components

In general, a concrete maturity system consists of the following components:

- temperature sensors,
- electronic data storage,
- a means of calculation, and
- a user interface.

The combination of these various system components into complete systems determines the overall functionality, costs, and relative benefits of each system. The following sections describe six different configurations of maturity systems and discuss the relative merits and limitations of each.

5.1.1. Temperature Sensors

Two different types of temperature sensors are typically used in maturity measurement equipment – thermocouples and thermistors. Whichever type of temperature sensor is used, it should comply with the ASTM C1074 standard practice, which states that the temperature measurement system shall be accurate to within ± 1 °C.

A thermocouple is composed of two dissimilar metal wires welded together at one end (referred to as the “hot” junction) and connected to an electrical circuit at the other end (referred to as the “cold” or reference junction). The wires produce a voltage difference whenever the temperature of the hot junction is different from the temperature of the cold junction. This voltage corresponds merely to the temperature *differential* between the hot and cold junctions. To determine the *actual* temperature at the hot junction, a second temperature measurement device (typically a thermistor) must be used to determine the actual temperature at the cold junction. The cold junction temperature measurement is then used in conjunction with the temperature differential measured by the thermocouple to determine the actual temperature at the hot junction.

Whereas thermocouple-based systems require two separate temperature-measurement devices, the overall temperature accuracy of the *system* must be assessed, not just the

stated accuracy of the individual components. For this reason, in order to obtain precise and unbiased temperature readings, each spool of thermocouple wire should be calibrated for the specific instrument channel to which it will be connected.

Thermistors are temperature-sensitive resistors. With thermistors, the impedance of the resistor changes as its temperature changes. To measure the actual temperature of the thermistor, its resistance is measured and then converted to temperature using a pre-established resistance-to-temperature conversion curve. This conversion calibration is typically performed by the manufacturer of the thermistor. As such, unlike thermocouple-based systems, maturity systems relying upon thermistors do not typically require any additional temperature calibration to meet their stated accuracy levels.

First-generation maturity sensors (depicted graphically in Figures 5.1 to 5.3) may use thermocouple- or thermistor-based temperature sensors (depending upon the make and model). However, second-generation maturity systems (shown in Figures 5.4 to 5.6) are typically only available as thermistor-based systems.

5.1.2. Electronic Data Storage

In addition to type of sensor, maturity systems can be classified into two groups related to how they store temperature and/or maturity data – those that store the data externally and those that store the data within the concrete itself. First-generation maturity systems (Figures 5.1 to 5.3) store the data externally, whereas second-generation systems (Figures 5.4 to 5.6) are those that provide electronic storage of temperature and/or maturity data within the concrete. The primary distinction between these two types involves the security and protection of the devices and their stored data (first-generation devices tend to be much more susceptible to theft, vandalism, sabotage, weather, construction vehicles, and other job-site hazards that frequently result in loss of data, equipment, or both). In addition, the following issues warrant consideration with respect to data storage:

- Data integrity,
- Accessibility,
- Ease-of-retrieval,
- Time required to access the data,
- Time interval between temperature measurements,
- Time interval between stored maturity values, and
- The extent to which additional project-, location-, or mix-specific data can be stored alongside the maturity data.

5.1.3. Means of Calculation

The means of calculation for maturity systems can be broken down into two categories – automated and manual, with most modern systems being fully automated. In addition, automated systems can be further subdivided into two groups – those that calculate maturity *outside* the concrete and those that calculate maturity *inside* the concrete.

Some automated devices perform calculations using both the Nurse-Saul and Arrhenius maturity functions while some devices will only calculate maturity using one equation or the other. In addition, some systems allow user input of the datum temperature (or activation energy when Arrhenius is used) while others are preset with a fixed value that cannot be changed by the end user.

For those systems that store temperature data within the concrete but perform the maturity calculations outside the concrete, a delay of several seconds or even minutes may be encountered as the user waits for the temperature data to be uploaded from the data storage device and for the handheld reader to perform the maturity calculations. The length of the delay depends upon the amount of data being transferred and the data transfer rate. By contrast, those systems that calculate maturity directly within the concrete can provide an instantaneous readout of the current maturity value. Similarly, those systems that calculate maturity external to the concrete via a continuous one-to-one wired connection also provide an instantaneous readout of maturity. Instantaneous maturity readings can also be obtained from wireless systems that have adequate range to remain continuously connected to the reader or to a base station.

5.1.4. User Interface

Available user interfaces for maturity systems include handwritten sheets, “permanently-attached” external displays, handheld readers, and desktop computers. Handwritten sheets are typically only used when the maturity calculations are performed manually. “Permanent” external displays are only available on those systems that remain continuously connected to the embedded sensors. Handheld readers are those that can be connected at will to an infinite number of embedded sensors. In addition, most systems at some point also provide the ability to view the data on a desktop computer. The ease with which the data can be transferred from the initial electronic data-storage location to a desktop computer varies with the configuration of the system and its communication interfaces.

5.2. *First-Generation Maturity Systems*

First-generation maturity systems can be grouped into three categories as follows:

- The Manual Method,
- External Data Loggers, and
- External Maturity Computers.

The following paragraphs provide in-depth discussion of the features, benefits, and limitations of each.

5.2.1. The Manual Method

The manual method of implementing concrete maturity (Figure 5.1) requires little more than a temperature probe, a notebook, and a calculator (and a lot of manual effort). With the manual method, the following procedure is common:

1. a wired temperature sensor is embedded into the concrete;

2. a single handheld “temperature reader” is periodically connected to the sensor to measure the temperature of the concrete;
3. each temperature reading is manually recorded in a notebook;
4. when maturity readings are desired:
 - a. the temperature data are tabulated from the notebook,
 - b. maturity values are calculated either manually or with a spreadsheet software package.

This configuration is extremely labor intensive, especially if the recording requirements of ASTM C1074 are adhered to (i.e. at least every ½ hour for the first 48 hours).

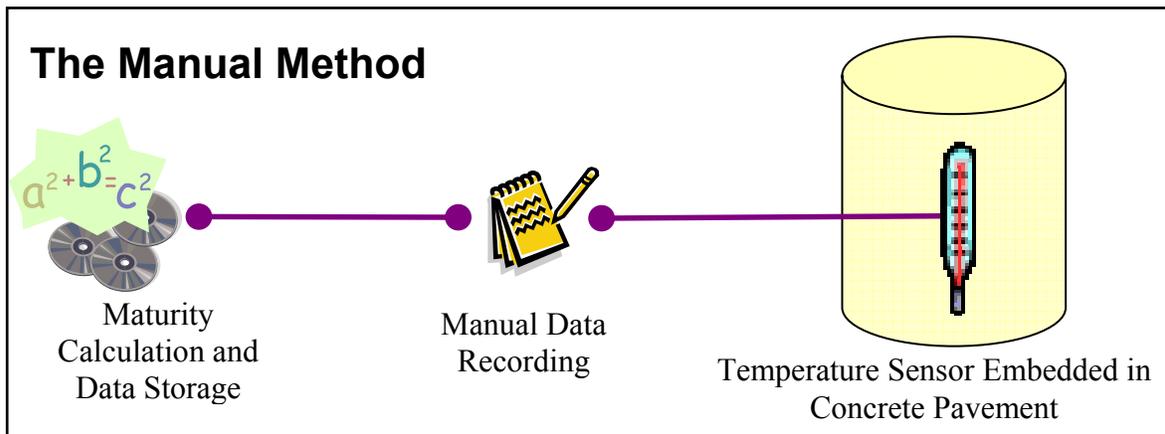


Figure 5.1 – First-Generation Maturity Systems / The Manual Method

5.2.2. External Data Loggers

External data loggers (Figure 5.2) provide a step forward in ease of use over the manual method. Systems that use external data loggers automatically record the concrete’s internal temperature over time using an external data storage device. The following is a typical procedure for this configuration:

1. a wired temperature sensor is embedded into the concrete;
2. an external datalogger is “continuously” attached to each temperature sensor, continuously measuring and recording concrete temperature;
3. when the current maturity reading is desired or when the historical temperature and maturity data are desired
 - a. each datalogger is disconnected from its temperature sensor (a new datalogger must be immediately connected if future maturity readings will be needed at that location);
 - b. the temperature data are downloaded from the dataloggers to a computer;
 - c. software on the computer calculates and displays maturity based on the temperature data from each datalogger.

As with the manual method, systems using external data loggers typically require physically transporting of the temperature data. For instance, the user may have to disconnect the data logger from the temperature sensor, transport the data logger to a computer, upload the temperature data to the computer, then wait for the maturity software to calculate and display the current maturity value. This can cause considerable delays in obtaining current maturity readings. Another disadvantage with external data loggers involves the fact that without special precautionary measures, dataloggers can be inadvertently switched whenever multiple locations are being checked at the same time, which would produce erroneous and potentially dangerous results. A peculiarity of most systems that use external data loggers is that whenever a data logger is removed to check maturity at a given location, another data logger must be reinstalled if any future maturity readings will be needed at that location.

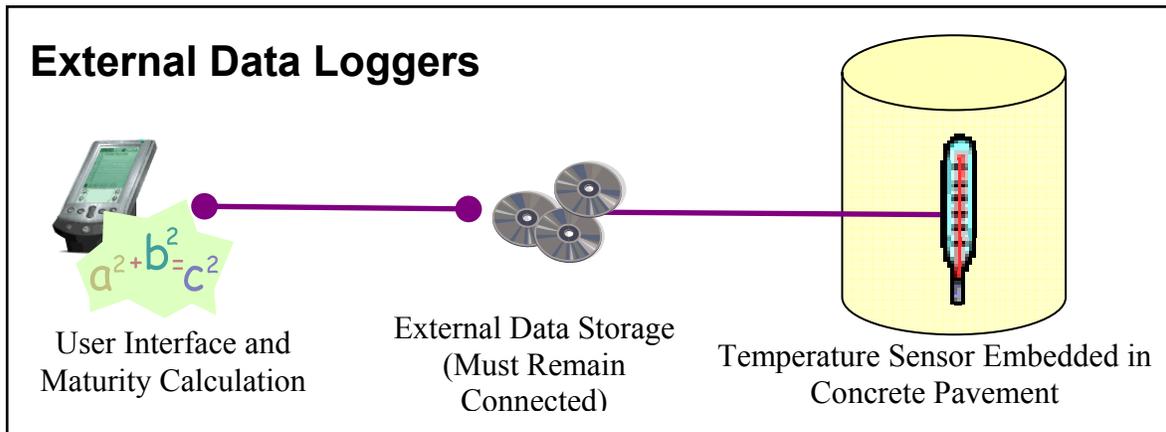


Figure 5.2 – First-Generation Maturity Systems / External Data Loggers

5.2.3. External Maturity Computers

External maturity computers (Figure 5.3) represent yet another step forward in terms of automation of maturity calculations and strength-from-maturity measurements. With external maturity computers, the maturity calculations are performed on-site by the use of a maturity computer that remains continuously connected to the embedded temperature sensor. The typical procedure for external maturity computers is as follows:

1. a wired temperature sensor is embedded into the concrete;
2. an external maturity meter is continuously attached to each temperature sensor (via a permanent, “fixed” connection – can have multiple channels);
3. the maturity meter continuously measures concrete temperature and calculates, displays, and records concrete maturity readings.
4. (optional feature) when the historical temperature and maturity data are desired; the temperature data are downloaded from the maturity meter to a PC or printed directly from the maturity meter.

The primary advantage of external maturity computers over the manual method and external data loggers lies in the fact that an instantaneous maturity reading can be obtained at any time. However, external maturity computers share a disadvantage with

external data loggers in that an external piece of equipment, in this case the maturity computer, must remain continuously connected to the temperature sensor, thus being subject to theft or damage due to vandalism, sabotage, weather, construction vehicles, and other job-site hazards.

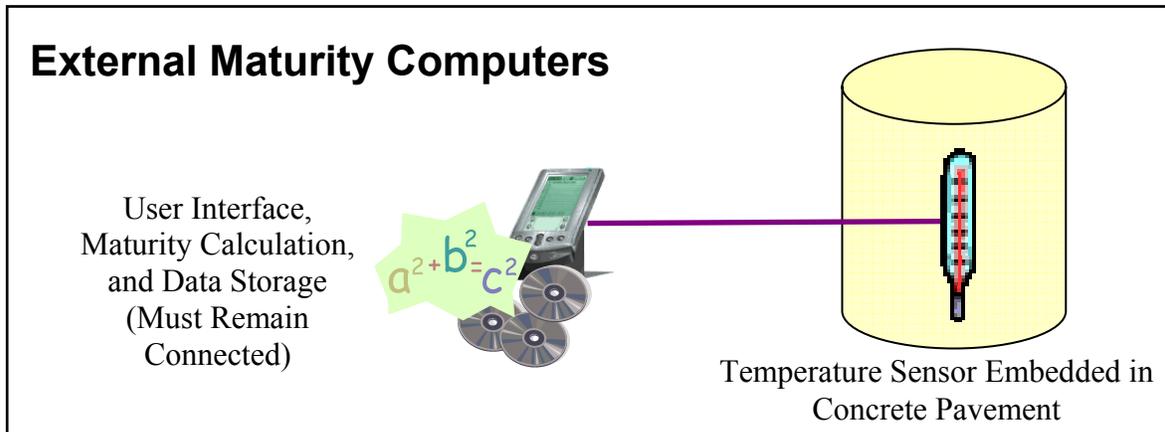


Figure 5.3 – First-Generation Maturity Systems / External Maturity Computers

5.3. Second-Generation Maturity Systems (*Internal Data*)

Second-generation maturity systems represent a major shift in technology for implementing concrete maturity. The major distinction with second-generation systems lies in their reliance upon embedded data-logging technology. This technology enables second-generation systems to provide on-site, anytime, real-time maturity readings without the need for permanently-affixed external devices (i.e. no external boxes).

Second-generation maturity systems can be grouped into three categories as follows:

- Internal Data Loggers,
- Internal Maturity Computers, and
- Internal Wireless Data Loggers.

The onset of second-generation systems played a major role in the adoption and implementation of concrete maturity methods in the United States. Although the maturity method for determining in-place concrete strength was originally demonstrated as early as 1949, first-generation systems tended to be too costly and/or cumbersome due to the labor-intensive nature of the manual method or the need for multiple external devices with automated methods. In addition, the external devices were prone to theft and damage, thus further increasing the implementation cost. By contrast, the Second Generation systems provide automated maturity calculations in conjunction with complete freedom from permanently-affixed external devices. And, whereas second-generation systems allow a single external device to interrogate numerous embedded sensors, the overall cost of implementation can be considerably less with Second second-generation maturity systems, especially when multiple locations need to be monitored simultaneously.

The following paragraphs provide in-depth discussion of the features, benefits, and limitations of each.

5.3.1. Internal Data Loggers

With internal data loggers (Figure 5.4), a temperature sensor and datalogger are embedded in the concrete and a handheld reader is used to download the temperature data and calculate maturity. The procedure is as follows:

1. a wired sensor (comprising a temperature sensor and datalogger) is embedded into the concrete;
2. a handheld reader is temporarily connected to initiate and activate the sensor;
3. the sensor continuously measures and records concrete temperature data;
4. when the current maturity reading is desired or when the historical temperature and maturity data are desired
 - a. a handheld reader is connected to the sensor,
 - b. the temperature data are downloaded from the embedded sensor to the reader,
 - c. the reader displays current temperature,
 - d. software on the reader calculates and displays current maturity (after all the temperature data are downloaded)
 - e. the historical data can be viewed on the reader, and
 - f. the historical data can be downloaded from the reader to a PC.

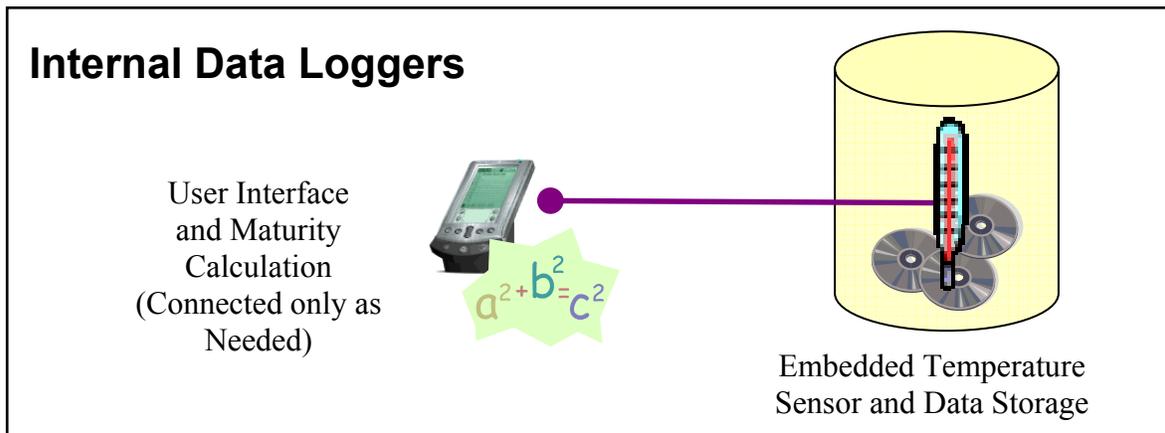


Figure 5.4 – Second-Generation Maturity Systems / Internal Data Loggers

The major advantage of internal data loggers lies in the fact that real-time maturity readings can be obtained on-site at any time without the need for an external device being continuously connected to the sensor, thus safeguarding the maturity equipment as well as the maturity data. A potential disadvantage with internal data logger systems deals with the potential time delay in obtaining a current reading. If the amount of logged temperature data is considerable, the user may have to wait up to a few minutes to obtain a current maturity reading.

5.3.2. Internal Maturity Computers

Internal maturity computers (Figure 5.5) represent yet another technological step forward in that the maturity calculations themselves can be performed within the concrete itself. As such, the user can obtain a current maturity reading on-site at any time without delay. This is due to the fact that the maturity calculations have already been performed and therefore only the current reading needs to be retrieved from the embedded datalogger. However, most internal maturity computers also provide the capability of downloading the temperature and maturity history if the user so desires. In this instance, the user must wait for the data to download just as with internal data logger systems. The steps for using internal maturity computers are as follows:

1. a wired sensor (comprising a temperature sensor, microprocessor, and datalogger) is embedded into the concrete;
2. a handheld reader is temporarily connected to initiate and activate the sensor;
3. the sensor continuously measures and records temperature data;
4. the sensor continuously calculates and records maturity values;
5. when only the current temperature or maturity value is desired;
 - a. a handheld reader is connected to the sensor, and
 - b. the reader displays current temperature and maturity;
6. when historical temperature and maturity data are desired
 - a. a handheld reader is connected to the sensor,
 - b. the temperature and maturity data are downloaded from the embedded sensor to the reader,
 - c. the historical data can be viewed on the reader, and
 - d. the historical data can be downloaded from the reader to a PC.

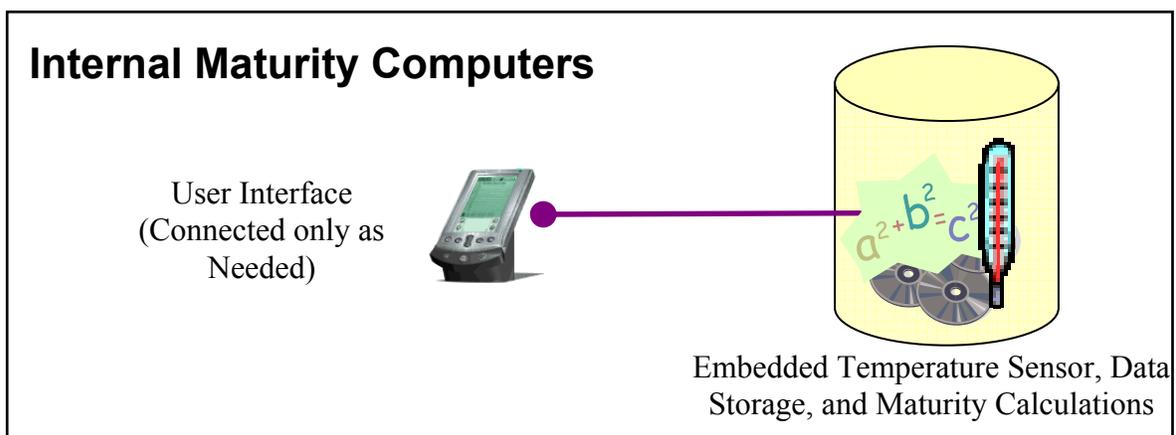


Figure 5.5 – Second-Generation Maturity Systems / Internal Maturity Computers

5.3.3. Internal Wireless Data Loggers

Internal wireless data loggers (Figure 5.6) also represent a technological step forward in that the temporary wired connections of internal data loggers or internal maturity computers can be replaced with a temporary (or, in some cases, permanent) *wireless* connection. The major advantage of this configuration over all others is the lack of exposed wires from the embedded sensors. However, wireless systems tend to be more expensive than comparable wired systems. In addition, limited range and excessive power consumption can limit the feasibility of such systems. The procedure for using an internal wireless data logger system is as follows:

1. a wireless sensor (comprising a temperature sensor and datalogger) is embedded into the concrete;
2. a handheld reader is temporarily wirelessly connected to initiate and activate the sensor;
3. the sensor continuously measures and records concrete temperature data;
4. when the current maturity reading is desired or when the historical temperature and maturity data are desired
 - a. a handheld reader is wirelessly connected to the sensor,
 - b. the temperature data are downloaded from the embedded sensor to the reader,
 - c. the reader displays current temperature,
 - d. software on the reader calculates and displays current maturity (after all the temperature data are downloaded)
 - e. the historical data can be viewed on the reader, and
 - f. the historical data can be downloaded from the reader to a PC.

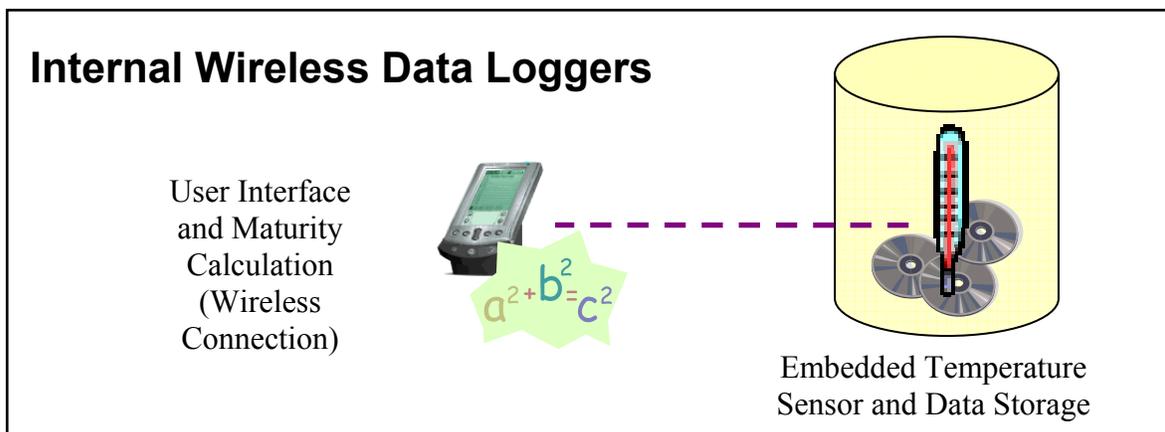


Figure 5.6 – Second-Generation Maturity Systems / Internal Wireless Data Loggers

6. Using Concrete Maturity on Airfield Pavement Projects

Implementation of concrete maturity on airfield construction projects will be most effective when introduced during the project planning stage. First and foremost, the contractor, field engineer, and testing laboratory personnel all must have a good working knowledge and understanding of the method and an appreciation for its limitations and potential sources of error. As such, a considerable amount of education and familiarization with the method may be required. In addition, whereas the method necessitates significant up-front testing prior to field implementation, proper time and attention must be given to this requirement during the planning stage. Maturity is most beneficial and impactful when it is included as part of the initial project plan, actively incorporated into the initial construction schedule, and made an integral part of the contractor's quality control program.

This section enables airport planners to proactively incorporate maturity into new airfield construction projects by providing the rationale for implementing concrete maturity methods on airfield projects.

6.1. Measuring Flexural Strength using Maturity

In 1987, when ASTM developed its standard practice for using concrete maturity to determine in-place strength (C1074), the method was only applied to the determination of concrete *compressive* strength. However, in 2004, ASTM C1074 was revised to include the application of concrete maturity for determining in-place flexural strength (in conjunction with ASTM C78).²

Determining in-place flexural strength using the concrete maturity method involves a four-step process. The first two steps are necessary before any in-place strength measurements can be obtained. Step 1 sets the stage by enabling accurate, real-time, in-place flexural strength measurements and Step 2 provides the framework for a robust quality-control mechanism to quickly catch undesirable changes to the concrete and to help ensure the veracity of the anytime, real-time flexural-strength-from-maturity measurements.

1. Due to the mix-specific nature of the method, a laboratory calibration must be performed for each mix design to establish each unique strength-maturity relationship.
2. Daily mix verification is required to verify that concrete incorporated into the project is representative of the concrete used to establish the strength-maturity relationship. In addition, this mix-verification process will quickly identify any adverse changes that might occur with the batching procedures or the raw materials.

² Concrete flexural strength has been shown to exhibit considerable sensitivity to the temperature of the specimens at time of test. As such, compensation for this potential source of error is recommended whenever elevated in-place concrete temperatures exist. Additional discussion on this topic can be found in Section 9.

3. Using the strength-maturity relationships established for each mix design, anytime, real-time field measurements of in-place flexural strength can be performed (using in-place maturity measurements in conjunction with the strength-maturity relationship for the mix as established during Step 2).
4. Monthly validation testing is necessary to periodically confirm the validity of the original strength-maturity relationship for each mix design. The purpose of this validation is to determine whether subtle yet significant changes in the raw materials or the batching process may have occurred. In addition, this step should be performed whenever known process or raw materials changes occur or if verification testing identifies the likelihood that such changes have occurred.

6.1.1. Laboratory “Calibration”

The calibration for each specific mix design is normally conducted in a laboratory setting. However, the concrete used for the calibration batch(es) can be produced either in the laboratory or in the field. Irrespective of how the concrete is batched, the calibration specimens should be cured under controlled temperature and humidity conditions (as specified in ASTM C192). The reason for this requirement is explained in the discussion on datum temperature contained in Appendix B.

The calibration typically involves casting sixteen or more specimens from a single batch of concrete, instrumenting one of the specimens with maturity sensors, then testing groups of specimens at different ages (with each group representing a different maturity level as shown in Figure 6.1). As each group is tested, the average strength of the specimens is plotted versus their average maturity. After all the specimens have been tested and all the strength-versus-maturity data plotted, a strength-maturity relationship curve can be drawn through the data as shown in Figure 6.1. Line segments connecting the data points will generally follow a straight line or a slightly bowed or S-shaped curve on a semi-log scale.

In order to further reduce the number of field-cast beams required for a project, a dual-calibration can be performed wherein both beam specimens and an alternative measure of concrete strength, such as splitting tensile (ASTM C496), direct tension (ASTM C1583), or compressive strength (ASTM C39) are tested at different maturity levels. When such a dual calibration is implemented, the alternative measure can then be used for field verification. A demonstration of the benefits of using direct tension for field verification of flexural strength was conducted in 2004 (Troost 2004). The example case study project detailed in Section 10 demonstrates the use of compressive-strength testing for field mix verification.

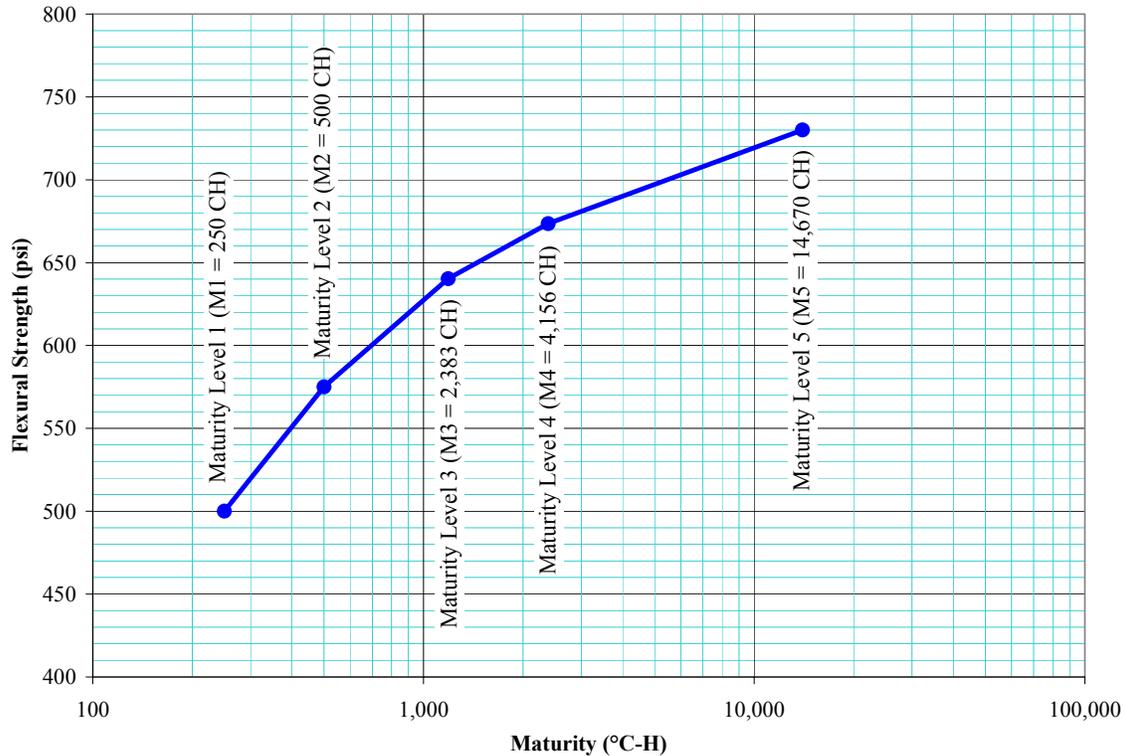


Figure 6.1 – Example Strength-Maturity Relationship

6.1.2. Daily Mix Verification

The field placements of maturity sensors should be frequently coupled with field casting of a set of verification specimens, one of which is instrumented with a maturity sensor. These verification specimens are then tested at an appropriate time, anywhere from a few hours to several days after casting depending upon the characteristics of the mix and the needs of the project. When the verification specimens are tested for strength, their resulting maturity is also recorded. This maturity-versus-strength value is then compared back to the original strength-maturity relationship curve for that concrete mix. If the verification point falls close to the strength-maturity relationship curve, the concrete at that particular placement has been verified. If the new point does not compare favorably with the original curve, something has most likely changed with the mix proportioning or the constituent raw materials. When this occurs, an immediate evaluation of the batching process and raw materials should be conducted so that the source of the change can be identified and corrected. If the root cause cannot be discovered or mitigated, a new strength-maturity relationship may need to be established.

6.1.3. Field Measurements

After the strength-maturity relationship has been established for a given concrete mix design, field measurements of maturity and strength-from-maturity can be performed for that mix. Field measurements involve placing maturity sensors within the pavement and periodically monitoring the subsequent strength gain of the concrete using those sensors. Whereas many different types of maturity measurement devices exist, the exact nature of this activity will vary. A common method is to read the maturity value via a handheld readout connected to the sensor, and then convert the maturity readout to strength via the strength-maturity relationship curve. Figure 6.2 shows this activity. Some devices can be preprogrammed with the specific strength-maturity relationship information for a given mix design and thus provide a direct readout of strength.



Figure 6.2 – Viewing and Downloading Maturity Data in the Field

6.1.4. Monthly Validation of the Strength-Maturity Relationship

Due to the mix-specific nature of the maturity method, any adjustments to the mix design run the risk of invalidating the previously-determined strength-maturity relationship curve. Technically, any such changes would necessitate recalibrating the strength-maturity relationship for the new mix design. However, a simpler alternative involves conducting a two-point validation whenever minor adjustments to the mix design are needed. A sample protocol and flowchart for implementing a two-point validation are provided in Section 7.4. The procedure essentially involves bracketing a desired maturity value with a two-point strength-maturity curve for the new mix. If this two-point calibration compares favorably to the previous strength-maturity relationship curve, the previous curve can be used with the adjusted mix.

6.2. Realizing the Benefits of Maturity on Airfield Projects

6.2.1. Using Maturity for Open-to-Traffic Decisions

Concrete maturity is extremely beneficial for open-to-traffic decisions. This benefit emerges from the fact that the flexural strength of the actual in-place pavement can be determined using real-time measurements that take the physical properties, dimensions, and curing conditions of the pavement into account, without the need for excessive numbers of field-cast beams. This ensures optimal timing for open-to-traffic decisions, whether construction traffic or aircraft. As such, the *anytime, real-time* nature of flexural-strength-from-maturity measurements greatly facilitates open-to-traffic decision-making. Using maturity for open-to-traffic decisions is accomplished by pre-determining

the open-to-traffic strength criteria, then simply monitoring the in-place pavement structure until the required strength is achieved.

Historically the Federal Aviation Administration (FAA) has required attainment of 550 psi flexural strength (or a 14-day wait) prior to opening a new concrete pavement to aircraft or construction vehicles (irrespective of the pavement thickness and support conditions and irrespective of the vehicle). However, this requirement was based on the use of beam specimens subject to different curing temperatures and curing conditions than those experienced by the actual pavement. In that circumstance, such extreme conservatism may be warranted.

Concrete maturity methods enable a reliable assessment of in-place strength which allows open-to-traffic decisions based on the *actual loads and stresses* imposed by the specific vehicles needing access to the pavement. However, if the actual tensile strength of the concrete is less than about 200% of the actual tensile stresses due to the applied load, fatigue damage will occur to the pavement. In recognition of this fact, the FAA would like to see a 250% safety factor before allowing traffic on newly-placed concrete pavements. In keeping with this desire, the examples throughout this handbook use a factor of safety multiplier of 2.5. In other words, if the maximum tensile stress imparted to the pavement due to a particular vehicle is 100 psi, that vehicle would not be allowed on the pavement until the concrete has achieved a flexural strength of at least 250 psi (as measured using maturity).

As such, maturity is particularly well-suited for accelerating airfield pavement projects by facilitating open-to-construction-traffic decision-making. In addition, the anytime, real-time nature of maturity makes it *uniquely* suited for *staged* open-to-construction-traffic decision-making. Under this scenario, a different threshold flexural strength value can be determined for each of the major types of construction equipment needing access to the pavement structure. These thresholds are pre-calculated based on pavement thickness, support conditions, and equipment footprints and contact pressures.³ As such, each type of vehicle or equipment can be allowed onto the pavement at the optimal time without risking damage to the pavement and without the need to cast and break a number of beam specimens.

6.2.2. Using Maturity as a Quality Control Tool

The concrete maturity method can be implemented as a powerful quality control tool in that contractors can rapidly identify major deviations from the specified mix designs (within a matter of hours or days after placement rather than several weeks later) and thus take corrective actions in a timely manner. Also, rather than using field-cast beams tested in accordance with ASTM C78, the verification testing itself can be performed using alternative methods of verifying physical strength, such as splitting tensile (ASTM C496), direct tension (ASTM C1583), or compressive strength (ASTM C39) testing. In

³ Two sample methods for determining stresses in a pavement slab due to different vehicles and equipment configurations are presented as Appendices C & E with corresponding example calculations provided in Appendices D & F.

addition, the power of the aforementioned quality control protocol can be greatly expanded through the application of statistical process control (SPC) techniques.⁴

Each concrete mix design has a unique strength-maturity relationship and any batch of concrete that deviates from that mix design may not follow the same strength-maturity relationship curve. This mix-specific nature of the maturity method represents a significant limitation in that the reliability of the strength-from-maturity determinations is directly affected by the variability of and any changes to the batching procedures or raw material characteristics.

This is due to the fact that any changes to the mix that affect the strength of the resulting concrete *or the rate of strength gain* will most likely alter the strength-maturity relationship as well. For instance, a significant change in the relative *proportions* of the raw materials can alter the shape and/or shift the strength-maturity curve. This includes not only changes in the cementitious materials content, but also changes in the relative proportions of other materials that significantly impact strength or the rate of strength gain, such as water, air content, and certain admixtures (particularly, set retarders and accelerators). Similarly, a change in the *characteristics* of any of the raw materials can affect the validity of the strength-maturity relationship. For instance, a decrease in the fineness of the cement will slow down the rate of strength gain, thus significantly altering the strength-maturity relationship.

The aforementioned circumstances expose the need for good stockpile management and consistent batching procedures. Notwithstanding this requirement for consistent operations at the batch plant, the maturity method itself can be used to overcome its own mix-specific limitation. This advantageous use of maturity's primary limitation is directly based upon its *sensitivity* to any changes in the mix – sensitivity to changes that affect strength or the rate of strength gain, as discussed above. This sensitivity to changes in the mix can be used to quickly alert the plant manager whenever such changes occur. This process turns the maturity method into not only a powerful tool to accelerate construction, but also an extremely beneficial means for robust quality control.

To realize these quality-control benefits, a systematic process of daily verifications must be implemented in conjunction with routine maturity testing. Figure 6.3 provides a graphical depiction of the quality-control benefits of concrete maturity. The figure illustrates a hypothetical scenario wherein a significant process or raw-material change occurs partway through a project (at the third frame from the top). The frames on the left depict the situation wherein maturity is NOT being used as a quality control tool, where the frames on the right show the results when the exact same events occur where maturity IS being consistently used to monitor quality.

⁴ Trost (2004) documented the use of direct tension for field validation of flexural strength and presented the use of SPC in conjunction with maturity as a quality control tool.

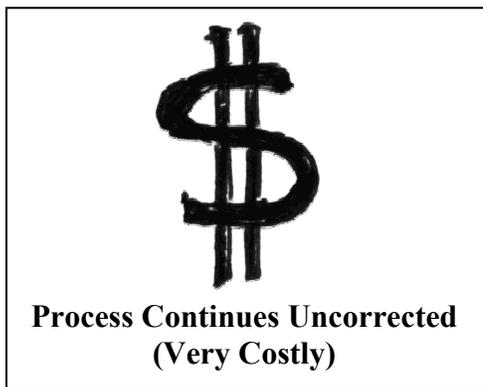
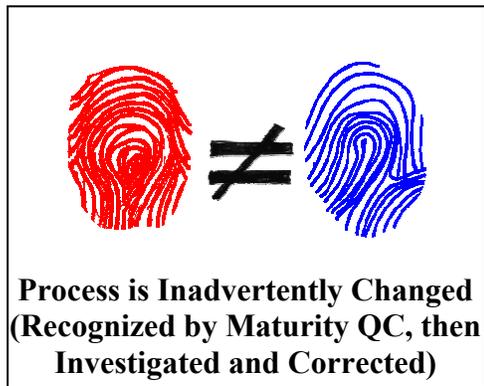
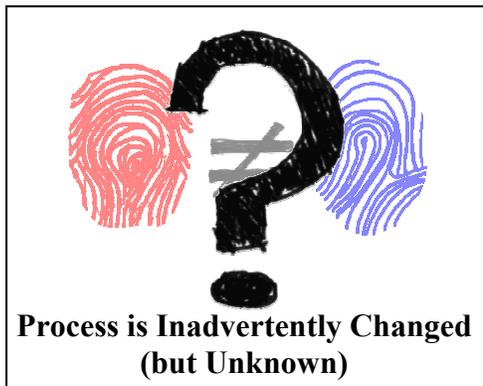
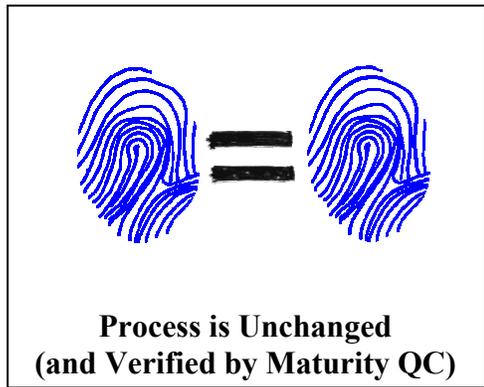
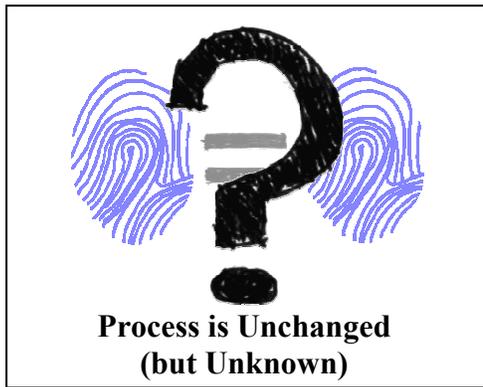
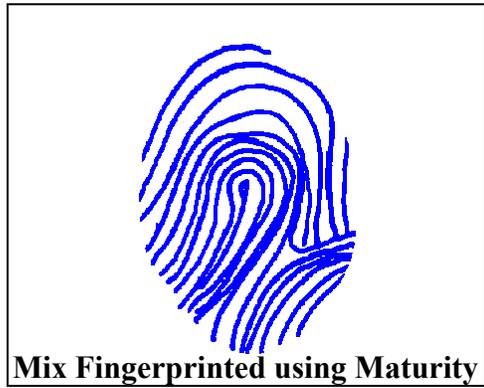


Figure 6.3 – Benefits of using Maturity as a Quality Control Tool

7. Sample Protocols and Process Flow Charts

This section provides a sample protocol for each of the four steps involved in implementing a maturity program. Each protocol includes a step-by-step procedure as well as a companion flowchart.

7.1. Laboratory “Calibration”

A laboratory calibration must be performed before any strength-from-maturity measurements can be made. The calibration is needed to establish the unique strength-maturity relationship for each mix design. A step-by-step sample protocol for establishing strength-maturity relationships is provided below. In addition, a flowchart of the calibration process is presented in Figure 7.1.

1. Cast a minimum of sixteen (16) beam specimens from a single batch of concrete. Instrument one specimen with one or two maturity sensors.⁵
2. Cure the specimens in accordance with ASTM C192.⁶
3. Estimate the elapsed time after casting (t_3) at which the specimens will likely achieve the desired flexural strength. If t_3 is greater than 14 days, use $t_3 = 14$ days (336 hours).
4. Calculate the maturity M_3 (in °C-hours), using the elapsed time t_3 (in hours) determined in Step 3, using Equation 7.1:⁷

$$M_3 = (23 - 5) \cdot t_3 \quad \text{Equation 7.1}$$

5. Test a minimum of three (3) beam specimens each at roughly 30%, 60%, 90%, 120%, and 240% of M_3 (calculated in Step 4).^{8,9}
6. Record the average flexural strength and average maturity of the specimens tested at each maturity age.
7. Plot each strength-maturity data point on a semi-log scale (i.e. log of maturity on the x-axis and flexural strength on the y-axis) as shown in Figure 6.1.

⁵ Whereas the entire maturity calibration procedure hinges upon the temperature history of the calibration specimens, redundancy of maturity sensors is prudent, but not absolutely necessary.

⁶ The appropriateness of using a 5 °C datum temperature hinges on the specimens being cured as close to 23 °C (73 °F) as possible. Strict adherence to the curing requirements of ASTM C192 helps facilitate this need. Detailed discussion of datum temperatures and this requirement is included in Appendix B.

⁷ In Equation 7.1, “23” represents the anticipated average curing temperature of the calibration specimens (23 °C) and “5” represents the datum temperature (5 °C).

⁸ NOTE: The points listed are good initial guidelines. Judgment and common sense may warrant deviation from this recommendation. The important issues are [1] to have closely-spaced points in the range of interest and also along the steep part of the strength-gain curve, especially for high-early mix designs and [2] to NEVER EXTRAPOLATE beyond the maturity levels included in the calibration.

⁹ NOTE: If a strength-maturity relationship curve is established from more than one batch, test an equal number of specimens from each batch at each maturity age (to spread the error associated with batch-to-batch variability across the entire strength-maturity relationship curve rather than concentrating the error along individual portions of the curve).

8. Draw a point-to-point “curve” through the data points. The overall shape of the curve should be a straight line, slightly curved, or slightly “S” shaped. However, none of the line segments should exhibit a negative (i.e. downward) slope.
9. If any of the line segments from Step 8 has a negative slope (as shown in Figure 8.1), a significant testing error has occurred and the curve should not be relied upon. Investigate and correct the sources of testing error, then return to Step 1.

7.2. Maturity as a Quality Control Tool via Daily Mix Verification

The concrete maturity method can be implemented as a powerful quality control tool via frequent mix verification. For a maturity-based quality-control program to provide quick and timely feedback, mix verification should be performed at least daily. A step-by-step sample protocol for using maturity as a quality control tool is provided below. In addition, a flowchart of the process is presented in Figure 7.2.

1. Develop a Concrete Quality Control Plan (CQCP) that establishes the frequency for performing verification testing and the maturity ages at which verification specimens will be tested.
2. Develop a strength-maturity relationship curve for at least one of the mix designs to be used on the project. If verification is to be performed using a test method other than ASTM C78, a separate strength-maturity relationship should be established for the alternative test method simultaneous with the flexural strength-maturity relationship.¹⁰
3. Cast at least three (3) verification specimens at the frequency set forth in the CQCP.
4. Instrument one of the verification specimens with a maturity sensor.
5. At the maturity age(s) set forth in the CQCP, measure the strength of the verification specimens using physical test methods (e.g. ASTM C78, C496, C1583, C39).
6. Compare the strength of the verification *specimens* (as measured by physical test methods) to the strength values predicted by the *specimen* maturity value (using the appropriate mix-specific strength-maturity relationship curve).¹¹

¹⁰ If more than one batch of concrete is required to complete this dual calibration, the specimens from each batch should be cast and tested such that at each maturity level, an equal number of specimens are tested from each batch for each test type (in order to spread batch-to-batch variability across all maturity levels).

¹¹ The measured strength of the verification specimens should NOT be used as a basis for acceptance or open-to-traffic decisions. The in-place temperature history of the pavement will not be the same as the temperature history of the verification specimens, As such, the verification specimens DO NOT represent the actual in-place concrete strength. The verification specimens are SOLELY a means to validate the strength-maturity relationship for the mix design and to verify that no adverse mix changes have occurred.

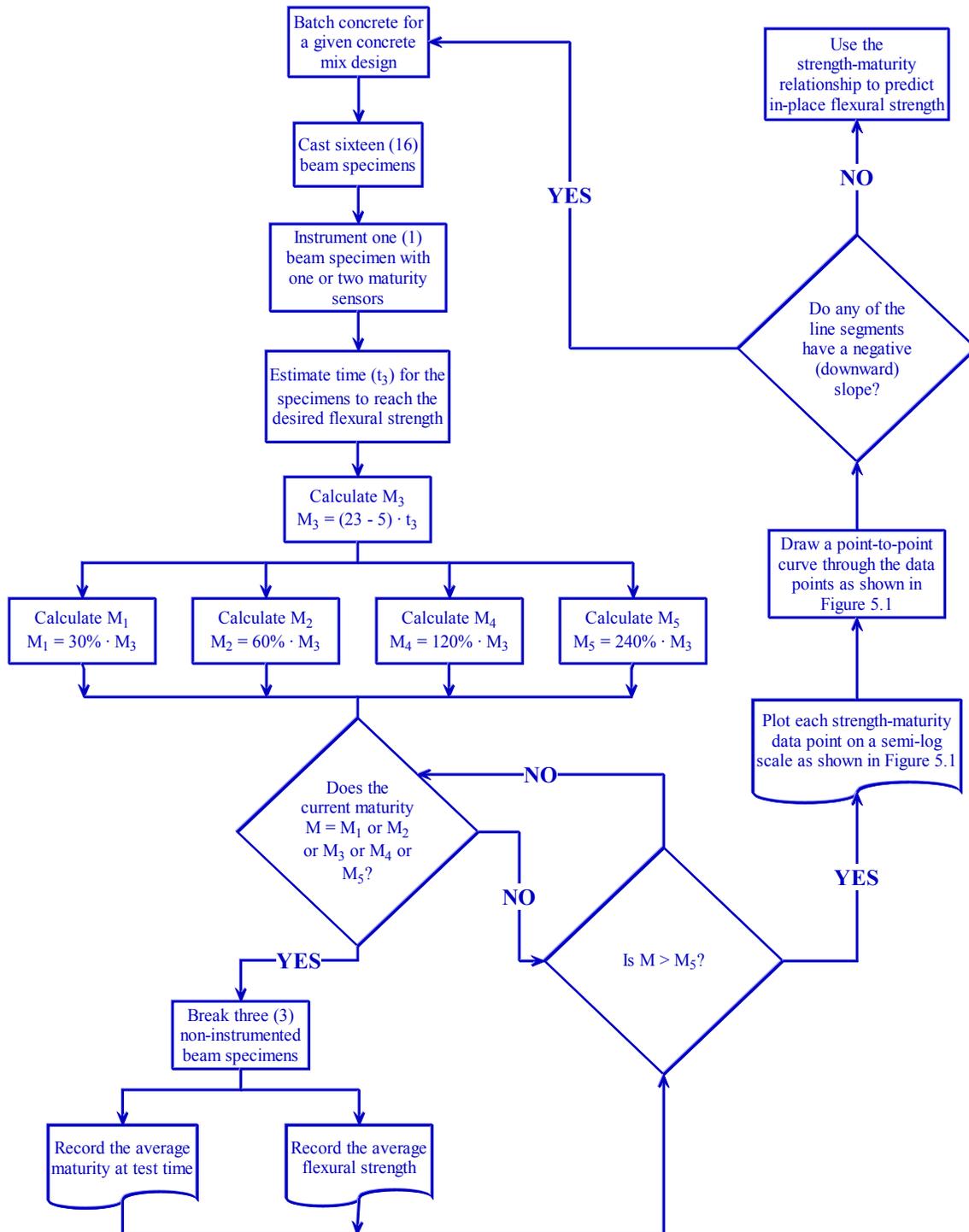


Figure 7.1 – Flowchart for Establishing Strength-Maturity Relationships

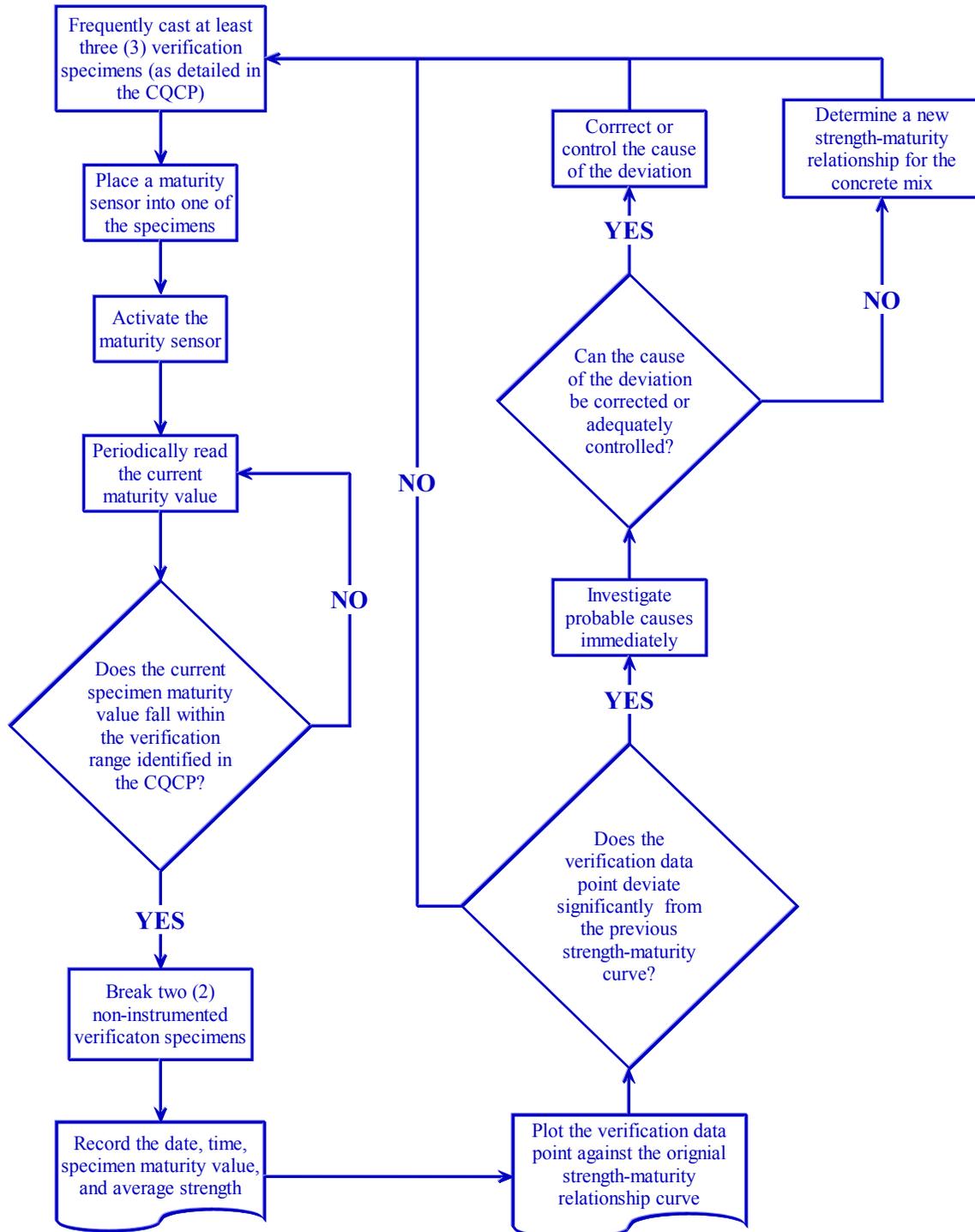


Figure 7.2 – Flowchart for using Maturity as a Quality Control Tool

7. If the measured specimen strength value is close to the predicted specimen strength value, the mix has been verified and the relationship curve has been validated.
8. If the measured strength is not within the range of normal variability for the batching process, the probable cause should be immediately investigated.
 - a. If the strength discrepancies are due to problems with the batching procedures, corrective actions must be taken to ensure that the problems are not repeated.
9. If the source of the observed differences is due to changes in the raw materials or cannot be readily determined, a new strength-maturity relationship curve should be established to account for any changes that may have occurred with the mixture components or the batching process.¹²

7.3. Using Maturity to Measure Flexural Strength in the Field

After the laboratory calibration has been performed, strength-from-maturity measurements can be made.

7.3.1. Using Maturity to Measure Flexural Strength in the Field

After the laboratory calibration has been performed, strength-from-maturity measurements can be made. A step-by-step sample protocol for using maturity to measure flexural strength in the field is provided below. In addition, Figure 7.4 provides a flowchart to assist with using maturity for open-to-traffic decisions.

1. Perform a strength-maturity calibration for each concrete mix design as detailed in Section 7.1.
2. Place maturity sensors in the pavement at the location(s) of interest. Activate the sensors immediately after concrete placement.
 - a. How often to place sensors is essentially a project management decision. It depends upon how quickly the contractor needs access to a given section of pavement. A preferred approach is to embed a maturity sensor at the beginning of a given day's placement, periodically embed additional sensors throughout the day, then embed a final sensor at the end of the day. With this approach, any particular location of interest will be bracketed by two maturity sensors.
3. Whenever a field strength measurement is desired,
 - a. Obtain maturity readings from the two sensors that bracket the location of interest,

¹² If uncorrectable changes occur to the batching process or raw materials, the subsequent need to establish a new strength-maturity relationship may negatively impact the construction schedule in the short term. However, as illustrated by Figure 6.3, the benefits of quickly identifying such process or mix changes typically far outweigh the consequences of failing to recognize them.

- Using the appropriate strength-maturity relationship, convert each maturity reading to a flexural strength measurement as shown in Figure 7.3.

NOTE: Certain maturity devices may automate this step so that in-place flexural strength can be read directly from the maturity sensor rather than requiring the above conversion.

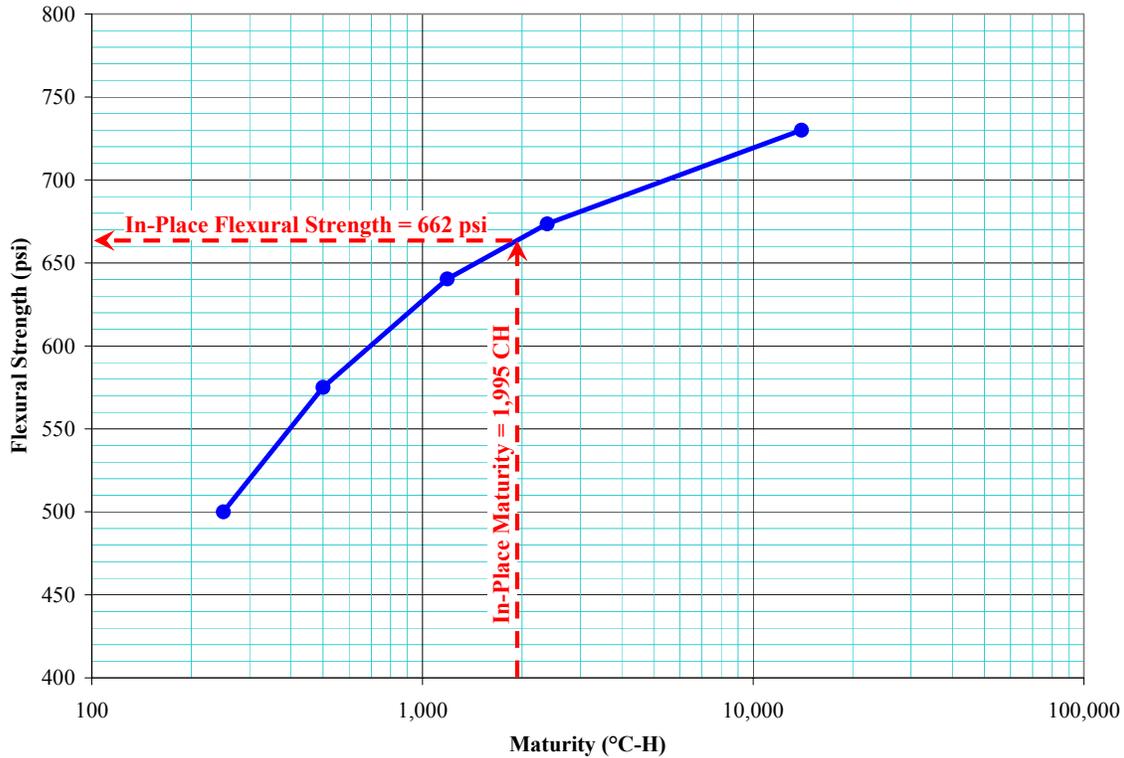


Figure 7.3 – Graphical Example for Converting Maturity to Flexural Strength

- Whenever a required threshold for in-place flexural strength has been exceeded for the location of interest,
 - Record the in-place maturity and associated in-place flexural strength values from the maturity sensors bracketing the location of interest.
 - Proceed with the allowable activities given the fact that the required threshold for in-place flexural strength has been exceeded.

7.3.2. Calculating Open-to-Traffic Threshold Strength Values

After the laboratory calibration has been performed, strength-from-maturity measurements can be made. However, before those strength-from-maturity measurements will be meaningful, the open-to-traffic thresholds for each major equipment category must be established. A step-by-step sample protocol for calculating open-to-traffic strength thresholds is provided below.

- Choose a suitable breakdown of equipment categories (e.g. light-duty pickups, concrete trucks, paving equipment).

2. Choose a method to be used to calculate maximum edge stresses (e.g. ACPA's AirPave software, FHWA's JSLAB software, influence charts, other finite-element analysis software).
3. Choose a strength-adjustment method (e.g. factor of safety multiplier only, multiplier with offset, multiplier with temperature correction factor).
4. Using the edge-stress calculation method chosen during Step 2, calculate the maximum edge stress caused by each piece of equipment within each equipment category for each pavement and support condition.
5. Using the strength-adjustment method chosen during Step 3 and the maximum edge stresses calculated during Step 4, calculate the strength threshold for each piece of equipment. Example results are shown in Table 7.1.

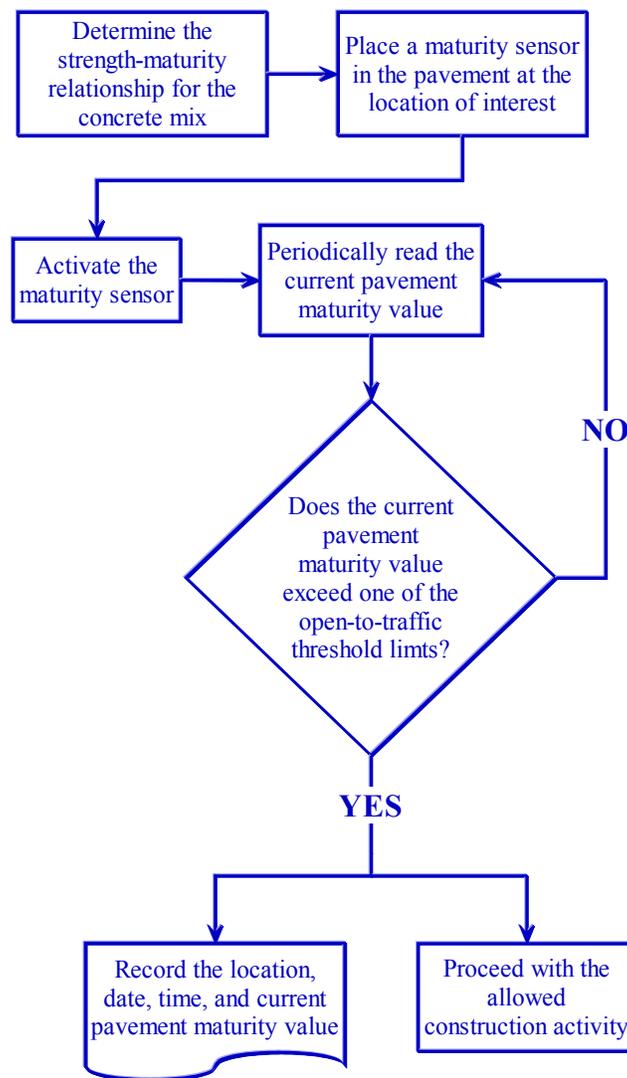


Figure 7.4 – Flowchart for Opening-to-Traffic using Maturity

Table 7.1 – Example Maximum Edge Stresses and Strength Thresholds for Various Pieces of Construction Equipment

Equipment / Vehicle	Maximum Edge Stress (psi)	Zero-Fatigue-Damage Safety Factor (2.5x) (psi)	Fatigue + Temperature Safety Factor (2.5x + 50) (psi)
1/2-ton Pickup	15	37	87
1-ton Pickup	27	67	117
Concrete Truck (Loaded)	72	180	230
Slipform Paver	124	310	360
Belt Placer / Spreader	139	347	397

1. Based on the categories chosen during Step 1, the strength threshold values calculated during Step 5, and the strength maturity relationship established in accordance with Section 7.1, tabulate the maximum open-to-traffic threshold strength for each equipment category for each pavement thickness and support condition as shown in Table 7.2.

Table 7.2 – Example Strength Thresholds by Equipment Category

Equipment Category	Open-to-Traffic Strength Threshold (psi)
Light Duty Trucks	117
Concrete Trucks (Loaded)	230
Slipform Paver	360
Belt Placer / Spreader	397

2. If the strength-adjustment method chosen does not require a temperature correction factor,¹³
 - a. Calculate the threshold maturity value for each strength threshold by interpolating between maturity levels from the strength-maturity relationship

¹³ If the chosen strength-adjustment method uses a temperature correction factor as discussed in Section 9.2.1.1, maturity threshold values cannot be used as the open-to-traffic criterion. Under this circumstance, open-to-traffic decisions must be based on strength thresholds in accordance with adjusted strength-from-maturity measurements. In other words, the pavement's maturity value must be converted to a strength value, then to an adjusted strength value via the temperature correction factor rather than simply monitoring in-place maturity.

for the appropriate concrete mix design. Table 7.3 provides some example results.¹⁴

- b. Plot the strength and maturity thresholds for each equipment category for each pavement thickness and support condition as shown in Figure 7.5.

Table 7.3 – Example Strength and Maturity Thresholds by Equipment Category

Equipment Category	Open-to-Traffic Strength Threshold (psi)	Open-to-Traffic Maturity Threshold (°C-Hrs)
Light Duty Trucks	117	747
Concrete Trucks (Loaded)	230	896
Slipform Paver	360	1,496
Belt Placer / Spreader	397	1,696

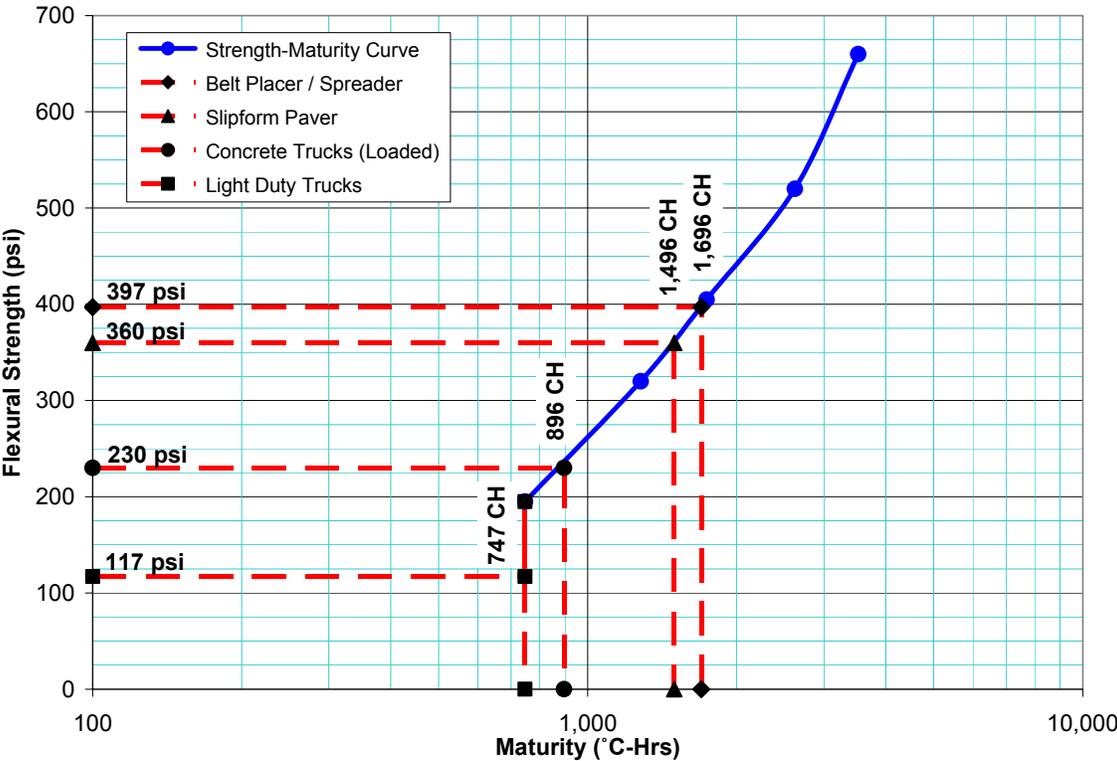


Figure 7.5 – Example Strength and Maturity Thresholds for Staged Opening to Traffic

¹⁴ If the calculated strength threshold for a given equipment type is below the strength value corresponding to the minimum maturity level of the strength-maturity relationship, use the minimum maturity value as the maturity threshold for that equipment type. Do not extrapolate beyond the maturity extremes of the strength-maturity relationship. See Section 8.4 for additional discussion on this topic.

7.4. Monthly Validation of the Strength-Maturity Relationship

Monthly validation of each strength-maturity relationship on a project is highly recommended. In addition, validation testing should be performed whenever significant changes to the batching process or the raw materials are known or suspected. However, even in the event that minor adjustments are *intentionally* made to the mix design, a completely new strength-maturity relationship may or may not be necessary. In order to determine whether or not a new relationship curve is required, a two-point validation can be performed. A step-by-step sample protocol for performing a two-point validation of the strength-maturity relationship is provided below. In addition, a flowchart of the two-point validation process is presented in Figure 7.8.

1. Select the portion of the strength-maturity relationship curve of greatest importance to the project (e.g. 697 °C-H, corresponding to 600 psi).
2. Cast a minimum of seven beam specimens using the adjusted mix design.
3. Instrument one of the beam specimens with a maturity sensor.
4. Break at least three (3) beam specimens at a maturity value somewhat less than the value chosen in Step 1 (e.g. 400 °C-H).
5. Break at least three (3) beam specimens at a maturity value somewhat greater than the value chosen in Step 1 (e.g. 1,000 °C-H).
6. On a semi-log scale, plot the average of each set of three beams versus their corresponding maturity alongside the previous strength-maturity relationship curve (as shown in Figures 7.6 and 7.7).
7. If BOTH validation points fall ABOVE the previous strength-maturity relationship curve BUT their extended line (on a semi-log plot) intersects the previous curve (as shown in Figure 7.6), the previous curve can be relied upon across the range of maturity values covered by the two-point validation (e.g. 400 to 1,000 °C-H). Outside this range, the previous curve should be used with caution – a separate strength-maturity relationship curve for the new mix may be needed.
8. If BOTH validation points fall clearly ABOVE the previous strength-maturity relationship curve in that their extended line (on a semi-log plot) does NOT intersect the previous curve (as shown in Figure 7.7), the previous curve can be relied upon.¹⁵
9. If BOTH validation points fall BELOW the previous strength-maturity relationship curve, the previous curve CANNOT be relied upon. A new strength-maturity relationship should be established.
10. If one of the points falls below the previous strength-maturity relationship curve and the other falls above, the two-point validation is INCONCLUSIVE. Another two-point validation should be performed.

¹⁵ However, if the two-point validation falls significantly above the previous curve, economic factors may warrant determination of a separate strength-maturity relationship curve for the adjusted mix.

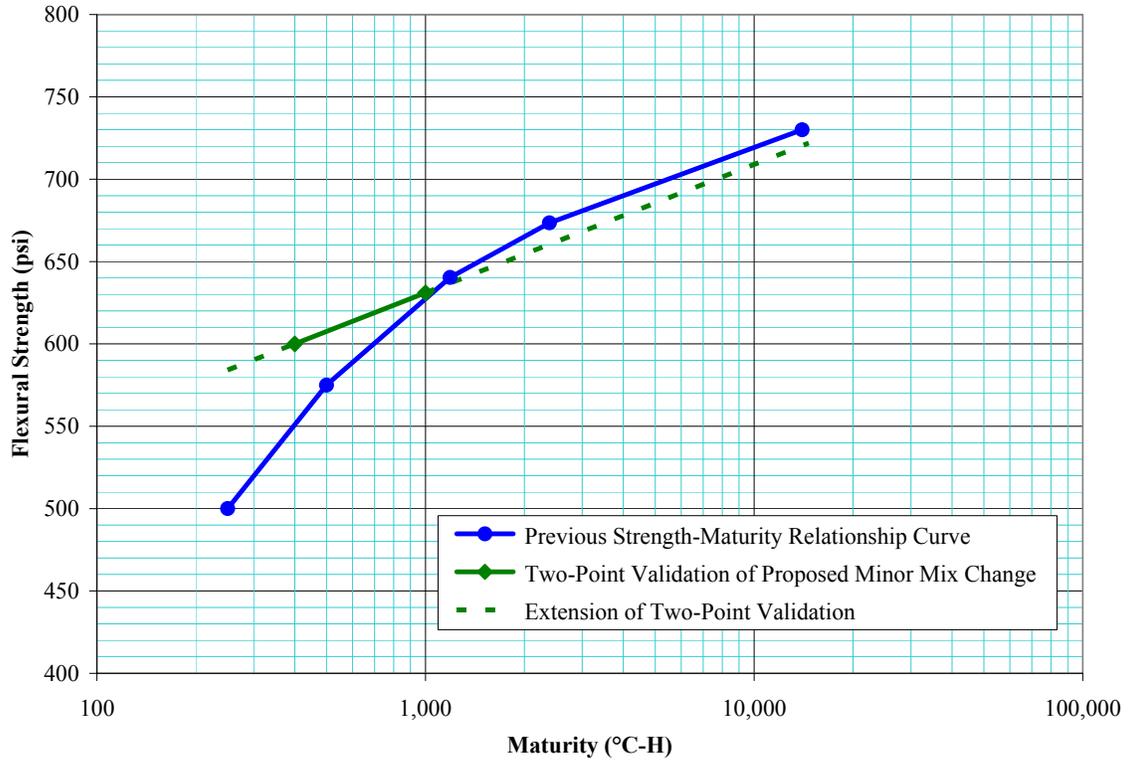


Figure 7.6 – Example Two-Point Validation Falling above but Extending to Intersect the Previous Strength-Maturity Relationship Curve

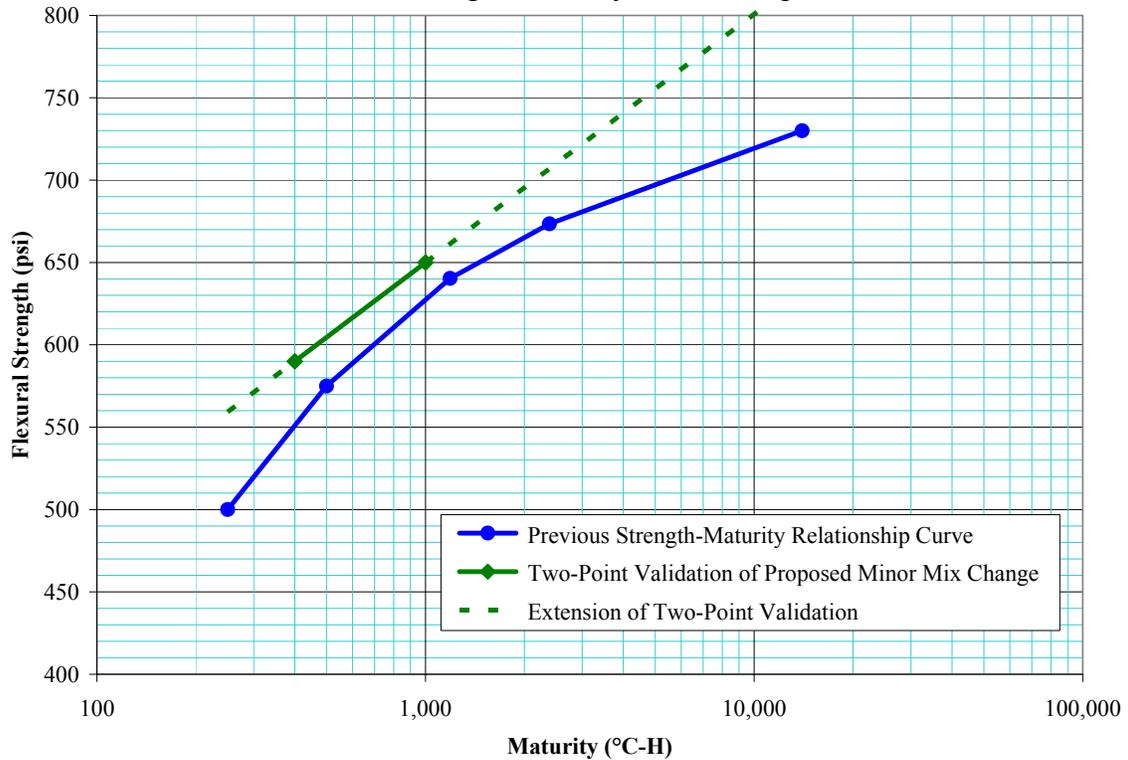


Figure 7.7 – Example Two-Point Validation Falling Clearly above the Previous Strength-Maturity Relationship Curve

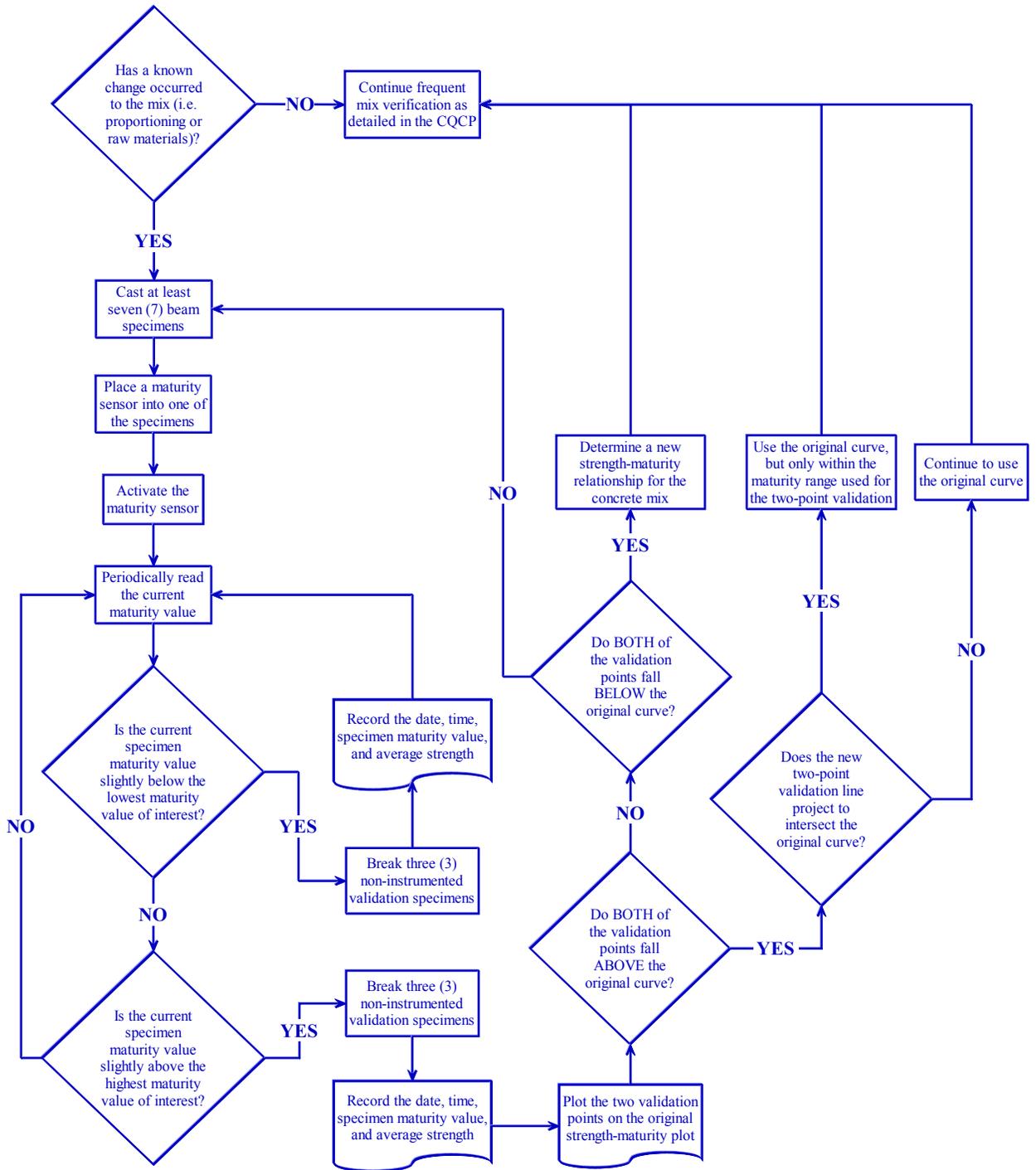


Figure 7.8 – Flowchart for Performing Two-Point Validation

8. The “Top 5” Need-to-Know Issues Related to Concrete Maturity

The concrete maturity method can be used most effectively when potential problems are understood and the program for implementing maturity is structured to prevent them or at least to minimize their impact. The most typical problems as well as preventative recommendations are discussed in this section.

8.1. Evenly distribute all potential sources of error during calibration testing across all maturity levels.

Whereas ALL future determinations of strength come back to the strength-maturity relationship established during the calibration process, it is imperative that any sources of error in the maturity calibration specimens be evenly spread across all five maturity levels.

In order to accomplish this, several practical recommendations should be adhered to. For example, if multiple technicians are involved in the casting of the specimens, the strength testing at a given maturity age should include a mix of specimens cast by different technicians. Similarly, all specimens throughout the entire calibration should be tested on the same testing frame and, ideally, by the same technician. If the specimens are cured in more than one curing room or curing tank, an equal number of specimens should be broken from each tank at a given maturity age. This same recommendation holds for specimens cast from more than one batch of concrete – an equal number should be tested at each maturity age. Another important issue in this regard is to ensure that no temperature gradients exist within a given curing tank. Any temperature gradient will cause some of the specimens to gain strength at different rates than other specimens. In addition, a minimum of three specimens should be tested for strength at each maturity level.¹⁶

Figure 8.1 shows what can happen if errors are allowed to accumulate at one or more maturity levels. In this hypothetical example, two batches of concrete were used, with maturity levels 1, 2, and 3 being tested out of the first batch and levels 4 and 5 out of the second batch. Whereas the second batch had a slightly higher water-cement ratio, a negative slope occurred between points 3 and 4.

¹⁶ Going from a single specimen to the average of two reduces the testing error by almost 30%. Going from the average of two specimens to the average of three further reduces the testing error by 20% (for a net reduction of 42% versus a single specimen).

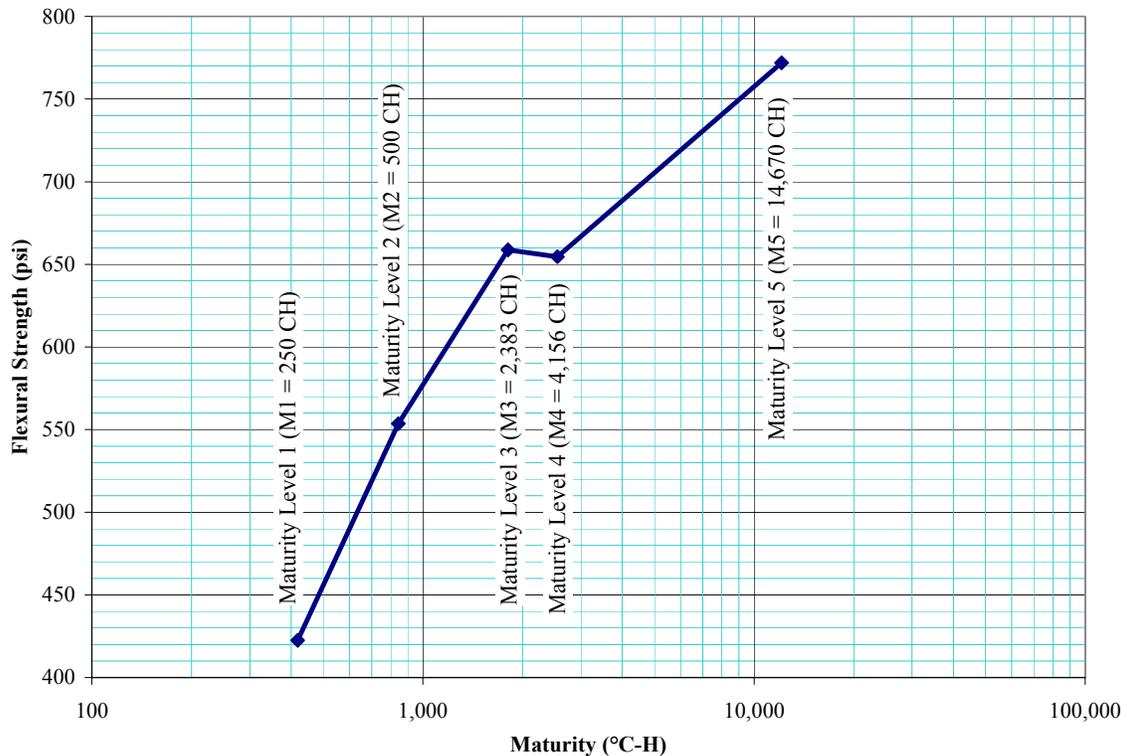


Figure 8.1 – Example where Testing Errors were not Properly Spread across Maturity Levels during Calibration

8.2. Perform frequent mix verification testing because of the mix-specific nature of strength-maturity relationships (i.e. the relationship may not be valid if the proportioning and/or quality of the raw materials changes).

Failure to provide adequate validation or verification coupled with poor quality control over the concrete batching process can yield potentially disastrous results. And, considering the fact that the mix-specific limitation of maturity can actually be used *advantageously* to signal unwanted changes to the raw materials and/or the batching process, this aspect of the maturity method should not go unimplemented.

Figure 8.2 below compares the strength-maturity relationships of two concrete mix designs where the only difference is the addition of an accelerator. In this instance, a distinct upward shift in the strength-maturity curve occurs when an accelerator is used. In essence, any change that potentially affects the ultimate strength of the mix or the rate of strength gain can potentially invalidate the strength-maturity relationship. This sensitivity to mix changes underscores the need for frequent mix verification.

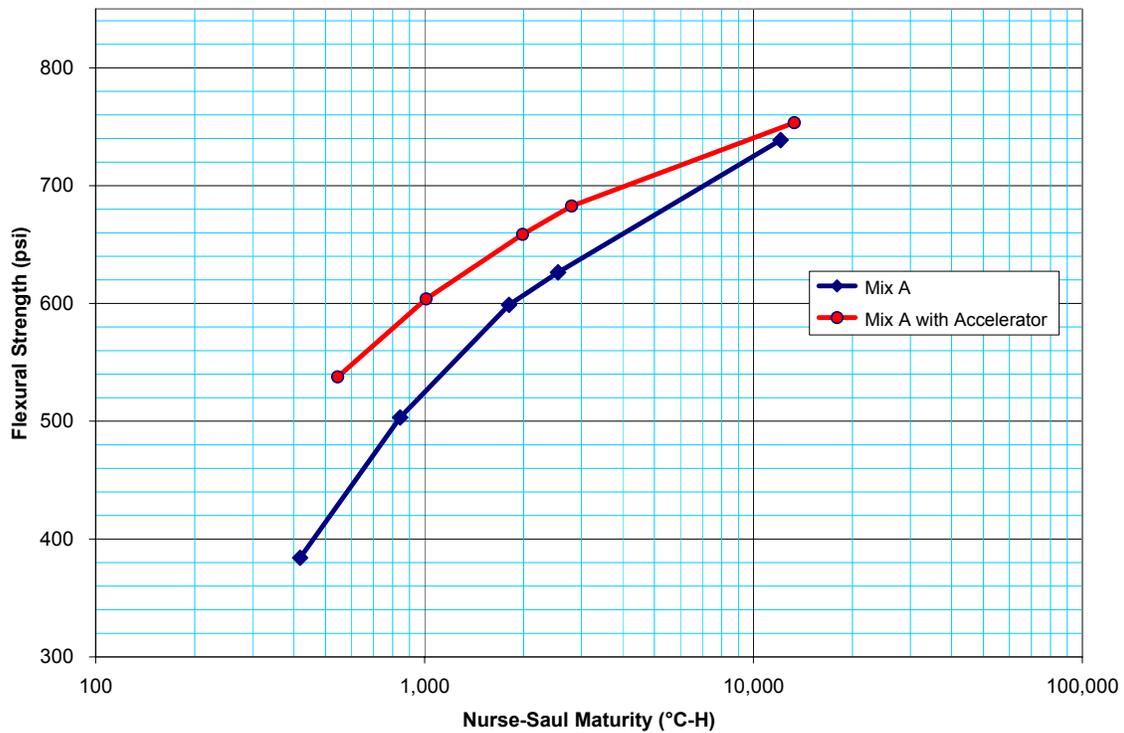


Figure 8.2 – Effects of a Change in the Mix

8.3. ***Confirm that the same datum temperature is being used at all times***

Using a different datum temperature in the field can result in completely erroneous strength predictions. Similarly, the proper strength-maturity relationship must also be used (i.e. the user in the field must be certain that the curve being used to convert maturity to strength is the right curve for the right mix).

Figure 8.3 shows the difference in accumulated maturity over time for a given pavement using two different datum temperatures. As can be seen, using a different datum temperature from the one used during calibration can produce drastic errors in the calculated maturity values.

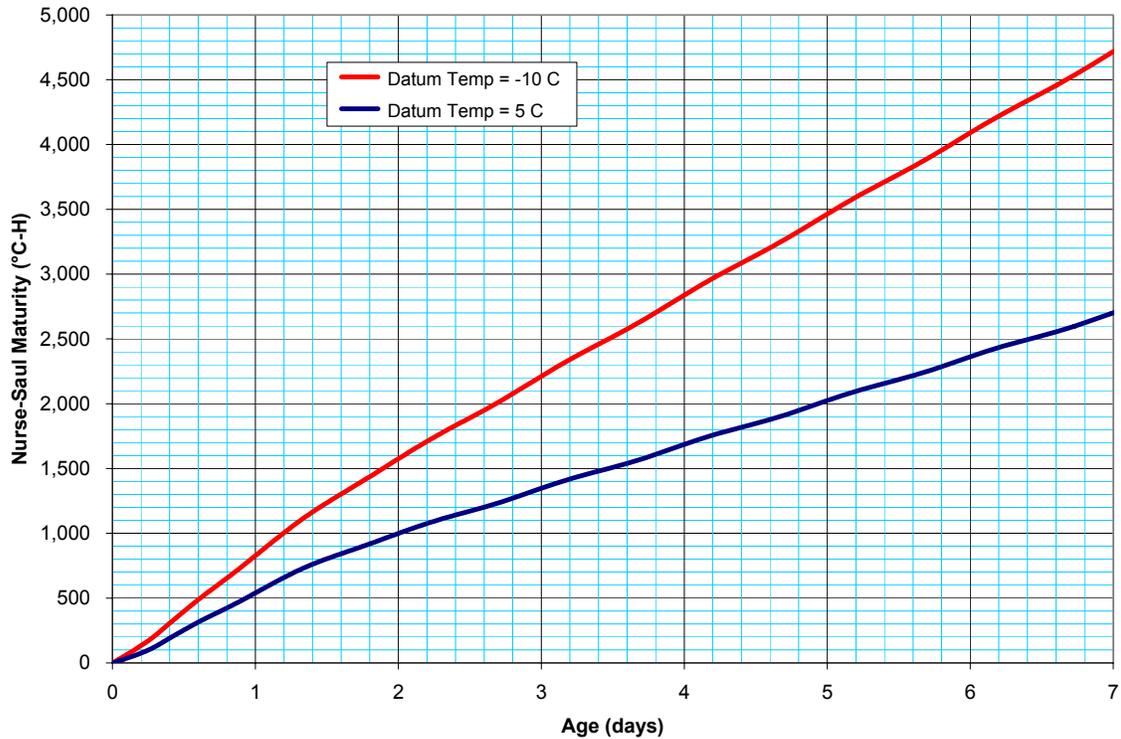


Figure 8.3 – Effect of Calculating Maturity using a Different Datum Temperature

8.4. Never extrapolate beyond the final maturity and strength level of the strength-maturity relationship

Whereas maturity calibrations are performed upfront, there is no reason why the strength-maturity curve should not fully encompass the desired strength values. As such, there should be no reason or need to extrapolate beyond the final maturity and strength levels bracketed by the strength-maturity relationship. Figure 8.4 shows this requirement graphically. Any extrapolation (at either end of the strength-maturity curve) has the potential for considerable error. This is even more so if a curve-fitting algorithm is being used. Simple point-to-point interpolation for standard maturity curves is recommended instead of applying curve-fitting to strength-maturity relationship curves. Most curve-fitting algorithms give more weight, or leverage, to the points farthest from the mean. However, with strength-from-maturity determinations, the users are usually most interested in those values in the middle of the strength-maturity range.

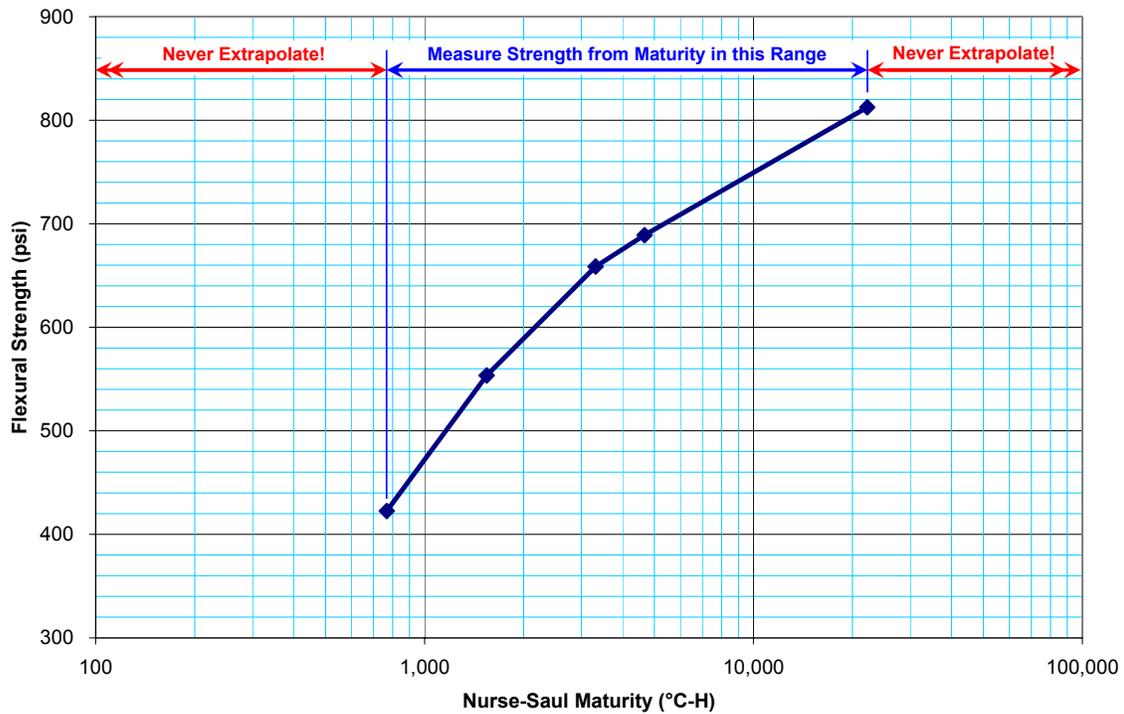


Figure 8.4 – Interpolation versus Extrapolation

8.5. Understand the influence of in-place temperature when estimating in-place flexural strength

Concrete flexural strength has been shown to be significantly affected by the temperature of the specimens at test time (Neville 1996). This effect has been observed to be as high as 0.01 to 0.02 MPa / °C (3 to 5 psi / °F) with higher temperatures relating to lower flexural strength values. As such, whenever the pavement's in-place temperature is considerably higher than the temperature of the specimens used to establish the strength-maturity relationship, the actual load-carrying capacity of the pavement may be less than the predicted values unless an appropriate error-correction is applied. NOTE: This source of error is not specific to the maturity method. If physical specimens are used to predict in-place flexural strength and if the temperature of those specimens is below the in-place temperature, the resulting prediction of in-place flexural strength will also be in error.

9. Precision & Bias and Potential Sources of Error

Concrete maturity is a measurement technique. As such, precision and bias issues as well as potential sources of error must be thoroughly understood and accounted for. This section provides frank discussion concerning the limitations of concrete maturity methods and available strategies for mitigating the risks associated with those limitations.

Ultimately, the key to successful implementation of concrete maturity methods lies in maintaining an awareness of and appreciation for the various sources of potential error coupled with proactive management of the associated risks. From a practical standpoint, this requires a sustained focus on consistency with respect to the concrete batching process, including exceptional stockpile management, as well as intentional, careful, consistent execution of a well-planned, well-documented mix verification program.

9.1. Precision & Bias

Any time a test is conducted or a measurement taken, the decision makers who will ultimately use those values must have an understanding of the reliability (i.e. precision and bias) of those values if they are to make truly meaningful decisions. This need stems from the fact that every process, no matter how tightly controlled, exhibits some degree of variability. The processes of performing tests and taking measurements are no different. ASTM International (ASTM) requires a “precision and bias” section for each and every one of their published standard test methods. According to ASTM, the precision and bias of a test method is foundational. However, with respect to using maturity methods to predict in-place concrete strength, ASTM states that “it is not possible to write statements about the precision and bias of the estimated strength.” This is primarily due to the mix-specific nature of the method.

Whereas the determination of concrete strength using the maturity method relies upon the pre-determination of strength-maturity relationships that are unique to each mix design, significant changes to the mix (with respect to the quality or relative proportions of the raw materials) can potentially render the pre-determined strength-maturity relationship invalid.

As a result of the maturity method’s reliance upon the relative consistency of the batching process itself, no precision and bias statement could ever purport to truly answer the question, “How reliable is this strength-from-maturity value?” For this reason, the establishment of and adherence to an ongoing mix-verification protocol is strongly recommended whenever maturity methods are employed. In fact, a properly designed and executed validation program can actually make advantageous use of this limitation of the maturity method as depicted in Figure 5.3.

With respect to sources of error due to batching variability, Trost (2002) conducted a study wherein the impact on maturity prediction errors (for compressive strength) was quantified with respect to batch-to-batch variations of water-to-cementitious-materials ratio (w/cm) and total air content. Trost found that the prediction error for strength-from-maturity measurements can be reduced by 50% by properly accounting for the air content and w/cm of the concrete.

9.2. Potential Sources of Error

This section discusses the specific sources of error that can potentially influence the accuracy and reliability of flexural-strength-from-maturity measurements. Although some of these error sources are peculiar to the maturity method, many are also present with standard “physical” test methods. For instance, errors due to elevated in-place temperatures as well as the crossover effect¹⁷ both influence the use of beam specimens to predict in-place flexural strength to the exact same extent as they affect strength-from-maturity determinations.

Although the potential sources of error described in this section can certainly occur concurrent with one another and, as such can be additive, they have been grouped into the following broad categories to enable more meaningful discussion of each:

- Errors due to Elevated In-Place Temperatures
- Batching Errors and Inconsistencies
- Changes in Raw Material Characteristics
- Testing Errors during Calibration
- Human Errors when Collecting Maturity Data or Calculating Strength from Maturity
- Nurse-Saul Errors
- The Crossover Effect

The paragraphs that follow provide detailed discussion and commentary on these seven sources of potential error.

9.2.1. Errors due to Elevated In-Place Temperatures

Laboratory testing was accomplished to evaluate the use of concrete maturity methods for estimating the flexural strength of rapid-strength concrete (i.e. concrete made with high-heat-of-hydration cementitious materials, such as Type III cement). As expected, the testing demonstrated the extreme self-heating capabilities associated with rapid-strength mixes. In addition, the testing showed that beam specimens tested “hot” resulted in approximately 0.05 MPa / °C (4 psi / °F) lower flexural strengths than companion beam specimens of the same maturity, but tested at cooler temperatures, a finding that corroborates similar data presented by Neville (1996).

These two observations suggest that caution should be exercised whenever early-age in-place flexural strength predictions are to be made in conjunction with rapid-strength mixes. This caution applies not just to maturity and not just to rapid-strength mixes, but to any procedure where there is a significant temperature differential between the in-place concrete and the specimens used to predict in-place flexural strength.

¹⁷ The term “crossover effect” refers to the condition wherein concrete cured at high early temperatures tends to have higher early-age strength relative to concrete cured at low early-age temperatures and the fact that this trend switches, or “crosses over”, for later-age (or ultimate) strengths. Figure 9.2 provides a graphical example of the crossover effect.

As such, nearly ALL methods for predicting in-place flexural strength will be subject to error if a considerable temperature differential exists between the in-place concrete and the specimens used to predict the in-place flexural strength. The magnitude of the error in large part depends upon the magnitude of the temperature difference. In recognition of the potential magnitude of this source of error, open-to-traffic decisions should apply an appropriate temperature correction whenever a considerable difference may exist between the in-place concrete temperature and the temperature of the specimens used to establish the strength-maturity relationship.

As stated above, however, this source of error applies equally to conventional methods of estimating in-place flexural strength, such as casting and testing beam specimens in accordance with ASTM C31 and C78.

The magnitude of this effect has been observed to be as high as 0.01 to 0.02 MPa / °C (3 to 5 psi / °F). However, a universal range of values has not been established. Two possible methods are presented below for addressing this source of error – a temperature correction factor and the use of an increased factor of safety. However, whereas the extent of this temperature effect is not fully understood, these methods are presented for illustrative purposes only. Airport administrators and engineers should be aware that *this source of error also applies to the use of conventional field-cast beams for measuring in-place flexural strength.*

9.2.1.1. Using a Temperature Correction Factor

The following is a sample protocol for correcting this source of error via a temperature correction factor:

1. Perform a standard strength-maturity calibration in accordance with the protocol detailed in Section 7.1.
2. Obtain an uncorrected in-place estimate of flexural strength in accordance with the protocol detailed in Section 7.3. This value will be referred to as MR_{UC} (which stands for “uncorrected Modulus of Rupture”).
3. Record the in-place concrete temperature and maturity value associated with the MR_{UC} value obtained during Step 2.
4. Calculate the temperature difference (ΔT) between the in-place temperature and the temperature at test time of the specimens used to establish the strength-maturity relationship. This calculation is shown graphically in Figure 9.1.
5. Choose a temperature correction factor (TCF) based on the known or assumed temperature-sensitivity of the flexural strength testing (e.g. TCF = 0.02 MPa / °C).
6. Calculate the temperature-corrected flexural strength (MR_{TC}) using the following equation:

$$MR_{TC} = MR_{UC} - \Delta T \cdot TCF \quad \text{Equation 9.1}$$

By way of example, Figure 9.1 below shows a hypothetical example where the specimens used to establish the strength-maturity relationship were cured at 74 °F and the in-place

pavement temperature at the time in-place strength measurements were taken was 99 °F, for a $\Delta T = 25$ °F.

As shown in the figure, the uncorrected maturity prediction was 555 psi. However, after assuming a 4 psi / °F temperature-correction factor, the temperature-corrected strength prediction was 455 psi.

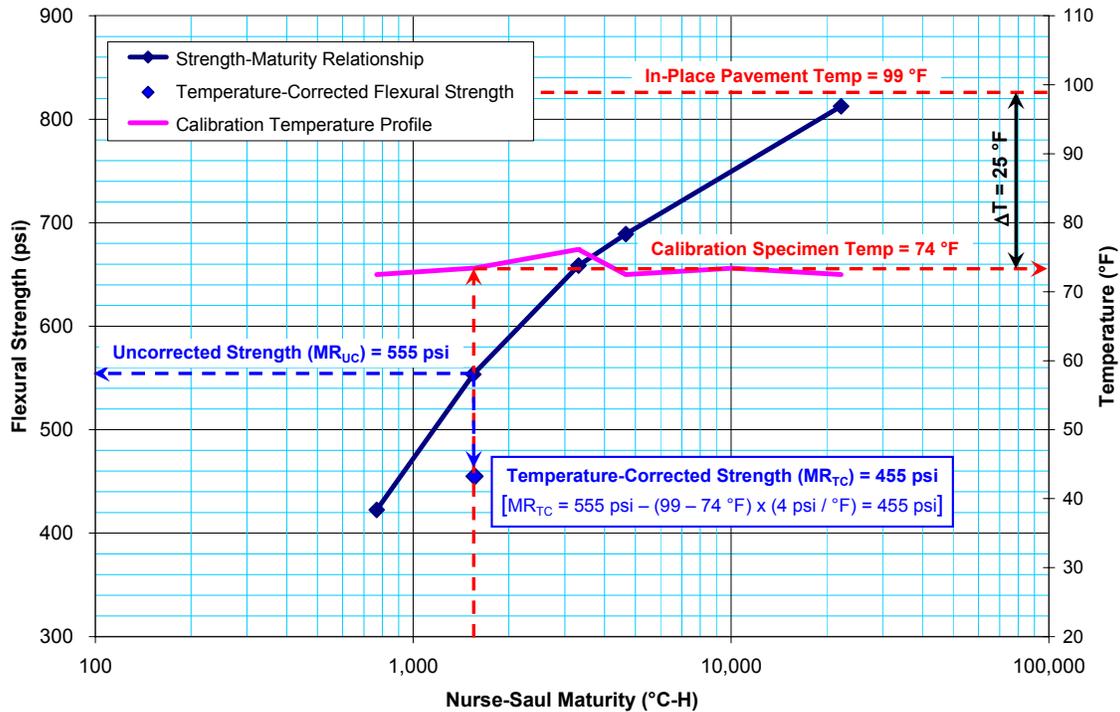


Figure 9.1 – Example Application of Temperature Correction Factor

9.2.1.2. Using an Increased Factor of Safety Multiplier

The Federal Aviation Administration (FAA) would like to see a 2.5 factor of safety multiplier when using maturity to make open-to-traffic decisions. This factor of safety ensures that no fatigue damage will be caused by the traffic allowed on the pavement at early ages. However, this factor does not account for the aforementioned temperature effect. Another method of addressing the error due to elevated in-place concrete temperatures is to apply an increased factor of safety when calculating minimum open-to-traffic strength requirements.

For instance, rather than using a factor of safety multiplier equal to 2.5, either a higher factor-of-safety multiplier can be used, such as 2.75 or 3.0, or a combination of a factor of safety multiplier and a factor of safety offset, such as $2.5x + 50$ psi. To illustrate the mechanics of this method, the example case study project in Section 10 details a scenario wherein the Engineer and Contractor agreed to apply a factor of safety multiplier equal to

2.5 and a factor of safety offset of 50 psi (for a net factor of safety equal to $2.5x + 50$ psi).¹⁸

9.2.2. Batching Errors and Inconsistencies

All concrete batching operations exhibit some degree of inconsistency. The level of inconsistency for a given batch plant is a function of many different factors including, but not limited to, the following:

- Precision and bias of the scales and meters,
- Timing and settings of the gates and batching controls,
- Order and method in which admixtures are added to the mix,
- Batch-to-batch differences in mixing time,
- Batch-to-batch differences in aggregate moisture content,
- Batch-to-batch differences in coarse and fine aggregate proportions,
- Batch-to-batch differences in temper water, and
- Human error.

The aforementioned factors create potential batch-to-batch variability in the following mix characteristics:

- Cementitious-materials content,
- Water-to-cementitious-materials ratio (w/cm), and
- Air content.

In general, the more automated the batch plant the more consistent the final product. A properly planned and executed mix-verification protocol can effectively manage the risks associated with batching errors and inconsistencies and can even serve as an improved quality control mechanism to help catch adverse changes in batching operations more quickly than conventional quality control methods. Trost (2002) demonstrated a method for significantly reducing strength-from-maturity prediction errors that incorporates the air content and water-to-cementitious-materials ratio into the strength-from-maturity calculation.

9.2.3. Changes in Raw Material Characteristics

Changes in raw material characteristics can be the result of the following factors;

- Changing suppliers,
- Changes in supplier operations or raw materials,

¹⁸ These values are provided for calculation demonstration purposes only. The factor of safety to be applied should be chosen after careful consideration of the types and sources of error on a specific project and their likely magnitude. For instance, an entirely different factor of safety would be warranted when elevated in-place concrete temperatures are unlikely, such as projects spanning the winter months in northern climates, versus summer projects in the south.

- Changes in quarry ledges,
- Poor stockpile management, and
- Admixture degradation due to excessive storage, freezing or extreme temperatures, mishandling or contamination.

The aforementioned factors can lead to the following changes in concrete raw material characteristics:

- Cement fineness,
- Aggregate cleanliness,
- Cement chemistry,
- Chemistry and/or efficacy of supplemental cementitious materials,
- Efficacy of air-entraining admixtures,
- Efficacy of water-reducing admixtures,
- Adverse interactions between raw materials, and
- Aggregate soundness.

A properly planned and executed mix-verification protocol can effectively manage the risks associated with changes in raw material characteristics and can even serve as an improved quality control mechanism to help catch adverse raw material changes more quickly than conventional quality control methods.

9.2.4. Testing Errors during Calibration

Errors during calibration can have a profound effect on the subsequent strength-from-maturity measurements. As such, every effort must be taken to reduce the amount of error during calibration. Despite these best efforts, errors still exist in any sampling and testing program. As such, great importance must be placed not only on the reduction of error during calibration but also on ensuring that any potential sources of error are spread equally across all maturity levels. The following factors can adversely affect the accuracy and reliability of the calibration process:

- Sampling errors and inconsistencies,
- Casting errors and inconsistencies,
- Batching errors and inconsistencies,
- Curing errors, such as
 - Inadequate humidity monitoring and control of curing rooms or cabinets,
 - Inadequate temperature monitoring and control of curing tanks, rooms, or cabinets,
 - Temperature gradients within curing tanks, rooms, or cabinets due to inadequate circulation,

- Leaching of reaction products due to insufficient levels of calcium-hydroxide in curing tanks,
- Rough handling and/or physical damage to specimens,
- Testing errors and inconsistencies, such as
 - Allowing specimens to dry out prior to testing,
 - Failing to load specimens at the specified loading rate,
 - Failing to properly align specimens in the test frame,
 - Specimens out of square,
 - Improper or malfunctioning equipment,
 - Improper equipment usage,
 - Improper equipment calibration,
 - Testing unsaturated specimens, and
 - Using different equipment and/or technicians at different maturity levels.

Steps should be taken to reduce or eliminate as many of these sources of error as practicable. For those potential sources of error that cannot be eliminated, every effort should be made to spread those sources of error equally across all maturity levels. For example, if multiple technicians are required for casting the specimens, do not test all specimens from a single technician at a single maturity level. Rather, test specimens from different technicians at each maturity level and average those test results for that maturity level. Similarly, if more than one batch is required, each maturity level should include an equal number of specimens from each batch (and averaged for that maturity level).

As for batching errors, the potential always exists that the batch(es) produced during the calibration phase may not be representative of the actual concrete supplied to the project. As such, if a different mixer is used for calibration, extensive validation and verification should be done as soon as the production batch plant is operational.

9.2.5. Human Errors when Collecting Maturity Data or Calculating Strength from Maturity

As with any operation involving human interaction, the potential for unintentional oversight, negligence or even outright manipulation exists. With respect to determining flexural strength using maturity methods, several opportunities for error due to human involvement are possible. As such, preference should be given to systems and safeguards that can cost-effectively protect against instances of human error. The following list identifies some of these potential sources of human error:

- Calculating maturity values using the wrong datum temperature,
- Calculating maturity values using the wrong temperature data (e.g. accidentally swapping temperature data for two different locations),

- Converting maturity to strength using the wrong strength-maturity relationship curve (e.g. from a different mix design),
- Starting maturity sensors before the concrete is placed,
- Failing to correct for the effect of high internal concrete temperature on in-place flexural strength,
- Failing to verify the mix or validate the strength-maturity relationship, and
- Extrapolating beyond the range of maturity values tested during calibration.

In addition, the following activities can be a source of intentional error when using maturity to measure in-place pavement strengths:

- Manufacturing or altering temperature data,
- Testing calibration specimens at low temperatures, or
- Increasing the cement content, decreasing the w/cm or air content, or otherwise adulterating calibration batches in order to apparently achieve higher strengths earlier.

When it comes to sources of intentional error, no list can adequately encompass all such actions or intentions. Whereas considerable time (and thus financial) savings can result from the use or even misuse of maturity methods, preference should be given to the use of maturity systems and safeguards that can cost-effectively protect against such activities.

9.2.6. Nurse-Saul Errors

The Nurse-Saul maturity function assumes a linear increase in the rate of hydration with increasing temperature. Whereas, in actuality, chemical reactions follow an exponential increase in reaction rate with temperature, the Nurse-Saul method contains inherent errors. However, as discussed in Appendix B, these errors can be managed so that the resulting maturity calculations are always conservative. This is done by using a datum temperature of 5 °C and curing the standard calibration specimens in strict adherence to ASTM C192 (i.e. at 23 ± 2 °C). As shown in the discussion in Appendix B, this will cause any Nurse-Saul-related errors to be conservative. This does not, however, eliminate or reduce any of the other sources of error.

9.2.7. The Crossover Effect

The crossover effect is a very real source of error not just with maturity methods, but any time surrogate specimens are used to directly or indirectly determine the in-place strength of a pavement (unless those specimens are exactly “match-cured” with the pavement). The greater the difference in early-age temperatures between the pavement and the specimens the greater the potential impact of the crossover effect. It bears noting, however, that the crossover effect will tend to produce *conservative* errors whenever maturity is being used to determine *early-age* concrete strengths (which is normally the case).

As stated above, the crossover effect is not merely a limitation of the maturity method; it is a limitation affecting all strength-determination methods that rely upon specimens that are cured at temperatures other than the exact temperature profile of the in-place pavement. As such, this limitation applies to virtually ALL concrete quality control and strength-determination procedures in use throughout the United States.

This limitation is most commonly associated with the maturity method simply because it was discovered in conjunction with an in-depth study on maturity conducted by the National Bureau of Standards (NBS) (Carino 1984). During that study, Carino discovered that concrete specimens subjected to higher early-age temperatures achieved higher strengths at lower maturity values but lower strengths at higher maturity (versus those cured at low initial temperatures). This effect can be seen graphically in Figure 9.2.

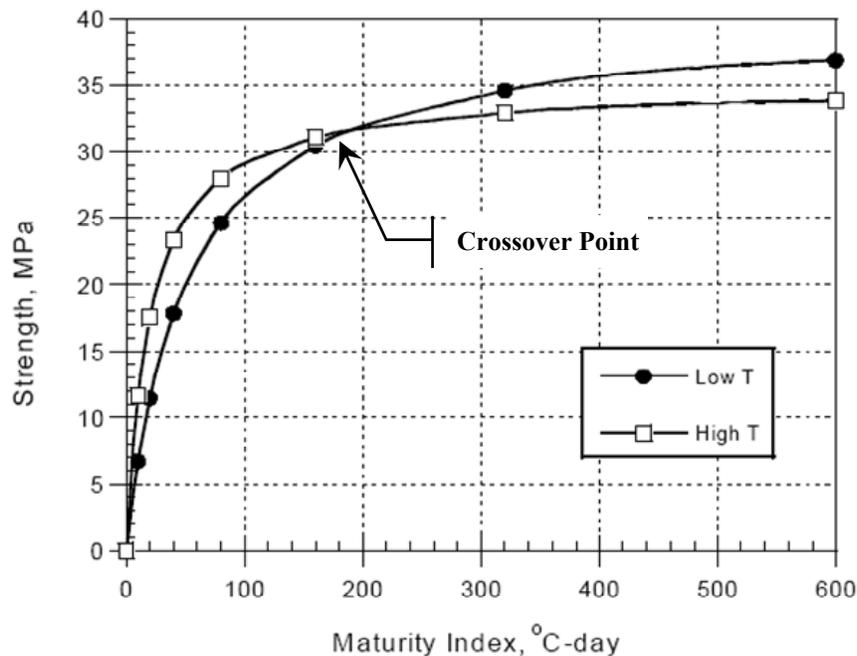


Figure 9.2 – Graphical Example of the Crossover Effect (Carino and Lew 2001)

The crossover effect can be better understood by way of a physical analogy – stacking blocks into a box. Suppose two people have each been given the task of stacking blocks into a small plastic box. We observe the two individuals attempt to accomplish this task in two very distinct ways. We see the first person (A) trying to get the blocks into the box as quickly as possible, while the second person (B) does so slowly and methodically. At the one-minute mark, we see that Person A has placed twice as many blocks in the box as Person B. We see Person A well ahead of Person B until Person A’s box is completely full. However, at this point, Person B steadily gains ground and eventually passes Person A with plenty of extra room in the box. In the end, Person B is able to stack 44% more blocks into the box than Person A. Figures 9.3 and 9.4 show this graphically.

With this hypothetical scenario, we see a crossover effect. Person A achieved higher block counts early on but a lower total block count. Person B’s block count ascended much more slowly but eventually “crossed over” Person A’s block count, thus achieving a higher ultimate block count (Figure 9.4).

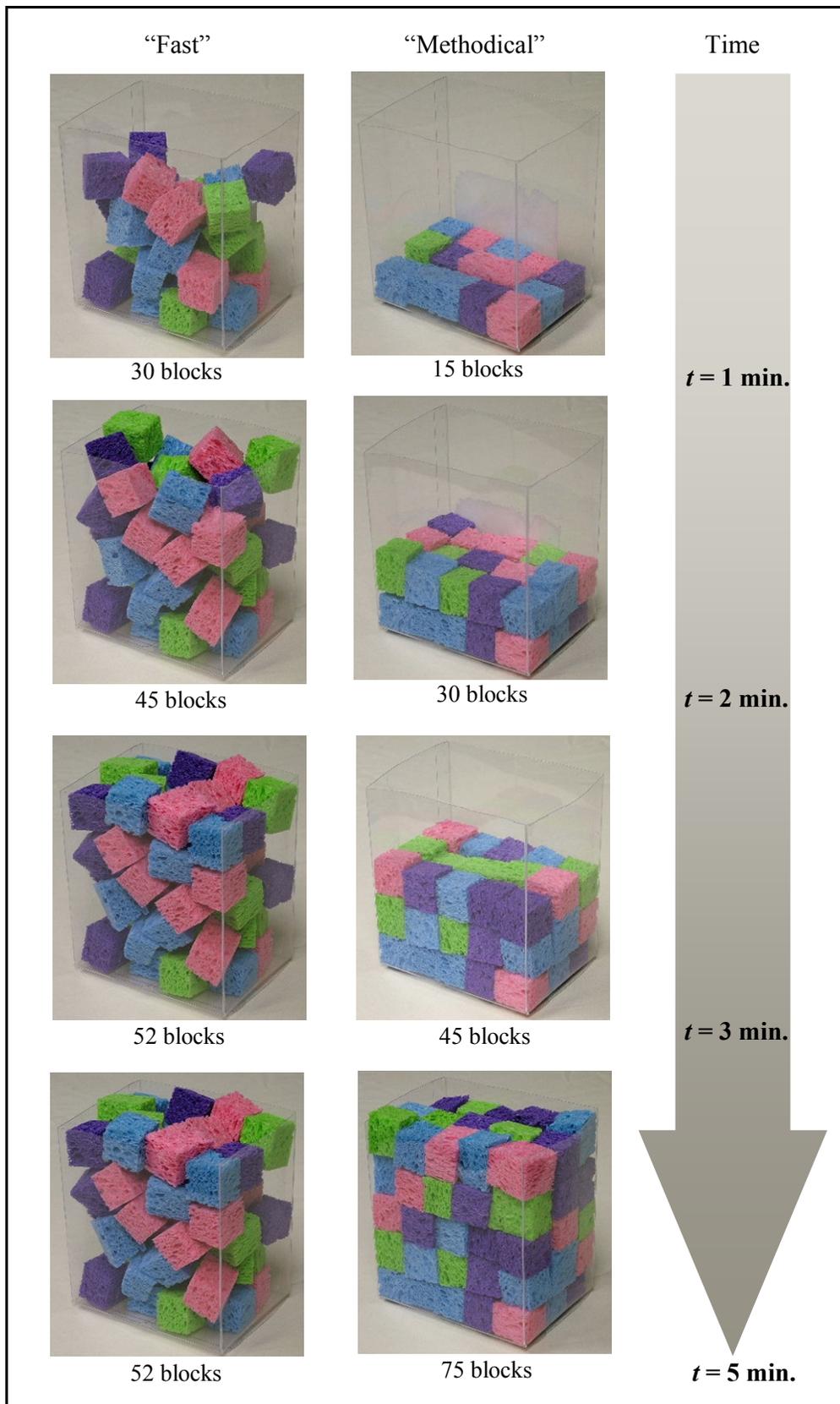


Figure 9.3 – Stacking Blocks: Visual Analogy to the Crossover Effect

This block-packing analogy has some distinct similarities to crystal growth. During crystal growth, new crystal molecules prefer to align themselves along the same spatial orientation as their nearest neighbors. However, when this process takes place very rapidly, the speed of crystal growth can outpace the affinity to self-align, thus leading to a “quicker” but “more random” and “less efficient” matrix. By contrast, a fairly slow rate of crystal growth enables the individual crystal molecules to self-align, thus leading to a “more uniform” and “more efficient” matrix.

Whereas the reaction products of hydrating cement are crystalline in nature (as shown in Figure 3.4), this block-packing analogy can help explain the crossover effect. Just as the slower packing of the blocks shown in Figure 9.3 led to a greater ultimate block count, slow cementitious hydration in concrete tends to yield higher overall strengths as shown in Figure 9.2. By contrast, more rapid cementitious hydration, though producing higher *early* strengths, tends to produce lower *ultimate* strengths than slow hydration. And, whereas the rate of cementitious hydration increases with temperature, concrete cured at high initial temperatures will gain strength very rapidly, but with a subsequent reduction in ultimate strength.

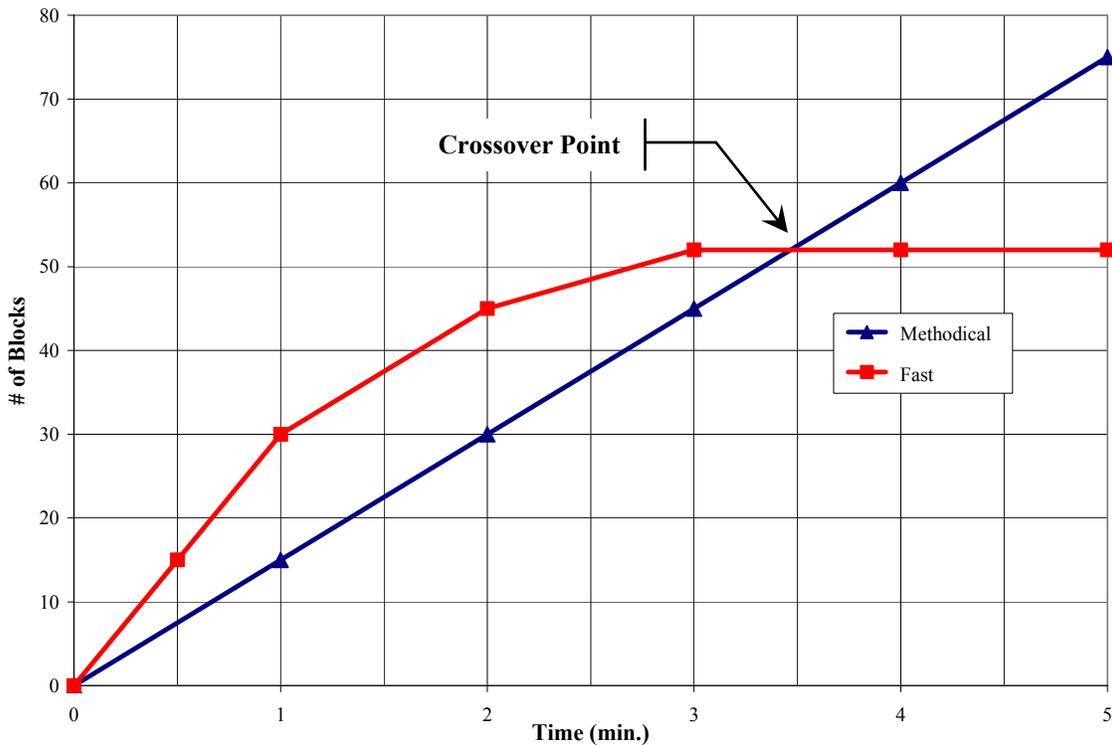


Figure 9.4 – Stacking Blocks: Graphical Analogy to the Crossover Effect

The crossover effect introduces the same amount of error to conventional strength testing as it does to maturity testing. The only way to completely nullify the crossover effect is to ensure that the specimens are cured at the exact same temperature as the pavement – a technique known as “match curing.”

10. Example Case Study Project

This hypothetical example provides a step-by-step demonstration of the implementation of maturity testing for the construction of an airfield runway extension.

10.1. Project Description

Consider an airfield paving project located in Tulsa, Oklahoma. The project consists of constructing a runway extension 150' x 1,500'; the typical pavement section for this project is shown in Figure 10.1. Placement of the airfield concrete is scheduled to begin July 25. The airport owner has decided to allow the use of concrete maturity in order to facilitate more strategic open-to-traffic decision-making. As such, the maturity method will be used to determine when the various pavement slabs may be opened to construction traffic. This will greatly facilitate placement of the lanes designated as Lane #3 and Lane #4 on Figure 10.1 below.

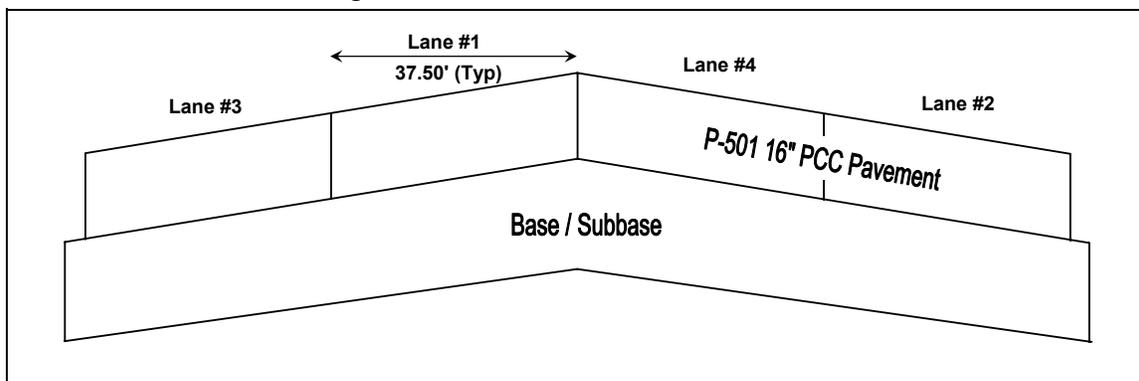


Figure 10.1 – Cross-Sectional View of Runway Extension

10.2. Establishing the Strength-Maturity Relationship

A flexural strength-maturity relationship curve will need to be established. This will enable in-place flexural strengths to be determined in real time, at any time. In addition, a two-point compressive strength-maturity curve will be established to enable ongoing, efficient mix verification throughout the project. The contractor has an on-site quality control laboratory consisting of two environmentally-controlled trailers. The trailers are equipped with calcium-hydroxide-saturated water tanks (for curing field-cast concrete specimens) as well as standard testing equipment for measuring flexural and compressive strength in accordance with ASTM C78 and C39.

10.2.1. Preparing the Calibration Specimens

During placement of the subbase, the contractor begins stockpiling materials for the P-501 portland cement concrete pavement. On July 11, fourteen days before airfield paving is scheduled to begin, the contractor mixes a 4 yd³ batch of concrete at the on-site concrete plant. This batch will be used to determine the strength-maturity relationship for the paving mix. This concrete is delivered to the quality control lab for the casting of sixteen (16) 6"x6"x21" beam specimens and nine (9) 4"x8" cylinder specimens.

The mix proportions, air content, and workability properties for this batch are verified to ensure that the strength-maturity relationship will be representative of the concrete that

will be used during construction (Table 10.1). Maturity sensors are also checked to verify that they are functioning properly before they are placed into the specimens.

Table 10.1 – Batch-Ticket Verification

Description	Mix Design Proportions		Mix Design Proportions (for a 4 CY Batch)		Actual Mix Proportions (as Recorded on Batch Ticket)		Fresh Concrete Properties (as Tested at Field Laboratory)	
	Batch Size: 4 CY							
Water-to-Cementitious	0.42	lb/lb	0.42	lb/lb	0.44	lb/lb	0.45	lb/lb
Portland Cement (Type I)	451	lb/cy	1,804	lb	1,820	lb		
Fly Ash (Class C)	113	lb/cy	452	lb	460	lb		
Coarse Aggregate	1,387	lb/cy	5,548	lb	5,575	lb		
Moisture Comp.					1.5	%		
Intermediate Aggregate	512	lb/cy	2,048	lb	2,045	lb		
Moisture Comp.					1.7	%		
Fine Aggregate	1,145	lb/cy	4,580	lb	4,598	lb		
Moisture Comp.					5.0	%		
Water	237	lb/cy	948	lb	1,002	lb		
Water Reducing Admixture	4	oz/cwt	16	oz	17	oz		
Air Entraining Admixture					24	oz		
Air Content	6.0	%	6.0	%			6.1	%
Unit Weight	142.4	pcf	142.4	pcf			143.4	pcf
Slump	1.25	in.					1.75	in.
Concrete Temp.							82.4	°F

After the mix proportions and fresh concrete properties are verified, the beam specimens are cast in accordance with ASTM C31. Two maturity sensors are inserted at approximately mid depth at the third points of one of the beams and as the sensors are activated, the time is noted as 14:15. The beams are covered and stored in the environmentally-controlled field lab for the first 16 to 32 hours in accordance with ASTM C192.

Concurrent with the beam casting, the cylinders are cast in accordance with ASTM C31. A maturity sensor is placed at approximately mid depth in one of the cylinders, the sensor is activated, and the time is noted as 14:30. The cylinders are capped and stored in the field lab for the first 16 to 32 hours in accordance with ASTM C192.

The following morning, July 12 at 10:00, the beams and cylinders are de-molded in accordance with ASTM C192, then, placed in the calcium-hydroxide-saturated water tanks meeting the requirements of ASTM C192.¹⁹

¹⁹ A datum temperature of 5°C is recommended. This recommended datum temperature is predicated on the curing conditions remaining as detailed in ASTM C192 (23 ± 2°C). In addition to adequate temperature controls, the lab should be free from vibration.

10.2.2. Testing the Calibration Specimens for Strength

Beam specimens are tested in accordance with ASTM C78 at 1 day, 2 days, 3 days, 5 days and 7 days. Three (3) beam specimens are tested at each age and the resulting flexural strength values are averaged. Results from outliers and obviously defective specimens are not included in the average strength calculations. Cylinder specimens are tested in accordance with ASTM C39 at 1 day and 3 days. Four (4) cylinder specimens are tested at each age and the resulting compressive strength values are averaged. Results from outliers and obviously defective specimens are not included in the average strength calculation.²⁰

The pertinent data for each strength test is recorded. The date and time of the test is included along with all the reporting requirements of ASTM C78 and ASTM C39. Table 10.2 and Table 10.3 show the data-collection results from the strength-testing performed during the strength-maturity calibration.

Table 10.2 – Results of Compressive Strength Testing

Compressive Strength Testing								
Project: Tulsa Airport Runway Extension								
Date / Time Cast: July 11 14:20								
Date / Time Tested	Lab Tech	Age (days)	Age (hrs.)	ID	Load (lbs.)	Diam. (in.)	Area (sq. in.)	f _c (psi)
July 12 14:00	PJM	0.99	23.67	C1A	16,300	4	12.57	1,297
July 12 14:10	PJM	0.99	23.83	C1B	17,100	4	12.57	1,361
July 12 14:15	PJM	1.00	23.92	C1C	17,400	4	12.57	1,385
July 12 14:20	PJM	1.00	24.00	C1D	16,800	4	12.57	1,337
1 day average strength								1,340
July 14 13:45	PJM	2.98	71.43	C3A	39,200	4	12.57	3,119
July 14 14:10	PJM	2.99	71.83	C3B	39,800	4	12.57	3,167
July 14 14:22	PJM	3.00	72.04	C3C	38,600	4	12.57	3,072
July 14 14:34	PJM	3.01	72.24	C3D	40,400	4	12.57	3,215
3 day average strength								3,140
Specimens stored and cured in accordance with ASTM C192								
All fractures were cone type								
No defects observed in specimens								
All specimens were molded (4" x 8")								
Neoprene caps were used for all tests								

²⁰ Regarding outliers, ASTM E178 provides guidance for determining whether an observation is an outlier and whether an outlier should be discarded. Alternatively, ASTM C1074 states that if the range of flexural strength of two specimens exceeds 15% of their average strength, test another beam and compute the average (but do not throw out any test results unless a low test result is due to an obviously defective specimen). In recognition of the relatively high variability associated with ASTM C78 flexural strength testing, averaging a minimum of three (3) beam specimens at each maturity level is recommended.

Table 10.3 – Results of Flexural Strength Testing

Flexural Strength Testing									
Project: Tulsa Airport Runway Extension									
Date / Time Cast: July 11 14:00									
Date / Time Tested	Lab Tech	Age (days)	Age (hrs.)	ID	Load (lbs.)	Width (in.)	Depth (in.)	Span (in.)	MR (psi)
July 12 15:00	GJF	1.04	25.00	F1A	2,400	6.05	6.05	18	195
July 12 15:10	GJF	1.05	25.17	F1B	2,450	6.05	6.10	18	196
July 12 15:20	GJF	1.06	25.33	F1C	2,390	6.00	6.00	18	199
1 day average strength									195
July 13 14:45	GJF	2.03	48.75	F2A	3,920	6.00	6.00	18	327
July 13 15:10	GJF	2.05	49.17	F2B	3,900	6.05	6.10	18	312
July 13 15:34	GJF	2.07	49.57	F2C	4,010	6.05	6.05	18	326
2 day average strength									320
July 14 15:14	GJF	3.05	73.23	F3A	4,870	6.20	6.00	18	393
July 14 15:38	GJF	3.07	73.63	F3B	3,000	6.05	6.10	18	240
July 14 15:56	GJF	3.08	73.93	F3C	5,010	6.05	6.05	18	408
3 day average strength									400
July 16 14:31	GJF	5.02	120.52	F3A	6,150	6.15	6.00	18	500
July 16 14:48	GJF	5.03	120.80	F3B	6,340	6.00	6.10	18	511
July 16 15:05	GJF	5.05	121.08	F3C	6,480	6.05	5.95	18	545
5 day average strength									520
July 18 15:07	GJF	7.05	169.12	F3A	8,150	6.00	6.05	18	668
July 18 15:24	GJF	7.06	169.40	F3B	8,200	6.05	5.95	18	689
July 18 15:41	GJF	7.07	169.68	F3C	7,920	6.05	6.20	18	613
7 day average strength									655
Specimens stored and cured in accordance with ASTM C192									
No beams required capping or grinding									
1/4-inch leather shims used for all tests (top and bottom)									
All specimens were molded (6" x 6" x 21")									
Test result F3B discarded - due to voids in specimen									

10.2.3. Collecting Maturity Data for the Calibration Specimens

The maturity data from the sensors that were placed in the calibration test specimens are downloaded subsequent to the strength testing at each age (1 day, 2 days, 3 days, 5 days and 7 days). These data files are stored for backup purposes. Upon conclusion of the final strength testing, the complete data set is downloaded and used to establish the strength-maturity relationship curves (one for flexural strength and one for compressive strength).

The temperature-time factor (TTF) is calculated for each set of strength specimens in accordance with ASTM C1074. A datum temperature of 5 °C is used to calculate the TTF maturity values (hereinafter referred to simply as “maturity” values). Table 10.5 shows the temperature history of the flexural strength specimens recorded at 15 min. intervals as well as the maturity values (°C-Hrs). The compressive strength specimens are treated in the same manner using the data from the maturity sensor that was embedded in the 4”x8” cylinder specimen.

10.2.4. Plotting the Strength-Maturity Relationship

The strength-maturity relationship is established in accordance with ASTM C1074. The strength and maturity values are graphed by plotting maturity on the x-axis (using a logarithmic scale) and flexural strength on the y-axis. Table 10.4 and Figure 10.2 represent the flexural strength-maturity relationship for the concrete paving mix.

Table 10.4 – Flexural Strength versus Maturity Calibration Data

Average Flexural Strength (psi)	Age (days)	Maturity (°C-Hrs)
195	1.05	747
320	2.05	1,280
405	3.07	1,739
520	5.03	2,620
660	7.06	3,520

The two-point compressive strength-maturity relationship curve is plotted in a similar manner as the flexural strength maturity curve (except that maturity is not plotted on a logarithmic scale). This two-point curve allows the contractor to frequently cast and test field cylinders during construction for mix-verification (to quickly identify potential changes to the batching process and/or the concrete testing). The two point compressive strength maturity curve data are shown in Table 10.6 and Figure 10.3.

10.3. Determining Staged Open-to-Traffic Thresholds

For this project, the contractor desires to open the pavement to construction traffic at the earliest possible times to facilitate placement of Lane #3 and Lane #4 (as shown in Figure 10.1). Various pieces of construction equipment will be used at different times during construction. The threshold open-to-traffic flexural strength and corresponding maturity value needs to be calculated for the following pieces of equipment: ½-ton pickup truck, 1-ton pickup truck, track-driven concrete belt placer/spreader, track-driven slipform paver, and tandem-axle dump trucks.

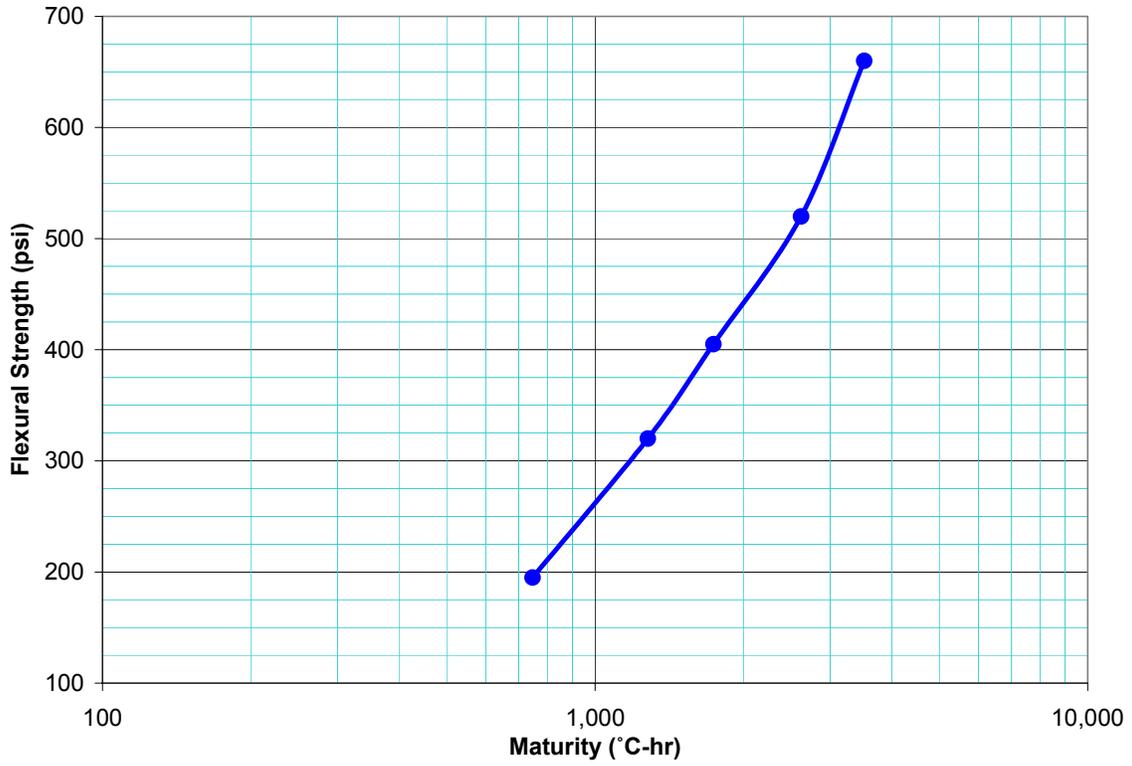


Figure 10.2 – Strength-Maturity Relationship Curve

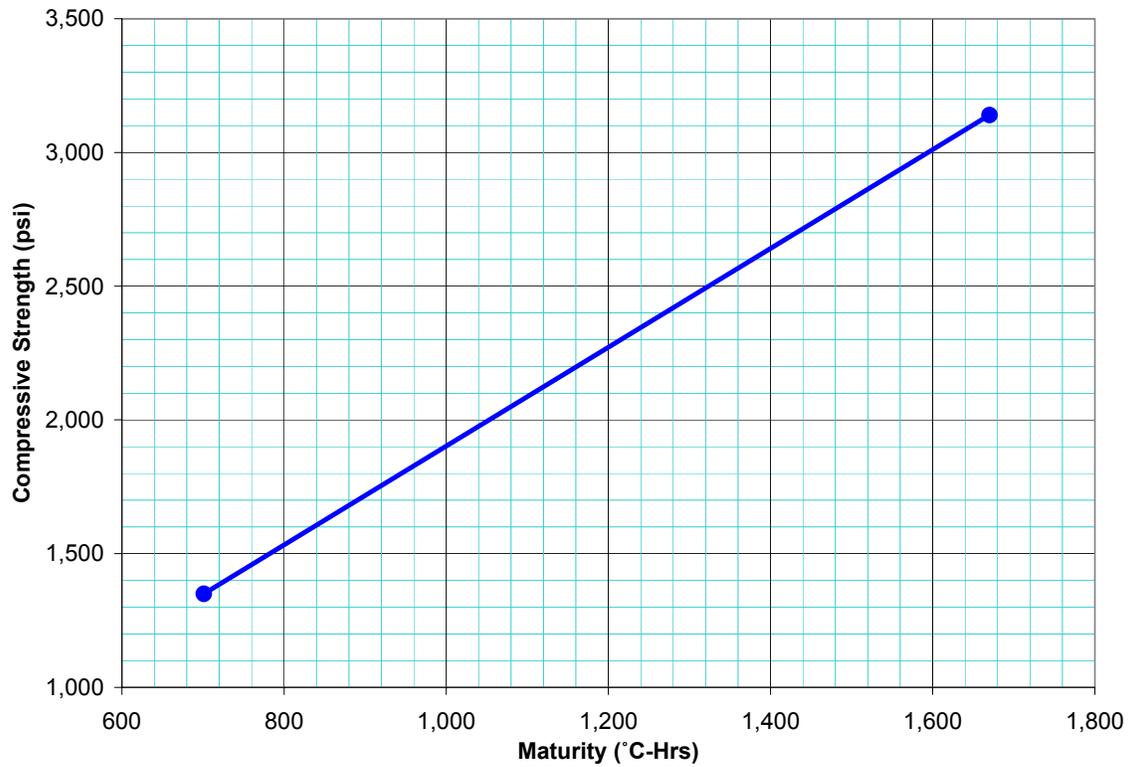


Figure 10.3 – Compressive Strength-Maturity Verification Curve

Table 10.5 – Maturity Sensor Download Data for Calibration Beams

Calibration Beam Specimens -- Maturity Sensor Data						
Datum temp = 5°C						
Date & Time	Temp. (°C)	Age Increment (hrs.)	Avg. Temp. (°C)	Maturity Increment (°C-Hrs.)	Cumulative Maturity (°C-Hrs.)	
July 11 14:15	28.5	-----	-----	-----	-----	
July 11 14:30	28.5	0.25	28.5	5.9	6	
July 11 14:45	29.5	0.25	29.0	6.0	12	
...	
July 12 14:30	33.5	0.25	33.5	7.1	730	
July 12 14:45	33.5	0.25	33.5	7.1	737	
July 12 15:00	33.0	0.25	33.3	7.1	744	
July 12 15:15	33.0	0.25	33.0	7.0	751	
July 12 15:30	33.0	0.25	33.0	7.0	758	
...	
July 13 14:15	24.5	0.25	24.5	4.9	1262	
July 13 14:30	24.5	0.25	24.5	4.9	1267	
July 13 14:45	24.5	0.25	24.5	4.9	1272	
July 13 15:00	24.5	0.25	24.5	4.9	1277	
July 13 15:15	24.5	0.25	24.5	4.9	1282	
July 13 15:30	24.5	0.25	24.5	4.9	1287	
July 13 15:45	24.5	0.25	24.5	4.9	1292	
...	
July 14 14:45	24.5	0.25	24.5	4.9	1721	
July 14 15:00	24.5	0.25	24.5	4.9	1726	
July 14 15:15	24.5	0.25	24.5	4.9	1731	
July 14 15:30	24.5	0.25	24.5	4.9	1736	
July 14 15:45	24.5	0.25	24.5	4.9	1741	
July 14 16:00	24.5	0.25	24.5	4.9	1746	
July 14 16:15	24.5	0.25	24.5	4.9	1751	
...	
July 16 14:00	24.5	0.25	24.5	4.9	2605	
July 16 14:15	24.5	0.25	24.5	4.9	2610	
July 16 14:30	24.5	0.25	24.5	4.9	2615	
July 16 14:45	24.5	0.25	24.5	4.9	2620	
July 16 15:00	24.5	0.25	24.5	4.9	2624	
July 16 15:15	24.5	0.25	24.5	4.9	2629	
...	
July 18 14:30	24.5	0.25	24.5	4.9	3513	
July 18 14:45	24.5	0.25	24.5	4.9	3518	
July 18 15:00	24.5	0.25	24.5	4.9	3523	
July 18 15:15	24.5	0.25	24.5	4.9	3528	
July 18 15:30	24.5	0.25	24.5	4.9	3532	
July 18 15:45	24.5	0.25	24.5	4.9	3537	

Table 10.6 – Compressive Strength versus Maturity Calibration Data

Average Compressive Strength (psi)	Age (days)	Maturity (°C-Hrs)
1,350	1.00	701
3,140	3.00	1,670

10.3.1. Identifying Construction Equipment Characteristics

The operating characteristics of each piece of equipment that will operate on the new pavement are researched and are found to be as follows:

Belt placer/spreader – Terex/CMI PS6004 – 37.50’ setup

- Gross weight = 136,000 pounds (includes concrete on belt) distributed equally over four identical tracks.
- Each track has a contact area of 18” x 72”, or 1,296 in².
- Total contact area = 4 x 1,296 in² = 5,184 in².
- Contact pressure = 136,000 pounds / 5,184 in² = 26.2 psi.

Slipform paver – Terex/CMI SF6004 – 37.50’ setup

- Gross weight = 120,000 pounds distributed equally over four identical tracks.
- Each track has a contact area of 18” x 72”, or 1,296 in².
- Total contact area = 4 x 1,296 in² = 5,184 in².
- Contact pressure = 120,000 pounds / 5,184 in² = 23.2 psi.

Tandem-axle dump truck loaded with 9 CY of concrete

- Gross weight = 54,000 pounds distributed equally over ten tires.
- Each tire has a contact area of 10” x 6”, or 60 in².
- Total contact area = 10 x 60 in² = 600 in².
- Contact pressure = 54,000 pounds / 600 in² = 90 psi.

1-ton dually pickup truck

- Gross weight = 12,000 pounds distributed equally over six tires.
- Each tire has a contact area of 9” x 5.4”, or 48.6 in².
- Total contact area = 6 x 48.6 in² = 291.6 in².
- Contact pressure = 12,000 pounds / 291.6 in² = 41.2 psi.

½-ton pickup truck

- Gross weight = 6,700 pounds distributed equally over four tires.

- Each tire has a contact area of 9” x 5.4”, or 48.6 in².
- Total contact area = 4 x 48.6 in² = 194.4 in².
- Contact pressure = 6,700 pounds / 194.4 in² = 34.5 psi.

10.3.2. Calculating Maximum Edge Stresses

The maximum edge stress applied by each piece of equipment is calculated using the American Concrete Pavement Association’s AirPave software. A step-by-step description of how to use AirPave to calculate maximum edge stresses for construction vehicles is provided in Appendix E. In addition, AirPave calculations for some of the equipment included in this example case study project are presented in Appendix F. Other methods such as influence charts, the Federal Highway Administration’s JSLAB software, generic finite element analysis software, and so forth, may also be used to calculate the maximum edge stresses caused by each piece of equipment. Detailed procedures and calculation examples using influence charts are provided in Appendices C and D.

The following assumptions are used for the maximum edge stress calculations in this example:

- Slab thickness, *h*, equals 16 inches;
- Modulus of subgrade reaction, *k*, equals 500 psi/in.
- Concrete modulus of elasticity (Young’s modulus), *E*, equals 4 x 10⁶ psi.

Table 10.7 summarizes the maximum edge stress calculations derived from the AirPave software for the aforementioned equipment.

Table 10.7 – Maximum Edge Stresses due to Construction Traffic (using AirPave)

Equipment / Vehicle	Gross Weight (lbf)	# of Wheels or Tracks	Contact Area (in ²)	Contact Pressure (psi)	Maximum Interior Stress (psi)	Maximum Edge Stress (psi)
1/2-ton Pickup	6,700	4	49	34	11	15
1-ton Pickup	12,000	6	49	41	20	27
Concrete Truck (Loaded)	54,000	10	54	100	54	72
Slipform Paver	120,000	4	1,296	23	93	124
Belt Placer / Spreader	136,000	4	1,296	26	104	139

10.3.3. Calculating Adjusted Strength Thresholds (using an factor of safety multiplier and offset)

For each piece of equipment, adjusted strength thresholds need to be calculated. The adjusted strength thresholds are calculated by applying a factor of safety equation to the maximum edge stresses for each equipment category.

Because the paving for this project is scheduled to take place in July, the Contractor and Engineer agree to use a strength-threshold adjustment based on a factor of safety multiplier equal to 2.5 with a factor of safety offset of 50 psi (for a resulting factor of safety = $2.5x + 50$ psi). This equation will be used to calculate the required staged opening strengths. In other words, the maximum edge stresses calculated from AirPave for each equipment category will be multiplied by 2.5 then increased by 50 psi in order to determine the minimum open-to-traffic threshold strength for equipment category. This strength-threshold adjustment is intended to provide for zero fatigue damage (via the multiplier) and also correct for errors due to elevated in-place temperatures. The resulting strength thresholds are presented in Table 10.8.

Table 10.8 – Strength Open-to-Traffic Thresholds by Equipment Category

Equipment Category	Maximum Edge Stress (psi)	Zero-Fatigue-Damage Safety Factor (2.5x) (psi)	Fatigue + Temperature Safety Factor (2.5x + 50) (psi)
Light Duty Trucks	27	67	117
Concrete Trucks (Loaded)	72	180	230
Slipform Paver	124	310	360
Belt Placer / Spreader	139	347	397

10.3.4. Calculating the Required Pavement Maturity Thresholds

The next step is to calculate the threshold open-to-traffic maturity values. This is accomplished by converting the opening *strength* criteria from Table 10.8 to opening *maturity* criteria using the strength-maturity relationship that was established for the mix (Figure 10.2). To do this, interpolate between the strength-maturity points (Table 10.4) to determine the corresponding maturity value that equates to each required opening strength. Table 10.9 provides the threshold strength and maturity values by equipment type.

Table 10.9 – Strength and Maturity Open-to-Traffic Thresholds by Equipment Category

Equipment Category	Open-to-Traffic Strength Threshold (psi)	Open-to-Traffic Maturity Threshold (°C-Hrs)
Light Duty Trucks	117	747
Concrete Trucks (Loaded)	230	896
Slipform Paver	360	1,496
Belt Placer / Spreader	397	1,696

It bears noting that the minimum required maturity value for “Light Duty Trucks” is 747 °C-Hrs even though the strength corresponding to 747 °C-Hrs is 195 psi (which is greater than the required strength threshold of 117 psi). The reason for this “discrepancy” is explained in Section 8.4, which states that strength-from-maturity values should never be extrapolated beyond the maturity extremes used to establish the strength-maturity relationship. Whereas the lowest maturity level tested was 747 °C-Hrs, that maturity value is taken as the lower limit and thus is used as the minimum threshold maturity value for the “Light Duty Trucks” equipment category.

Figure 10.4 below shows the strength and maturity open-to-traffic thresholds plotted against the strength-maturity relationship curve for the paving mix.

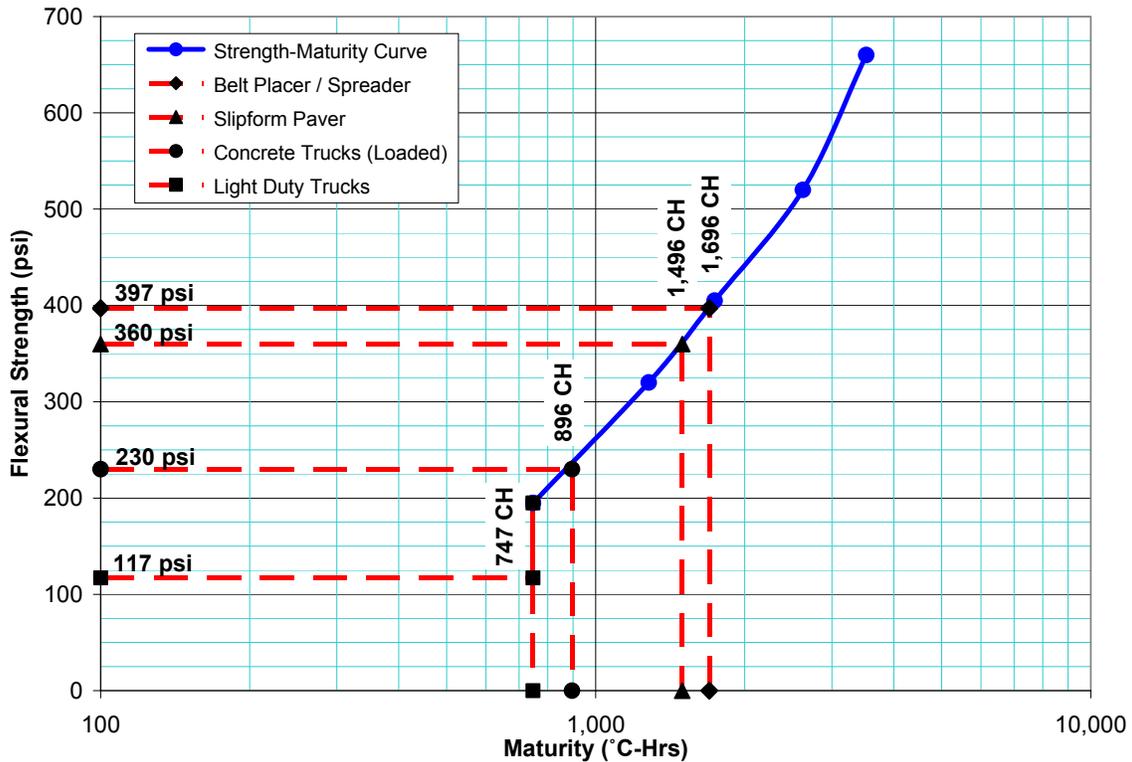


Figure 10.4 – Strength and Maturity Thresholds for Staged Opening to Traffic

10.4. Determining In-Place Maturity

Concrete paving begins on July 25 as scheduled with Lane #1 as shown on Figure 10.1. During construction, maturity sensors are placed in the concrete pavement at approximately mid-depth of the slab. Three sensors are placed during each day’s paving at the beginning, middle and end of the placement. Four (4) 4”x8” mix-verification cylinder specimens are cast at the same time each maturity sensor is placed; a maturity sensor is also placed into one of the cylinder specimens. To enable the mix-verification specimens to cure more rapidly, they are placed into conventional ice-chest style insulated “coolers” immediately after casting.

This process is repeated for Lane #2 on July 26. Figure 10.5 shows a plan view of the maturity sensor placement locations and times.

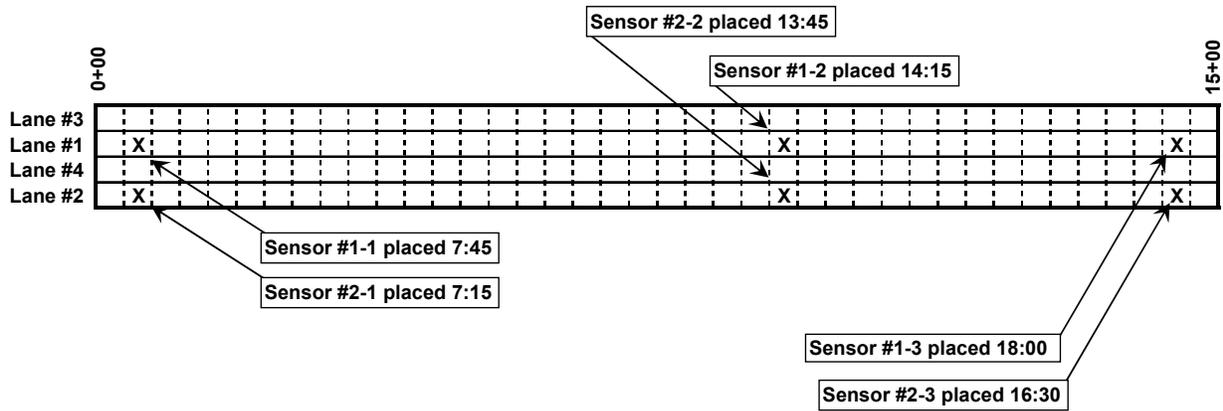


Figure 10.5 – Plan for Sensor Placement

The mix-verification cylinders are tested the day after being cast. The compressive test results from the three non-instrumented cylinders are averaged and plotted on the two-point compressive-strength mix-verification curve (Figure 10.3). Points that plot significantly below the line should be investigated. Figure 10.6 shows the verification points from Lane #1 and Lane #2 plotted against the verification curve. The verification results for Lane #2 (locations 2-1, 2-2 and 2-3) appear considerably higher than the results from the first day’s paving, suggesting that something may have changed with the mix.

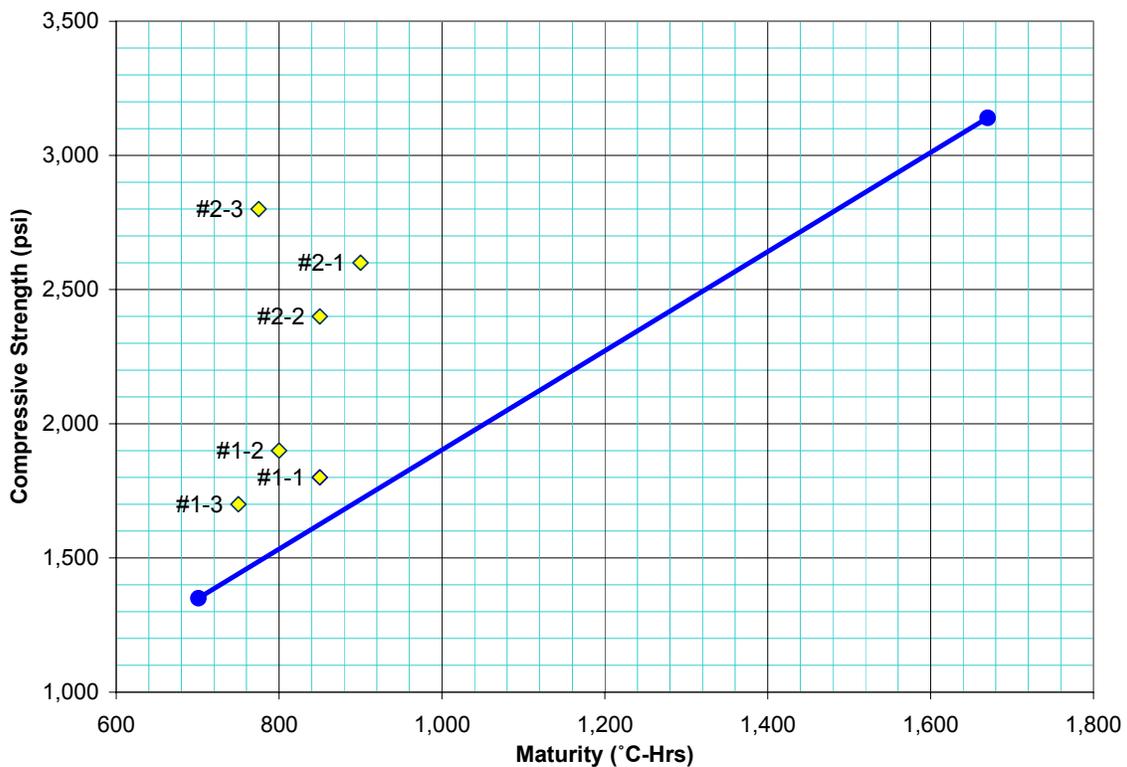


Figure 10.6 – Maturity Mix-Verification Plot

As soon as the compressive verification test results are available for set #2-1, a review of the batch tickets for the concrete that was used for Lane #2 is conducted. The batch weights from these tickets do not reveal any potential errors. Plant production is temporarily halted so that the scales can be checked for possible errors. Checking the scales reveals that the cement scale is out of adjustment and had been over batching cement by approximately 40 lb/yd³. Plant production resumes after all the scales have been verified and the cement scale recalibrated.

10.5. Opening the Pavement to Construction Traffic using Maturity

Before paving can commence on Lane #3, the contractor needs to verify and document that the pavement can be opened to construction traffic. On July 26 at 7:00 p.m., maturity sensors #1-1, #1-2 and #1-3 are downloaded to check the current maturity and in-place flexural strength of the concrete placed in Lane #1. The in-place maturity and the open-to-traffic times are presented in Figure 10.7 and Table 10.10. The pavement can be opened to construction traffic when the slab has reached the opening criteria shown in Table 10.9 and Figure 10.4 (which is 1,696 CH for the belt placer / spreader).

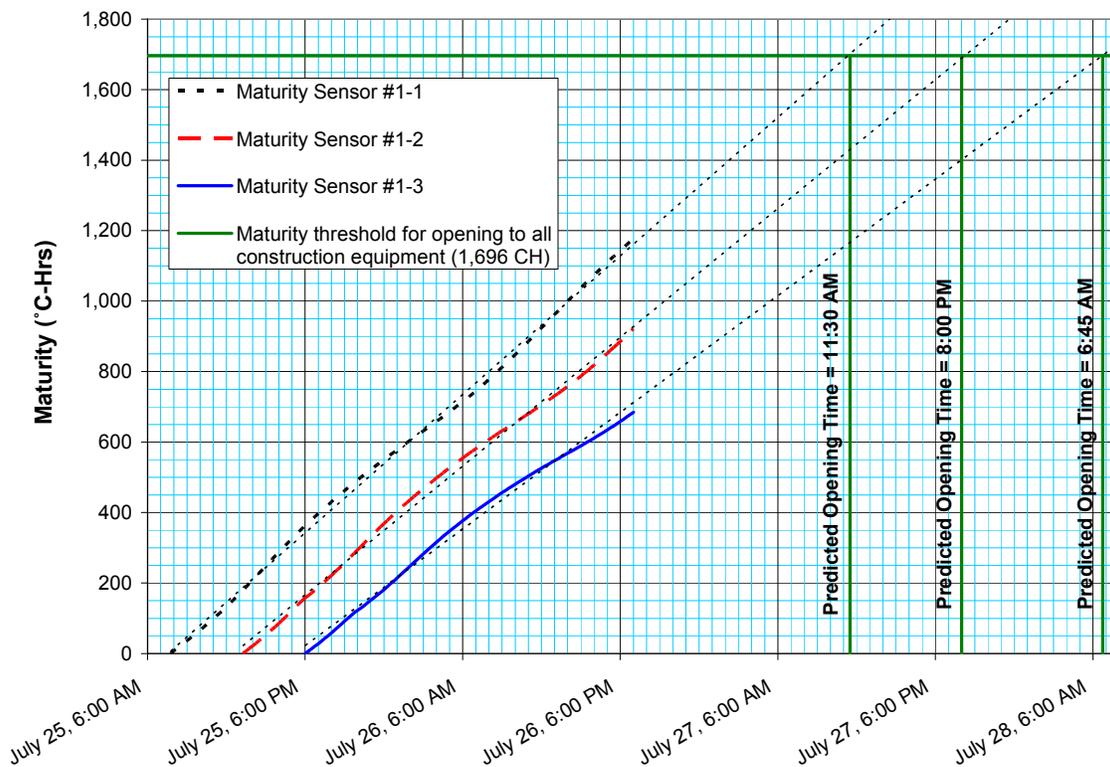


Figure 10.7 – Cumulative in-Place Maturity and Predicted Open-to-Traffic Times for Lane #1 (as of 7:00 p.m. on July 26)

Table 10.10 – In-Place Maturity & Strength Readings for Lane #1
(as of 7:00 p.m. on July 26)

Maturity Sensor (Location)	Current Maturity	Current Flexural Strength	Currently Allowed Equipment	Estimated Time to ALL Equipment
#1-1	1,177 CH	296 psi	Pickups, Concrete Trucks	11:30 a.m. July 27
#1-2	921 CH	236 psi	Pickups	8:00 p.m. July 27
#1-3	685 CH	< 195 psi	None	6:45 a.m. July 28

The estimated times in Figure 10.7 and Table 10.10 are based on a linear trendline (least-squares regression) plotted through the historical cumulative maturity data for each sensor, then extended until it intersects the desired maturity threshold. These regression lines are shown as thin dashed lines in Figure 10.7. Based on the trendline predictions, paving on Lane #3 (between locations 1-1 and 1-2) could begin as early as 8:00 p.m. the next day (July 27). However, paving between locations 1-2 and 1-3 cannot begin until around 6:45 a.m. on July 28. Based on average production rates for the contractor’s paving operation, it will take about 6 hours to reach the location adjacent to sensor #1-2 and another 4 hours to reach the location of sensor #1-3. Using this information, the paving superintendent schedules the paving and plant crews to start paving at 12:45 a.m. on July 28. This will allow uninterrupted paving for Lane #3 to begin at the earliest possible time.

At 1:15 p.m. on July 27, the paving superintendent downloads the maturity data from Lane #1 again and recalculates the anticipated times to meet the required open-to-traffic threshold. The latest maturity data, presented in Table 10.11 and Figure 10.8 show that the predicted open-to-traffic times have not changed – paving for Lane #3 should still be able to start shortly after midnight.

At 12:15 a.m. on July 28, the paving crew and batch plant operator arrive on the job site. The paving superintendent downloads the maturity data from sensor #1-2 to document that the required threshold maturity value has been achieved. At 12:45 a.m., paving for Lane #3 begins. Throughout the placement, the paving superintendent periodically checks the maturity at location 1-3 to make certain that the required maturity and strength threshold will be met by the time the belt placer / spreader reaches that point.

At 6:25 a.m., approximately 30 minutes before the paving equipment reaches location 1-3, the maturity at location 1-3 exceeds the required threshold. The paving superintendent downloads the maturity data in order to provide documentation that the required strength was achieved prior to the paving equipment reaching that location.

At 9:00 a.m. on July 28, Lane #3 is complete.

Table 10.11 – In-Place Maturity & Strength Readings for Lane #1
(as of 1:15 p.m. on July 27)

Maturity Sensor (Location)	Current Maturity	Current Flexural Strength	Currently Allowed Equipment	Estimated Time to ALL Equipment
#1-1	1,754 CH	407 psi	ALL	Now
#1-2	1,468 CH	355 psi	Pickups, Concrete Trucks	8:00 p.m. July 27
#1-3	1,201 CH	301 psi	Pickups, Concrete Trucks	6:45 a.m. July 28

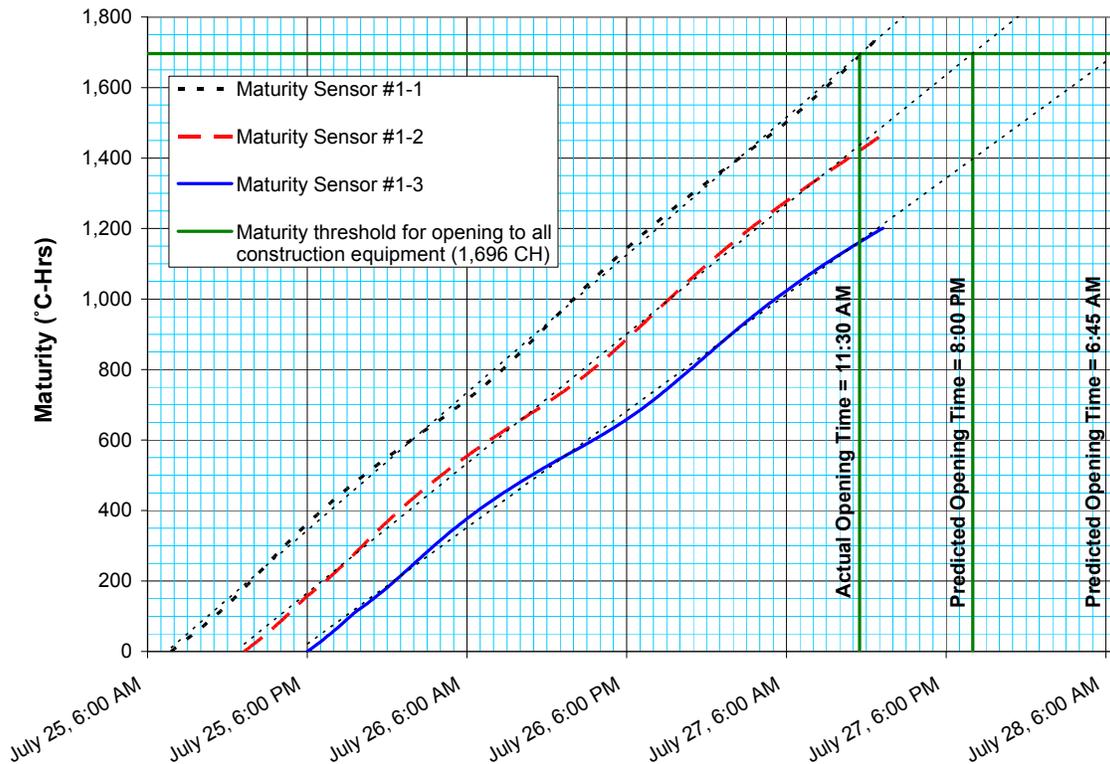


Figure 10.8 – Cumulative In-Place Maturity and Predicted Open-to-Traffic Times for Lane #1 (as of 1:15 p.m. on July 27)

10.6. Performing a Two-Point Validation of a Mix Change.

On July 29, the fly ash source needs to be changed due to an unplanned shutdown at the power plant supplying fly ash to the project. When any mix change occurs, the strength-maturity relationship must be validated prior to continuing to use maturity for open-to-traffic decisions. Whereas the contractor has experienced considerable time savings from using maturity, the project manager quickly arranges for the new mix to be validated.

The same morning that the source change occurs (July 29), seven beams are cast. Two maturity sensors are placed at approximately mid-depth in one of the beam specimens (at the third points). To validate the existing strength-maturity relationship, the beams

should be broken at ages that bracket the maturity opening criteria for the majority of construction traffic loading. For this project, the validation beams will be broken at maturity levels that encompass the opening criteria for loaded tandem-axle dump trucks and the belt placer/spreader (896 °C-Hrs to 1,696 °C-Hrs). The contractor decides to break the beam specimens in two groups (average of three beams at each maturity level); the first at approximately 800 °C-Hrs and the second set at approximately 1,700 °C-Hrs.

Periodic monitoring of the maturity sensors placed in one of the validation beams determines when the beams will be broken. A tabulation of the validation test results is shown in Table 10.12.

Table 10.12 – Maturity versus Strength for Changed Mix

Maturity (°C-Hrs)	Average Flexural Strength (psi)
797	295
1,709	410

These values are plotted on the original strength-maturity relationship curve as shown in Figure 10.9. A line is also drawn between the two points and extended in both directions.

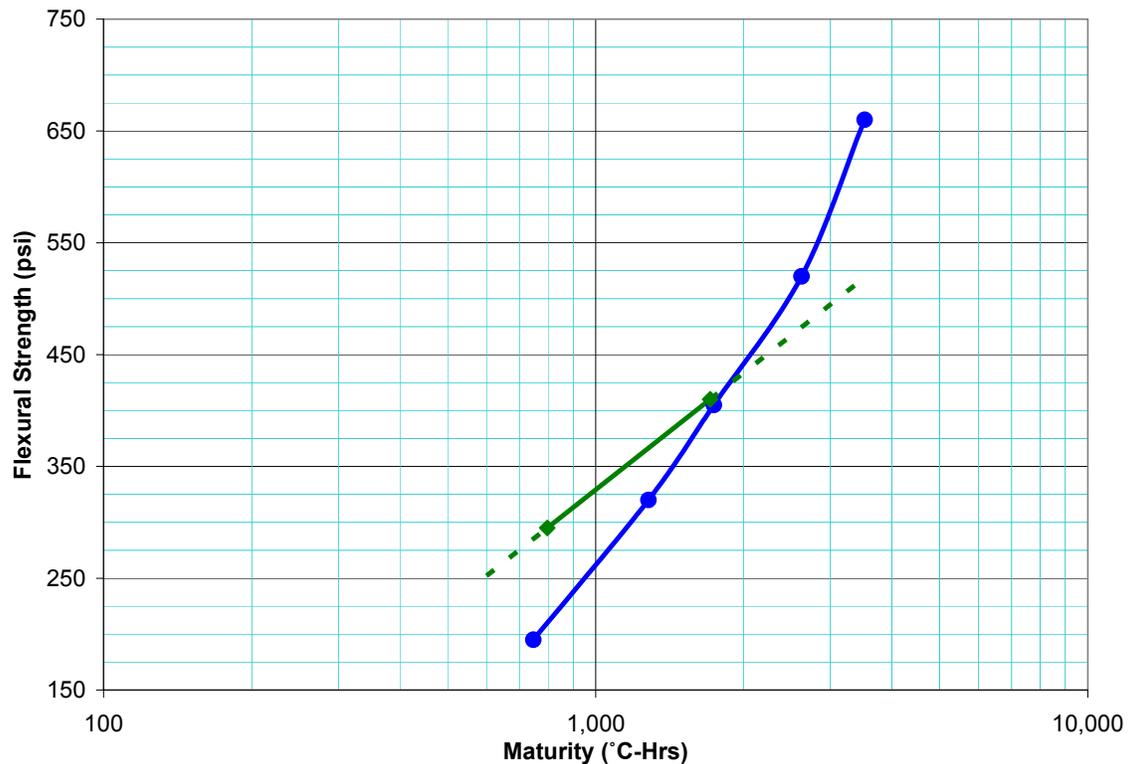


Figure 10.9 – Mix Change Plot versus Original Maturity Curve

Whereas both validation points fall above the original strength-maturity relationship curve, the original curve is determined to be valid within the maturity limits of the two-point mix validation (797 to 1,709 °C-Hrs). However, whereas the extension of the two-

point validation line intersects the original curve, the use of maturity beyond 1,709 °C-Hrs is not warranted – a wider two-point validation or a new strength-maturity relationship curve would be needed to validate the mix change outside this range. However, whereas the project manager wisely chose an upper maturity value for the two-point validation that is greater than the maturity threshold for the heaviest equipment category, the original strength-maturity curve can continue to be used just as it has been.

11. Appendix A – Glossary

Average Cure Temperature

Average cure temperature refers to the average internal concrete temperature over the period of interest. When current maturity is known in terms of temperature-time factor (TTF), the average cure temperature is easily back-calculated as the current TTF divided by the elapsed time plus the datum temperature. For example, if the current TTF is 600 °C-Hours, the elapsed time is 24 hours, and the datum temperature is 5 °C, then the average cure temperature is 30 °C ($= 600 / 24 + 5$).

Calibration Specimens

The term “calibration specimens” refers to the concrete specimens cast and tested for development of the Maturity Calibration Curve for a given concrete mix design.

Concrete Maturity

Concrete maturity refers to the degree of cementitious hydration that has occurred within a mass of concrete. Concrete maturity can be expressed in various ways (e.g. percent-hydration, age, temperature-time factor, equivalent age). In the context of this handbook, the terms “concrete maturity” and “maturity” will mean concrete maturity expressed as “temperature-time factor”.

Concrete Quality Control Plan (CQCP)

Concrete Quality Control Plan (CQCP) refers to a quality control plan prepared by the Contractor as part of the Contractor Quality Control Program. The CQCP should detail the necessary methods and procedures to assure that all concrete materials and completed concrete construction items conform to contract plans, technical specifications and other requirements. With regards to concrete maturity, the CQCP will incorporate the necessary methods and procedures to assure that the limitations and potential sources of error identified in this handbook will be adequately addressed throughout the project.

Contractor Quality Control Program

Contractor Quality Control Program refers to a quality control program prepared by the Contractor in conformance with the requirements of SECTION 100-01. In general, under the Contractor Quality Control Program, the Contractor must establish, provide, and maintain an effective quality control program that details the methods and procedures that will be taken to assure that all materials and completed construction conform to contract plans, technical specifications and other requirements, whether manufactured by the Contractor, or procured from subcontractors or vendors.

Datum Temperature

Theoretically, datum temperature refers to the temperature below which the cementitious hydration in a mass of concrete will cease. As such, test methods are available for experimentally determining the datum temperature of a particular concrete mix design (see ASTM C1074-04). However, common practice in the industry involves establishing

and adhering to a default datum temperature, in lieu of experimentally-determined values. When used to calculate maturity, the datum temperature represents the lower boundary for the area calculation on the temperature-time curve. The use of a default datum temperature of 5 °C and curing calibration specimens in accordance with ASTM C 192 is recommended in lieu of using experimentally-determined datum temperatures.

Maturity Calculation Method

Numerous methods for calculating concrete maturity have been proposed over the past several decades. The two most prominent methods are the Nurse-Saul method, determined empirically by R. W. Nurse and A. G. A. Saul between 1949 and 1951, and the Arrhenius method, first presented by P. Freiesleben-Hansen and E. J. Pedersen in 1977 (based on the exponential rate law proposed by Svante Arrhenius in 1888). The Nurse-Saul method computes maturity as a maturity index value, or temperature-time factor (TTF), in units of temperature times time (such as °C-Hours), while the Arrhenius method calculates maturity in units of “equivalent age” via an age conversion factor called the equivalent age factor. The Nurse-Saul method is recommended.

Maturity Calibration Curve

The terms “calibration curve” and “maturity calibration curve” refer to the mix-specific strength-maturity relationship that must be empirically established prior to using maturity methods to measure in-place concrete strength. The concrete maturity method is based on the assumption that a unique strength-maturity relationship (i.e. a unique “maturity calibration curve”) exists for a given concrete mix design. This assumption was succinctly summarized by one of the founders of the maturity method (A. G. A. Saul) as follows:

Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity.

NOTE: The mix-specific nature of each strength-maturity relationship requires adequate quality control of the concrete batching process to ensure that the quality and proportioning of the raw materials remain consistent.

Maturity Level

Maturity level refers to the enumeration of the distinct ages (or maturity values) at which the strength-maturity relationship, or calibration, testing is performed. For example, if tests are performed at specimen ages of 1, 3, 5, 7, 14 and 28 days, the tests performed on day “5” could also be referred to as those of maturity level “3”, representing the third data point on the strength-maturity relationship table or graph.

Temperature-Time Factor (TTF)

Temperature-time factor (TTF), sometimes referred to as the “maturity index value”, or more simply as “maturity”, refers to the area under the concrete temperature curve when

plotted as a function of time. The area is typically calculated as a summation of trapezoidal areas after dividing the time scale into discrete time units (e.g. 0.25-hours). The incremental area is then calculated by averaging the starting and ending temperatures for the time unit, subtracting a lower temperature boundary from the average temperature value, then multiplying by the discrete time unit. The lower temperature boundary for the area calculation is known as the “datum temperature.” Whereas TTF represents area on a temperature-time curve, the corresponding units are temperature times time (e.g. °C-Hours). This expression of concrete maturity is most commonly associated with the Nurse-Saul method for determining concrete strength from maturity.

SECTION 100-01

SECTION 100-01 establishes the minimum requirements for the Contractor’s Quality Control Program, requiring the Contractor to establish, provide, and maintain an effective Quality Control Program that details the methods and procedures that will be taken to assure that all materials and completed construction conform to contract plans, technical specifications and other requirements. The intent of SECTION 100-01 is to enable the Contractor to establish a necessary level of control that will:

- (a) Adequately provide for the production of acceptable quality materials.
- (b) Provide sufficient information to assure both the Contractor and the Engineer that the specification requirements can be met.
- (c) Allow the Contractor as much latitude as possible to develop his or her own standard of control.

Strength-Maturity Relationship

“Strength-maturity relationship” refers to the unique strength-development curve for a given concrete mix design expressed in terms of concrete maturity. For purposes of this handbook, concrete maturity for strength-maturity relationships will be calculated and reported as temperature-time factor (TTF) (in °C-Hours, sometimes referred to by the shorthand notation “CH”) in accordance with the Nurse-Saul equation. Strength can be measured as compressive, flexural, splitting-tensile, direct tension, or pullout strength. Strength is typically displayed as a function of maturity (i.e. maturity plotted along the axis of abscissas, or x-axis, and strength on the axis of ordinates, or y-axis).

Validation of the Strength-Maturity Relationship

Validation refers to the process of demonstrating that the strength-maturity *relationship* for the concrete mix has not changed. Some issues that could potentially affect the strength-maturity relationship include raw material variability, raw material source changes, mixture proportion changes, admixture changes, and excessive batching variability (e.g. batch proportions not meeting required tolerances).

Validation Specimens

The term “validation specimens” refers to the concrete specimens cast and tested for the purpose of validating that the strength-maturity *relationship* for a given concrete mix has not changed.

Verification of the Concrete Mix using the Strength-Maturity Relationship

Verification refers to the process of making sure that the *concrete* supplied to the project site is truly representative of the concrete used to establish the mix-specific strength-maturity relationship. Verification is a powerful technique of using maturity methods to provide timely feedback and quality control with respect to concrete strength and the rate of strength gain.

Verification Specimens

The term “verification specimens” refers to the concrete specimens cast and tested for purposes of verifying that the concrete supplied to the project site is truly representative of the concrete used to establish the mix-specific strength-maturity relationship.

12. Appendix B – Why use Nurse-Saul? Why use a 5 °C Datum Temperature?

The Nurse-Saul equation for calculating concrete maturity relies upon a “datum temperature” as the basis for the maturity calculations. By contrast, the calculation of maturity using the Arrhenius equation is governed by the “apparent activation energy” of the concrete mix. ASTM C1074 provides recommended procedures for experimentally determining the datum temperature and the apparent activation energy for a specific concrete mix. However, as will be discussed herein, the use of an experimentally-determined datum temperature or apparent activation energy to characterize a concrete mix for *all possible* curing conditions can produce undesirable effects. In lieu of experimentally-determined values, the use of the Nurse-Saul equation with a universal default datum temperature of 5 °C is recommended. The following paragraphs explain the rationale for this recommendation.

The Arrhenius Equation

The Arrhenius equation for calculating concrete maturity assumes an *exponential* relationship between internal curing temperature and the rate of strength gain. The Arrhenius equation for calculating maturity is as follows:

$$t_e = \sum_0^t \left[e^{-\frac{E_a}{R} \left(\frac{1}{T+273} - \frac{1}{T_{ref}+273} \right)} \cdot \Delta t \right] \quad \text{Equation 12.1}$$

where

t_e = concrete maturity expressed as equivalent age²¹ (in hours or days)

e = natural logarithm constant (= 2.7183)

E_a = apparent activation energy (in J/mol)²²

R = universal gas constant (= 8.3144 J/mol/K)

T = average internal curing temperature (in °C) during time interval Δt

T_{ref} = reference temperature (in °C)

Δt = length of time interval (in hours or days)

²¹ Equivalent age represents the “age” of a mass of concrete expressed in terms of the actual age (in actual hours or days) of a separate, but similar, mass of concrete cured at a reference temperature. Two concrete masses having the same equivalent age are said to be equivalent in terms of the degree of cementitious hydration that has occurred within each mass. This expression of concrete maturity is most commonly associated with the Arrhenius method for determining concrete strength from maturity. However, the Nurse-Saul equation can be rearranged so as to calculate the Nurse-Saul maturity value to an equivalent age or equivalent age factor.

²² Sometimes the ratio E_a/R is replaced by the term Q , which is simply the apparent activation energy (E_a) divided by the universal gas constant (R), where the resulting Q value is in units of Kelvin. (Conversion from °C to Kelvin: Kelvin = temperature in °C + 273)

The Nurse-Saul Equation

The Nurse-Saul method assumes a *linear* relationship between curing temperature and strength gain and, as such, uses the following equation to calculate maturity:

$$M = \sum_0^t [\max[0, (T - T_o)]] \cdot \Delta t \quad \text{Equation 12.2}$$

where

M = concrete maturity expressed as temperature-time factor (TTF) (in °C-Hours)

T = average internal curing temperature (in °C) during time interval Δt .

T_o = datum temperature (in °C)

Δt = length of time interval (in hours)

The theoretical explanation of datum temperature is that temperature for a given concrete mix below which all hydration reactions cease. As such, when the temperature of the concrete falls below the datum temperature, no net gain in maturity is recorded by the Nurse-Saul equation. Early practitioners of the maturity method, reckoning that no hydration occurs below the freezing point of water, used 0 °C (32 °F) for their datum temperature. Later, researchers demonstrated that concrete continues to gain strength even as low as -10 °C (14 °F). As such, many current proponents of the Nurse-Saul maturity function use or recommend -10 °C (14 °F) for a datum temperature. However, as will be discussed later, the use of a -10 °C (14 °F) datum temperature is not recommended.

Comparison of the Nurse-Saul and Arrhenius Equations

As for the Arrhenius equation, experts recognize that its exponential model provides a theoretically more accurate portrayal of the temperature-dependence of the hydration reactions that occur within concrete (Carino and Lew 2001). This is due to the fact that chemical reactions are known to follow an *exponential* rate law with respect to temperature, rather than the *linear* model assumed by the Nurse-Saul equation. Even so, the hydration of cementitious materials within a concrete mass involves many different chemical reactions, each ramping up and down differently and at different times throughout the curing process and each having its own unique activation energy. As such, the use of a *single* apparent activation energy value to characterize the temperature-dependence of the concrete's strength-gain for *all curing conditions* may, at times, provide quite unexpected or undesirable results. This is because apparent activation energy is the significant variable in the exponent and the activation energy is reaction-dependent and, therefore, time-dependent as the concrete hydrates. The time-dependent nature of apparent activation energy was well-documented by Abdel-Jawad (1988) and follows logically from the understanding that different chemical reactions are occurring at different times as the concrete continues to hydrate (with each reaction having its own activation energy).

The net result of the exponential nature of apparent activation energy is that small variations in apparent activation energy can effectuate large changes in the calculated maturity value. This effect is then exacerbated by the time-dependent nature of apparent activation energy. These variations in calculated maturity can lead to substantial variations in predicted strength. At times, these variations may err on the conservative side. However, at other times these variations may be unconservative and, as such, can lead to undesirable conditions (e.g. loading the pavement prior to achieving the required strength).

In summary, the apparent activation energy for the concrete mix cannot be precisely determined ahead of time and the apparent activation energy can vary throughout the curing process (as different reaction products are used up and others are created) and/or throughout the life of a project (as cementitious materials with differing chemical compositions and/or other quality characteristics may be supplied throughout the life of a construction project, even when the materials are received from the same “source”). This uncertainty about the “true” apparent activation energy of the concrete mix creates a situation wherein one cannot know whether the corresponding maturity calculations are conservative or unconservative and, subsequently, whether the strength predictions based on those maturity calculations are conservative or unconservative. In a similar, but less severe, fashion, the Nurse-Saul method can, at times, be unconservative. The impact is usually less severe due to the fact that the Nurse-Saul method assumes a linear rather than exponential relationship between temperature and hydration reaction rates.

Maturity Calculation Errors

Figure 12.1 below provides a graphical comparison of two different datum temperatures (-10 °C and 5 °C) compared against two extreme values for apparent activation energy (30 kJ/mole and 60 kJ/mole). Any time a chosen curve falls above the “true” curve, an unconservative error will result. For instance, if the “true” apparent activation energy is 60 kJ/mole and a -10 °C (14 °F) datum is chosen, the subsequent maturity calculations will be conservative whenever the in-place concrete temperature is above 23 °C (73 °F) and unconservative below 23 °C (73 °F). By contrast, if a 5 °C (41 °F) datum is chosen, the resulting maturity calculations will be conservative irrespective of the in-place concrete temperature and irrespective of the “true” apparent activation energy.

Also, Figure 12.1 demonstrates the danger of using the Arrhenius method and choosing a wrong apparent activation energy. This is evident from the figure in that if the “true” apparent activation energy is high (e.g. 60 kJ/mole) and the chosen apparent activation energy is low (e.g. 30 kJ/mole), the maturity calculations will be unconservative at low temperatures (i.e. below 23 °C). And, if the reverse is true (i.e. too low a value is chosen), the resulting calculations will be unconservative at high temperatures (i.e. above 23 °C).

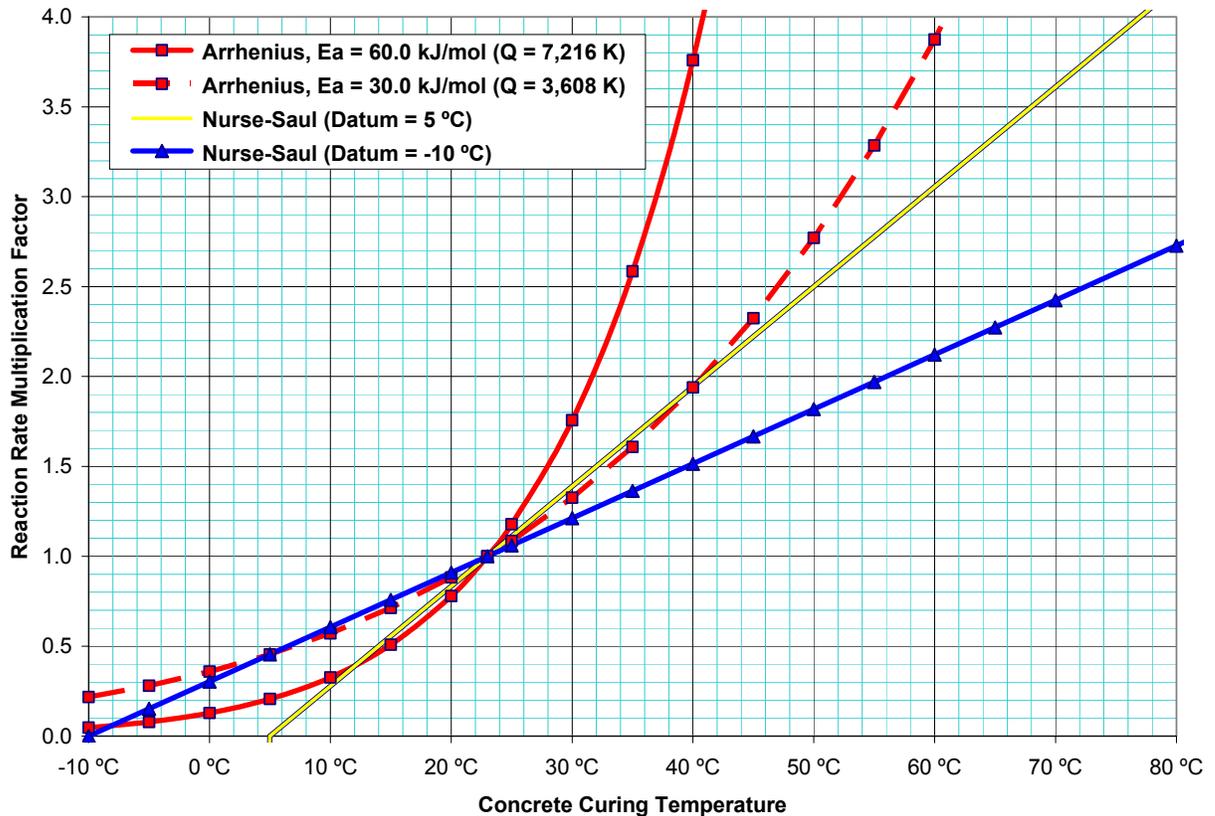


Figure 12.1 – Graphical Comparison of Datum Temperatures (adapted from Carino and Lew 2001)

Strength Prediction Errors

Figure 12.2 demonstrates the danger of using a -10 °C datum temperature by way of a hypothetical example while Figure 12.3 shows the conservative nature of a 5 °C datum temperature. The examples shown in Figures 12.2 and 12.3 are based on the hypothetical strength-maturity relationships shown in Figure 12.4 and the hypothetical in-place temperature profile shown in Figure 12.5. As can be seen in this hypothetical example, Nurse-Saul maturity can over predict in-place strength by as much as 60% when a -10 °C datum is used; however the hypothetical strength predictions remain conservative with the 5 °C datum temperature. A similar analysis of Arrhenius-based strength predictions (which is beyond the scope of this document) shows that similar and, at times, even greater prediction errors can occur when the Arrhenius equation is used and the chosen apparent activation energy is above or below the “true” activation energy.

In light of the aforementioned discussion, the use of the Nurse-Saul maturity equation with a 5 °C datum temperature is recommended.

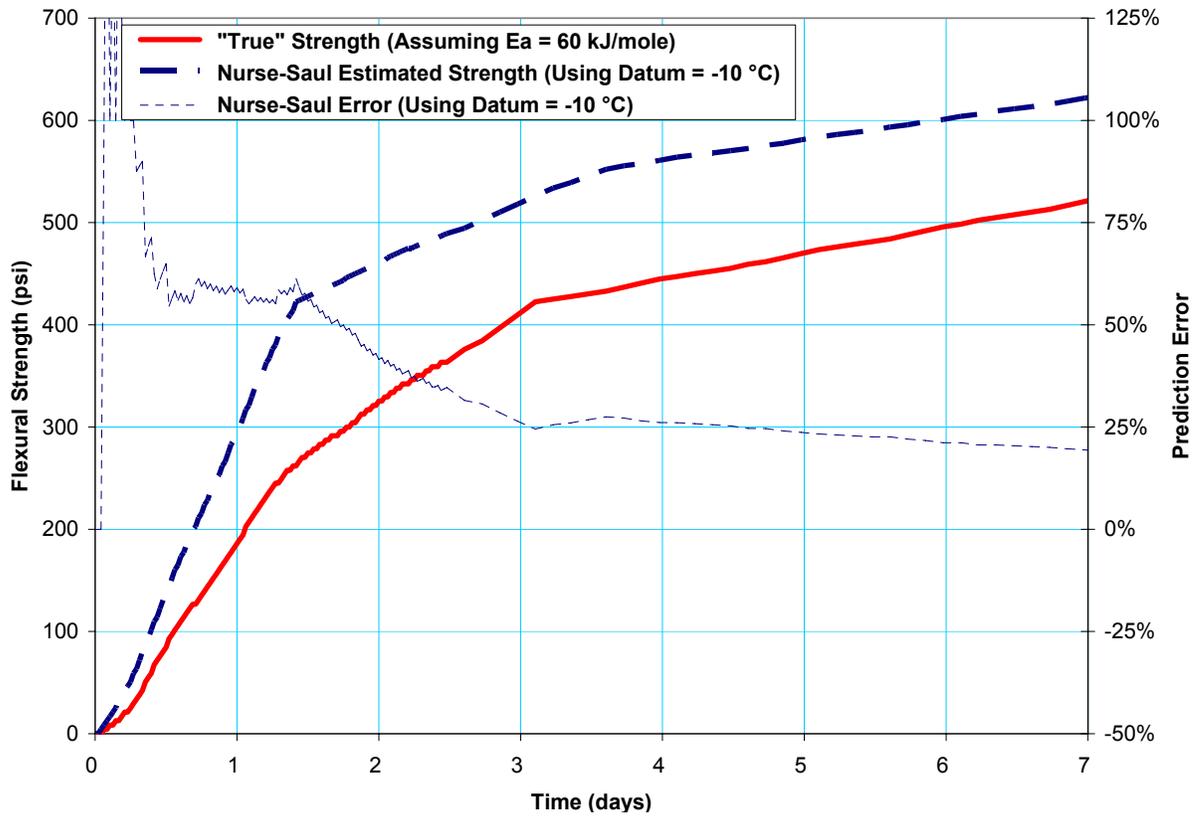


Figure 12.2 – Hypothetical Strength-Prediction Error using -10 °C Datum Temperature

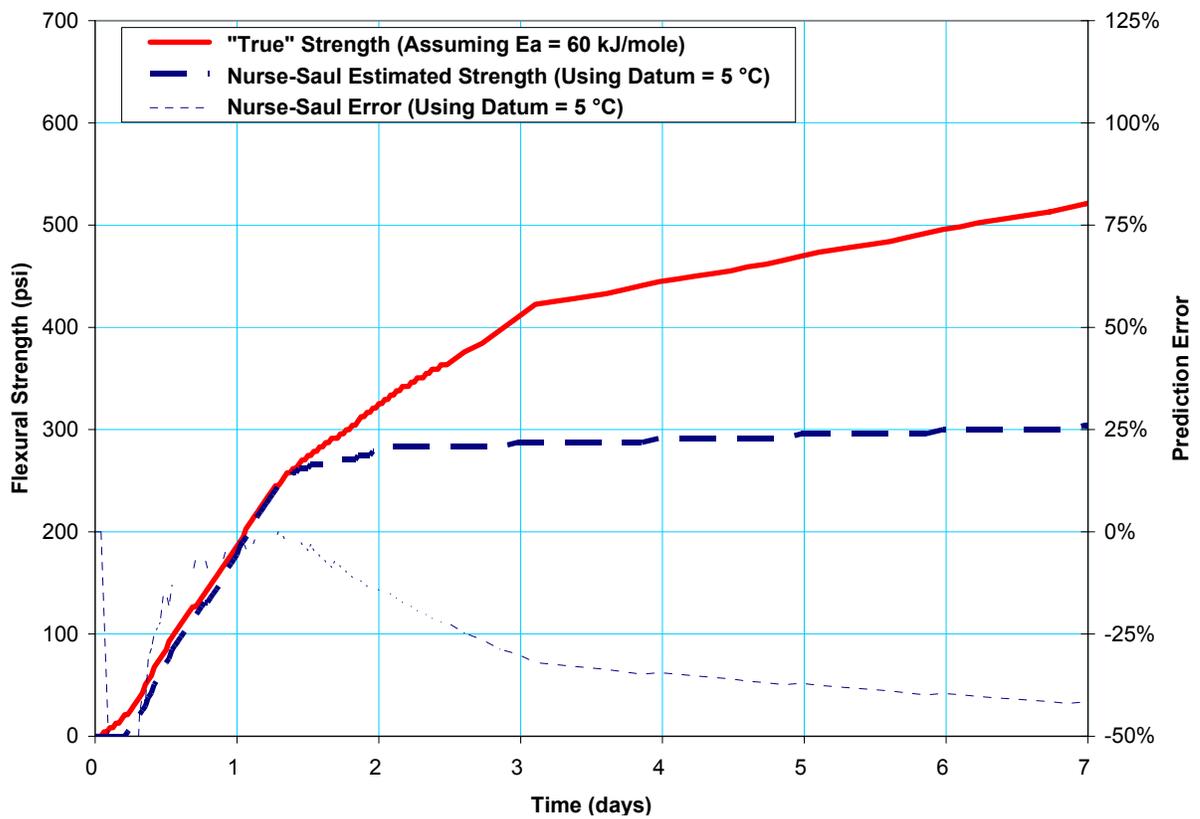


Figure 12.3 – Hypothetical Strength-Prediction Error using 5 °C Datum Temperature

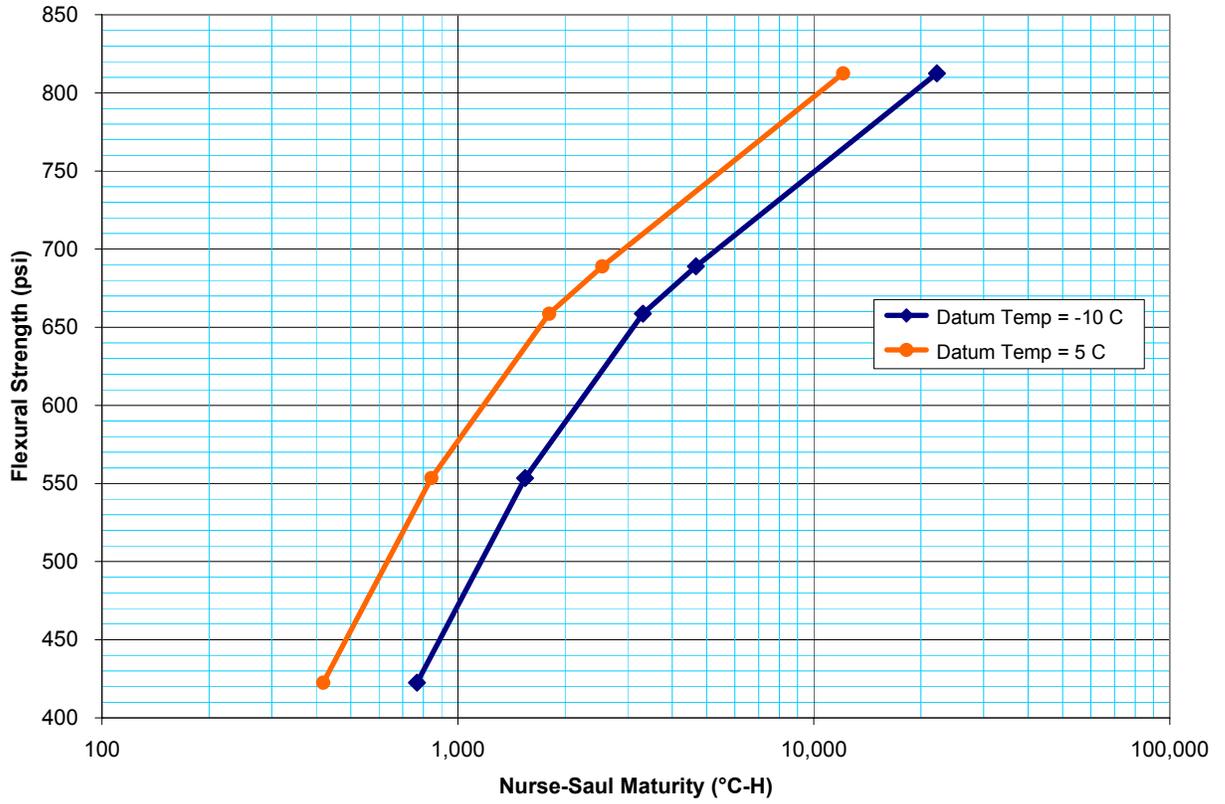


Figure 12.4 – Hypothetical Strength-Maturity Relationships

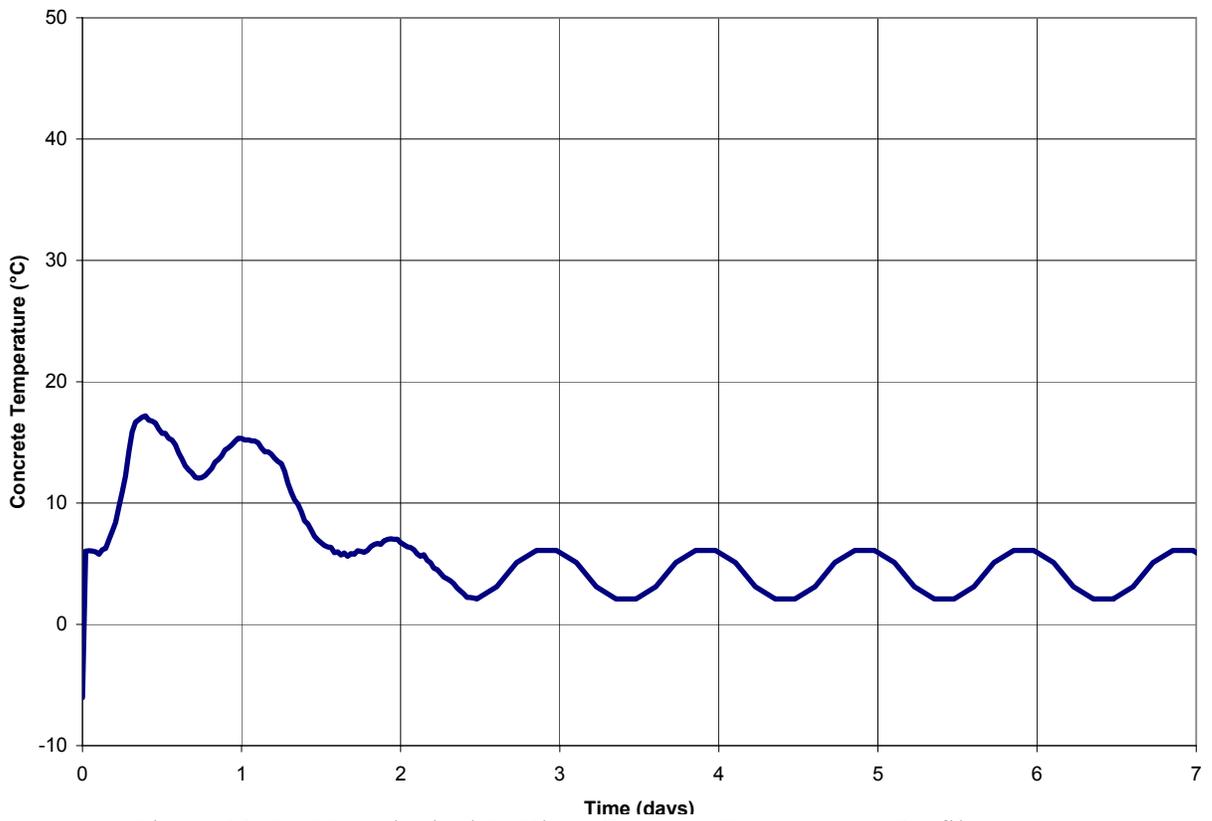


Figure 12.5 – Hypothetical In-Place Concrete Temperature Profile

13. Appendix C – Using Influence Charts to Estimate Maximum Edge Stresses

Influence charts have been used for decades to determine load-induced stresses for rigid pavement designs based on liquid foundation theory. The chart demonstrated in this example was originally constructed by Pickett and Ray (1951) based on Westergaard’s and Hogg’s theoretical equations and later adapted by Huang (1993). The following step-by-step procedure is an adaptation of the procedure presented by Huang (1993).

1. Calculate the radius of relative stiffness (l) using Equation 13.1:

$$l = \left[\frac{Eh^3}{12(1-\nu^2)k} \right]^{0.25} \quad \text{Equation 13.1}$$

where E is Young’s modulus of elasticity for the concrete, h is the thickness of the slab, ν is Poisson’s ratio for concrete (assumed to be 0.15)²³, and k is the modulus of subgrade reaction.

2. Calculate the reduction factor (RF) using Equation 13.2 to enable proper scaling of the vehicle footprint. The reduction factor converts the radius of relative stiffness (l) from Equation 13.1 to the graphical scale of l as shown on Figure 13.1.²⁴

$$RF = \frac{l_{chart}}{l_{equation}} \quad \text{Equation 13.2}$$

3. Scale the vehicle’s footprint and overlay it onto the influence chart.²⁵ This is done by multiplying each linear dimension of the footprint by the reduction factor, then positioning the scaled footprint onto the influence chart such that the maximum possible number of blocks is covered by the footprint. Note that the highest density of blocks occurs near the edge of the slab and near point “O” on the chart.

²³ The influence charts used in this example were constructed (by Huang 1993 after Pickett and Ray 1951) based on Westergaard’s and Hogg’s theoretical equations with an assumed Poisson’s ratio of 0.15.

²⁴ Figure 13.1 below is the influence chart for edge loading. This influence chart is based on the ratio of the dimensions of the footprint of the applied load to the radius of relative stiffness (l) calculated from Equation 13.1 above.

²⁵ The reduction factor is dependent upon the radius of relative stiffness (l), which is a function of pavement thickness (h) and support conditions (k). As such, if multiple pavement thickness or support condition exists on a project, multiple influence charts would be required for each piece of equipment analyzed.

4. After the footprint has been placed on the chart, count the blocks covered by the footprint. In the event the footprint is symmetric about point “O” only half the blocks need be counted (those on one side or the other of the line extending vertically from point “O”), with the resulting value then multiplied by two. Any portions of the footprint extending beyond the left, right, or top edges of the chart can be ignored.²⁶
5. With the total number of blocks counted, the moment induced by the footprint can be found from Equation 13.3, where q is the contact pressure of the footprint, N is the number of blocks counted during Step 4, and M is the resulting moment.

$$M = \frac{q \times l^2 \times N}{10,000} \quad \text{Equation 13.3}$$

6. Finally, the stress at point “O” is determined by dividing the moment, M , by the section modulus Z (where $Z = h^2/6 \text{ in}^3/\text{in}$) as shown in Equation 13.4.

$$\sigma_i = \frac{M}{Z} = \frac{6 \times M}{h^2} \quad \text{Equation 13.4}$$

²⁶ The influence chart shown in Figure 13.1 is adapted from the edge-loading influence chart developed by Pickett and Ray (1951) which was later adapted by Huang (1993). The original charts only included a portion of the “Positive” zone to the left of point “O”, but also included a “Negative” zone to the right of the right edge of the chart shown in Figure 13.1. To allow a full presentation of the “Positive” zone, the negative zones have been omitted from Figure 13.1. The net result is a slightly more conservative calculated stress value whenever a portion of the vehicle footprint extends beyond the left or right limits of the chart.

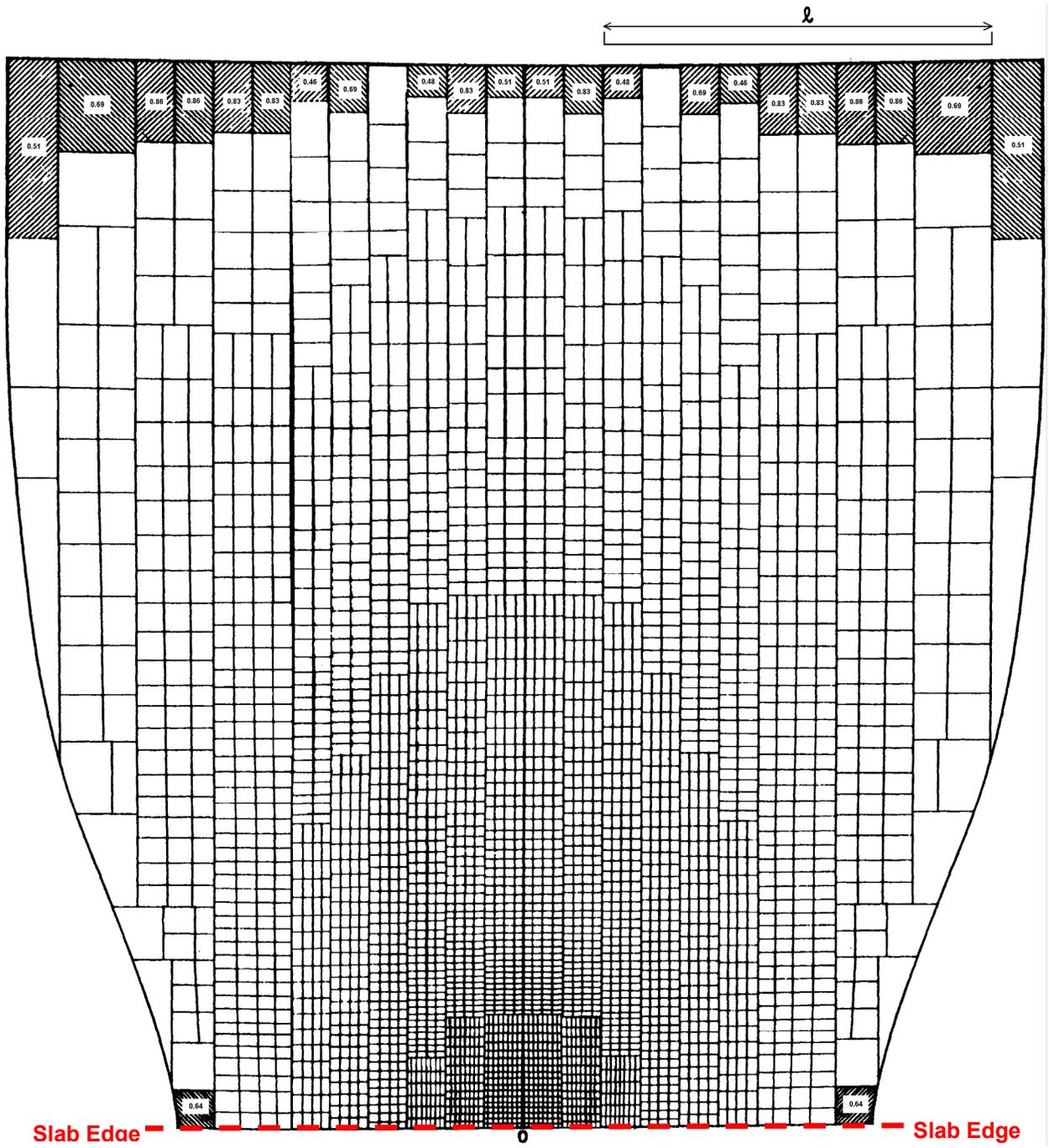


Figure 13.1 – Influence Chart for Edge Loading
(adapted from Huang 1993 and Pickett and Ray 1951)

14. Appendix D – Example Edge-Stress Calculations using Influence Charts

The following examples demonstrate the use of influence charts to calculate the maximum edge stresses applied by various types of equipment based on the hypothetical example detailed in Section 10. The following assumptions are used for these example calculations:

- Slab thickness, h , equals 16 inches;
- Modulus of subgrade reaction, k , equals 500 psi/in.
- Concrete modulus of elasticity (Young's modulus), E , equals 4×10^6 psi.
- Concrete Poisson's ratio, ν , equals 0.15.

In addition, the following vehicle configurations are considered:

- Slipform paver
 - Gross weight = 136,000 pounds distributed equally over four identical tracks.
 - Each track has a contact area of 18" x 72", or 1,296 in².
 - Total contact area = $4 \times 1,296 \text{ in}^2 = 5,184 \text{ in}^2$.
 - Contact pressure = 136,000 pounds / 5,184 in² = 26.2 psi.
 - Longitudinal center-to-center spacing between tracks = 286 in.
- Tandem-axle dump truck loaded with 9 CY of concrete
 - Gross weight = 54,000 pounds distributed equally over ten tires.
 - Each tire has a contact area of 10" x 6", or 60 in².
 - Total contact area = $10 \times 60 \text{ in}^2 = 600 \text{ in}^2$.
 - Contact pressure = 54,000 pounds / 600 in² = 90 psi.
 - Wheelbase = 235 in.
 - Spacing between tandem axles = 50 in.
 - Wheel spacing = 81 in.
- 1-ton dually pickup truck
 - Gross weight = 12,000 pounds distributed equally over six tires.
 - Each tire has a contact area of 9" x 5.4", or 48.6 in².
 - Total contact area = $6 \times 48.6 \text{ in}^2 = 291.6 \text{ in}^2$.
 - Contact pressure = 12,000 pounds / 291.6 in² = 41.2 psi.
 - Wheelbase = 180 in.
 - Wheel spacing = 80 in.
- ½-ton pickup truck
 - Gross weight = 6,700 pounds distributed equally over four tires.
 - Each tire has a contact area of 9" x 5.4", or 48.6 in².
 - Total contact area = $4 \times 48.6 \text{ in}^2 = 194.4 \text{ in}^2$.
 - Contact pressure = 6,700 pounds / 194.4 in² = 34.5 psi.
 - Wheelbase = 150 in.
 - Wheel spacing = 70 in.

For the slipform paver, the influence chart calculations proceed as follows:

1. Calculate the radius of relative stiffness (l) using Equation 13.1 (where $E = 4 \times 10^6$ psi, $h = 16$ in., $\nu = 0.015$, and $k = 500$ psi/in).

$$l = \left[\frac{(4 \times 10^6 \text{ psi}) \times (16 \text{ in})^3}{12 \times (1 - 0.015^2) \times 500 \text{ psi/in}} \right]^{0.25} = 40.88 \text{ in} \quad (\text{from Eq. 13.1})$$

2. Calculate the reduction factor (RF) using Equation 13.2 (where $l_{chart} = 2.4$ in. and $l_{equation} = 40.88$ in.).

$$RF = 2.4 \text{ in} / 40.88 \text{ in} = 0.0587 \quad (\text{from Eq. 13.2})$$

3. Scale the vehicle's footprint and overlay it onto the influence chart using the reduction factor calculated during Step 2 ($RF = 0.0587$). For this example, the slipform paver has four tracks with each track having a contact area of 18" x 72" spaced at 286" and 531", which reduces to:

$$18" \times 0.0587 = 1.06"$$

$$72" \times 0.0587 = 4.23"$$

$$286" \times 0.0587 = 16.8"$$

$$531" \times 0.0587 = 31.2"$$

Therefore, the track size to be drawn on the influence chart is 1.06" x 4.23". In addition, the placement of the multiple tracks in relation to each other are defined by the same scaling factor. In this example, two of the tracks are supported by another slab (and are thus not considered) and the remaining track would end up being plotted off the chart (and is therefore not included).

Figure 14.1 shows the track overlaid onto the influence chart. In this example, the maximum number of covered blocks occurs when the track is positioned along the bottom edge of the chart (corresponding to the edge of the slab) and symmetrically positioned on either side of the point "O"²⁷.

4. After the footprint has been placed on the chart, count the blocks covered by the footprint. Due to symmetry, only half of the footprint needs to be counted. However, the number of blocks covered by a half-footprint must be doubled before continuing. Both the left and right half-footprint for the slipform paver is shown on Figure 14.1. Again, only one half needs to be counted and the resulting number doubled. Careful counting shows that the number of blocks in the half-

²⁷ The point labeled "O" on the influence chart shown in Figures 1 and 2 represents the location of the maximum edge stress calculated by the procedure.

footprint for this slipform paver is 619. As such, the total number of blocks for the entire footprint equals 1,238. This number, N , will be used in Equation 13.3.

- Calculate the moment induced by the footprint using Equation 13.3 (where $q = 26.2$ psi and $N = 1,314$).

$$M = \frac{26.2 \text{ psi} \times (40.88 \text{ in})^2 \times 1,314}{10,000} = 5,753 \text{ in} - \text{lb} / \text{in} \quad (\text{from Eq. 13.3})$$

- Calculate the stress at point "O" by using Equation 13.4 (where $M = 5,753$ in-lb/in and $h = 16$ in.).

$$\sigma_i = \frac{6 \times 5,753 \text{ in} - \text{lb} / \text{in}}{16^2 \text{ in}^3 / \text{in}} = 134.8 \text{ psi} \quad (\text{from Eq. 13.4})$$

This calculation yields a maximum tensile stress equal to 134.8 psi. This value represents the maximum stress applied to the 16-inch concrete slab by one track of the slipform paver placed directly at the edge of the slab as shown in Figure 14.1.

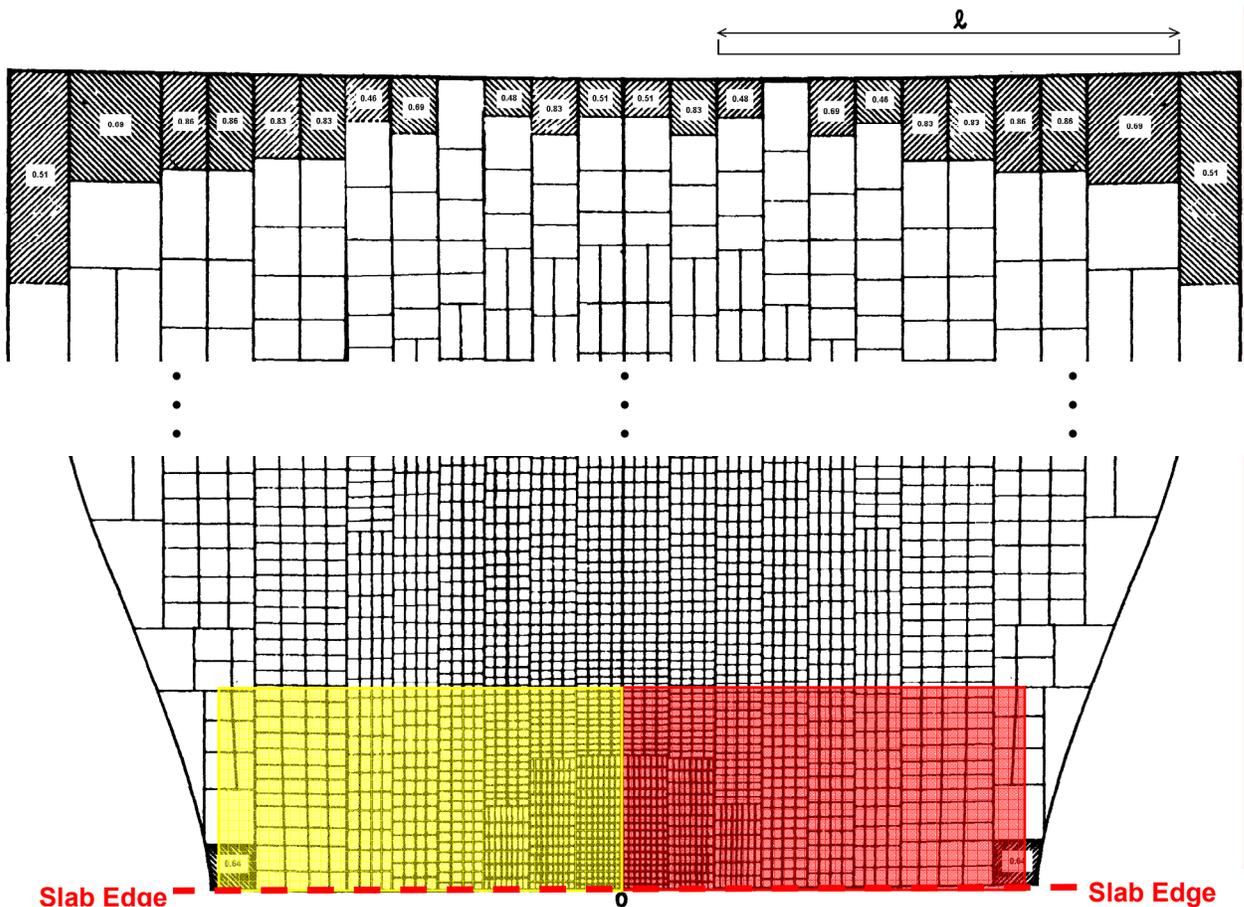


Figure 14.1 – Influence Chart for a Single Track of a Slipform Paver

For the loaded concrete truck, the influence chart calculations proceed as follows:

1. Same as above.
2. Same as above.
3. Scale the vehicle's footprint and overlay it onto the influence chart using the reduction factor calculated during Step 2 ($RF = 0.0587$). For this example, the concrete truck has ten tires each having a contact area of 10" x 6", a pair of tandem axles spaced at 50", a steering axle spaced 185" in front of the front tandem axle, and a width of 81". These dimensions reduce to:

$$6" \times 0.0587 = 0.352"$$

$$10" \times 0.0587 = 0.587"$$

$$50" \times 0.0587 = 2.94"$$

$$81" \times 0.0587 = 4.75"$$

$$185" \times 0.0587 = 10.86"$$

Figure 14.2 shows the footprint overlaid onto the influence chart. In this example, the maximum number of covered blocks occurs when one side of the tandem axles are positioned along the bottom edge of the chart (corresponding to the edge of the slab) and one of the outside tires is symmetrically positioned on either side of point "O". Note that, in this instance, the steering axle plots off the chart and therefore will not contribute to the calculated stress.

4. After the footprint has been placed on the chart, count the blocks covered by the footprint. Careful counting shows that the number of blocks in the footprint for this concrete truck is 310. This number, N , will be used in Equation 13.3.
5. Calculate the moment induced by the footprint using Equation 13.3 (where $q = 90$ psi and $N = 310$).

$$M = \frac{90 \text{ psi} \times (40.88 \text{ in})^2 \times 310}{10,000} = 4,663 \text{ in} - \text{lb} / \text{in} \quad (\text{from Eq. 13.3})$$

6. Calculate the stress at point "O" by using Equation 13.4 (where $M = 4,663$ in-lb/in and $h = 16$ in.).

$$\sigma_i = \frac{6 \times 4,663 \text{ in} - \text{lb} / \text{in}}{16^2 \text{ in}^3 / \text{in}} = 109.3 \text{ psi} \quad (\text{from Eq. 13.4})$$

This calculation yields a maximum tensile stress equal to 109.3 psi. This value represents the maximum stress applied to the 16-inch concrete slab by a loaded concrete truck positioned directly at the edge of the slab as shown in Figure 14.2.

Similar calculations can be performed on the remaining vehicles. For this example, the following maximum edge stresses are expected:

- Slipform paver
 - 134.8 psi
- Tandem-axle dump truck loaded with 9 CY of concrete
 - 109.3 psi
- 1-ton dually pickup truck
 - 49.7 psi
- ½-ton pickup truck
 - 28.2 psi

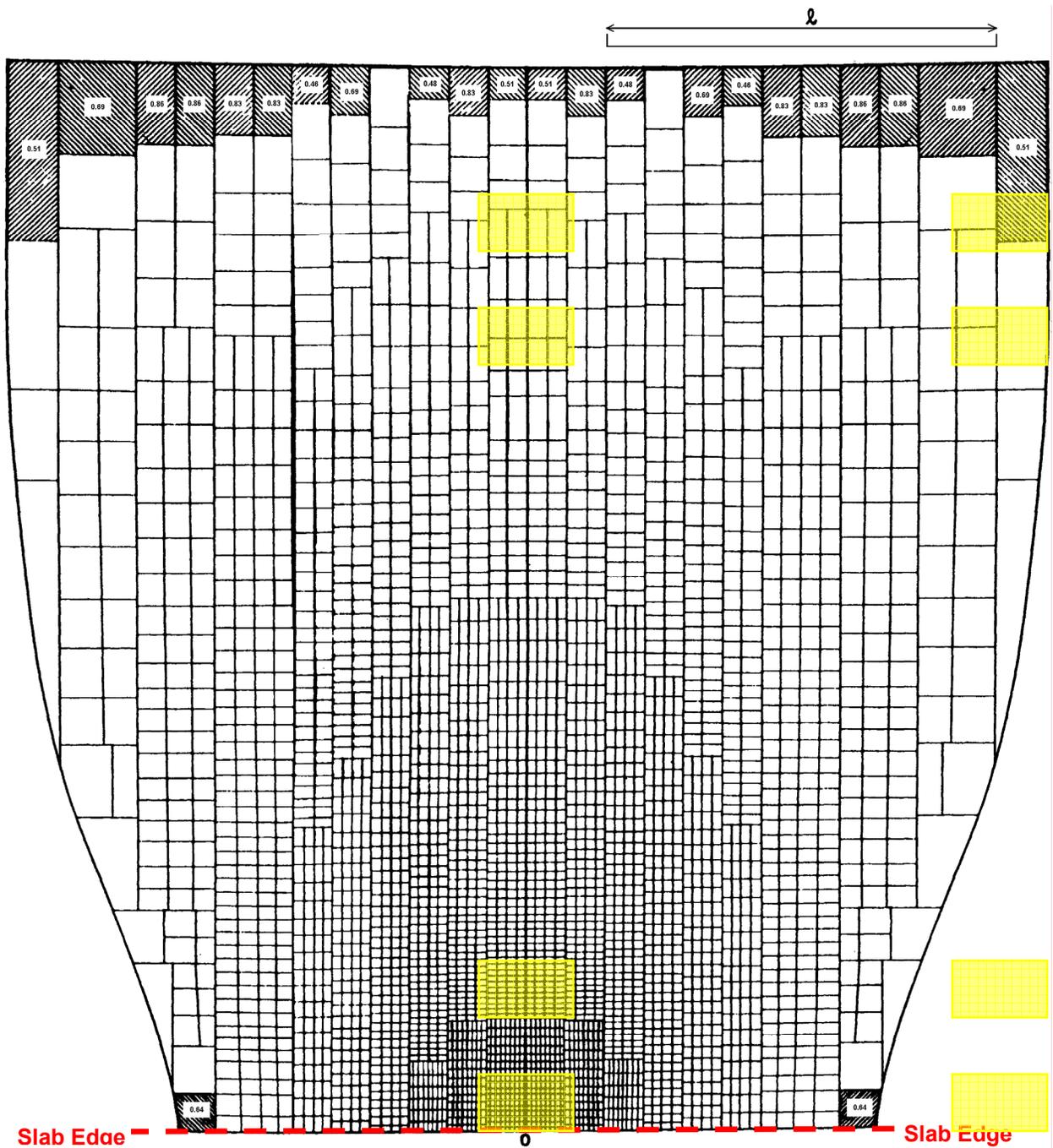


Figure 14.2 – Influence Chart for a Tandem-Axle Concrete Truck

15. Appendix E – Using ACPA’s AirPave Software to Estimate Maximum Edge Stresses

ACPA AirPave is a Windows®-based computer program developed by Construction Technology Laboratories, Inc. (CTL) under the sponsorship of the American Concrete Pavement Association (ACPA) for valuation of airport concrete pavements subjected to aircraft traffic. The software is based on the “AIRPORT” computer program originally developed by Mr. Robert G. Packard of the Portland Cement Association (PCA) for mainframe computers and later converted to microcomputers by Roger Millikan (Packard 1967; PCA 1967). The program is designed to be intuitive and user friendly with clearly captioned option buttons, command buttons, text boxes, and other operation tools. The analysis procedure used in the AIRPORT program is based on an extension by Pickett et al (1951) of Westergaard’s analysis for loads at the interior of a slab supported by a dense liquid subgrade. Influence Chart No.2 of Pickett and Ray (1951) was used as a graphical solution to the analysis.

To use the AirPave software to estimate maximum edge stresses, the following data are required:

1. Spacing of wheels (loads)
2. Gear configuration
3. Load contact area
4. Load contact pressure
5. Strength of subgrade-subbase
6. Concrete modulus of elasticity

The procedure for calculating edge stresses using AirPave is as follows (see Figures 15.2 through 15.4 for views of the primary AirPave input and output screens):

1. Launch the AirPave software.
2. In the <Airport Pavement Evaluation> <Loading Condition> area, verify that the <Interior Loading> option button is selected.²⁸
3. In the <General Design Input> area, enter the appropriate “Slab Thickness”.
4. In the <User Defined Input> area, click on the <Modulus of Elasticity (E)>, <Modulus of Rupture (MR)>, and <Modulus of Subgrade Reaction (k)> buttons and enter appropriate values for each.

²⁸ Use of the <Edge Loading> option is not recommended due to the limitations this option places on the use of custom wheel configurations. The procedures outlined in this Appendix calculate the maximum stresses due to interior loading, then convert those to estimated edge stresses (via Equation 15.1). The interior-to-edge stress conversions are the same as those recommended and implemented by the AirPave software.

5. In the <User Defined Input> area, click on the <Aircraft Loading> to bring up the Aircraft screen.
 - a. Click the <User Defined> button under the <Aircraft> area.
 - b. In the <Aircraft Data> area:
 1. In the <Aircraft Name> text box, type in the name of the equipment, such as “Slip-Form Concrete Paver”.
 2. Using the <Gear Configuration> drop-down box, select “Others” then enter the number of wheels or tracks for the equipment being evaluated.
 3. In the <Contact Pressure (psi)> text box, enter the tire pressure (for rubber-tired equipment) or the contact pressure for each wheel or track.²⁹
 4. In the <Contact Area (in²)> text box, enter the average contact area for each wheel or track.³⁰
 - c. In the <Wheel Location Coordinates> area, enter the “X” and “Y” coordinates corresponding to the center of each wheel or track. NOTE: The “X” direction is the direction of travel of the vehicle and the wheel or track at <Point 1> should be an interior wheel (for dual-wheeled axles) of an interior axle (for tandem-axle vehicles). These scenarios are shown graphically by “Sketch 3” and “Sketch 5” of Figure 15.1.
 - d. Click <OK> to return to the main input screen.

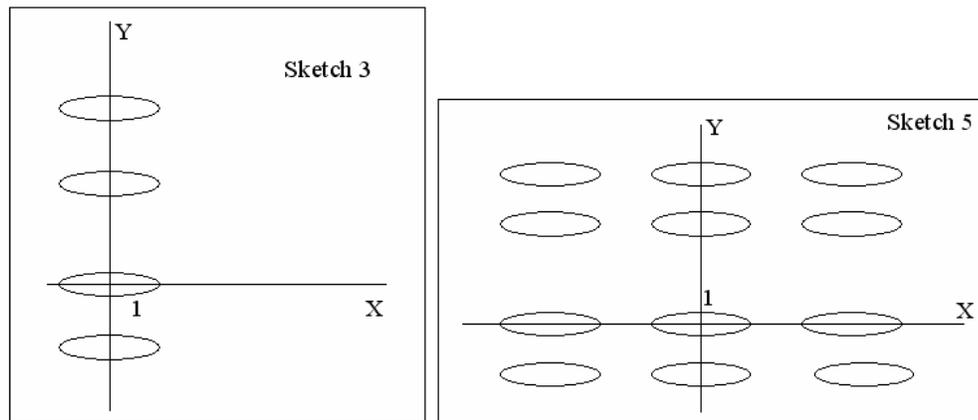


Figure 15.1 – Wheel Coordinate System and Numbering (from ACPA 2001)

6. In the <Operation Command Buttons> area of the main input screen, click the <Compute> button, then click <Yes> to review the report.
7. On the resulting “Pavement Evaluation Report”
 - a. Under the “GENERAL DESIGN INPUT” heading, verify the pavement thickness.

²⁹ Contact pressure for non-rubber-tired vehicles can be calculated as the gross weight of the vehicle divided by the number of wheels or tracks divided by the average contact area of each wheel or track.

³⁰ Contact area for rubber-tired vehicles can be calculated as the gross weight of the vehicle divided by the number of wheels divided by the tire pressure.

- b. Under the “USER DEFINED INPUT” heading, verify the following:
 1. Modulus of Elasticity (E),
 2. Modulus of Subgrade Reaction (k),
 3. Loading Condition (should be “Interior Loading”),
 4. Number of Wheels,
 5. Contact Area,
 6. Contact Pressure, and
 7. Total Load.³¹
 - c. Under the “COMPUTATION RESULT” heading, record the “Maximum Stress” value. This is the maximum calculated INTERIOR stress (σ_{int}). This is the value shown circled on Figure 15.4.
8. Convert the calculated maximum interior stress (σ_{int}) to an estimated maximum edge stress (σ_{edge}) using Equation 15.1.³²

$$\sigma_{edge} = \frac{\sigma_{int}}{0.75} \quad \text{Equation 15.1}$$

³¹ The “Total Load” displayed on the “Pavement Evaluation Report” will be the contact area times the number of wheels times the contact pressure (which should match the gross vehicle weight of the equipment being evaluated). However, this will not match the “Gross Weight” value reported in the <User Defined Input> area of the main input screen (the number displayed on the main input screen will be “incorrect”). The reason for the incorrect “Gross Weight” value on the main screen is due to the fact that AirPave assumes the user-defined load data are for *one-half* of an *aircraft’s* main landing gear. As such, the reported “Gross Weight” value will actually be slightly more than two times the actual gross vehicle weight. This incorrect value should simply be ignored.

³² Whenever AirPave calculates the maximum interior stress, it reduces the calculated stress by 25% based on the assumption of adequate load transfer across the joints. The denominator in Equation 15.1 (0.75) corrects for this 25% reduction. This correction is necessary due to the fact that the free edge of the slab does not benefit from any load transfer.

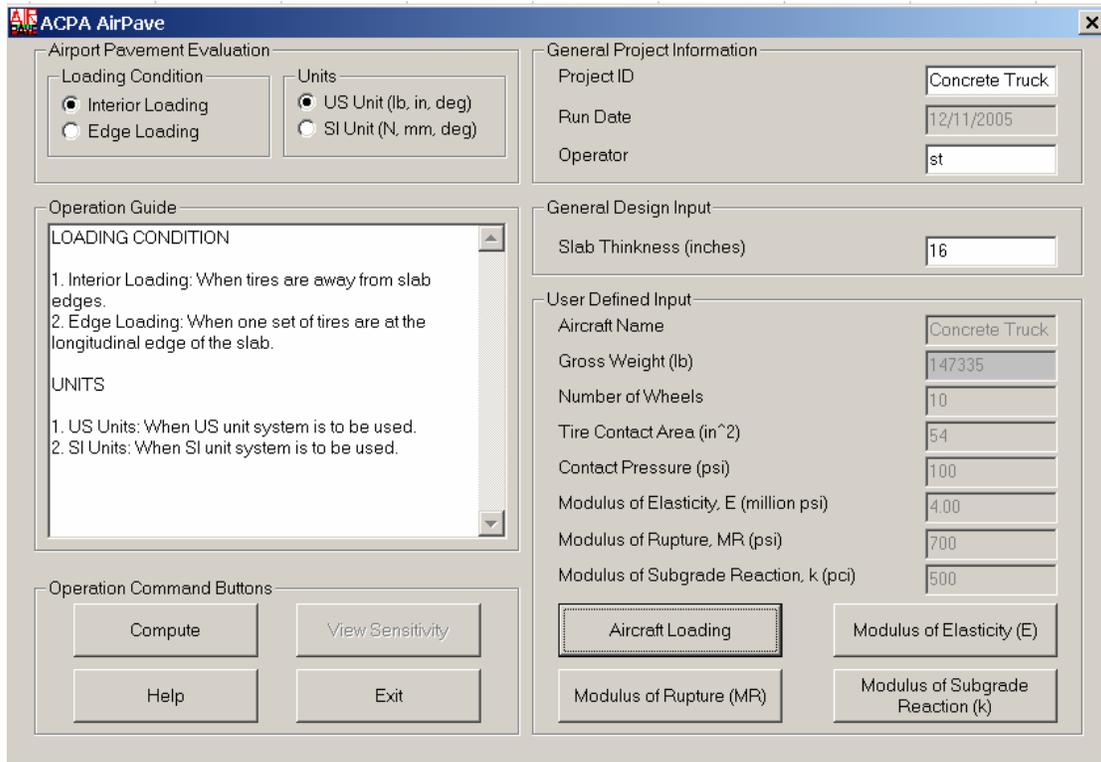


Figure 15.2 – Example AirPave Main Screen

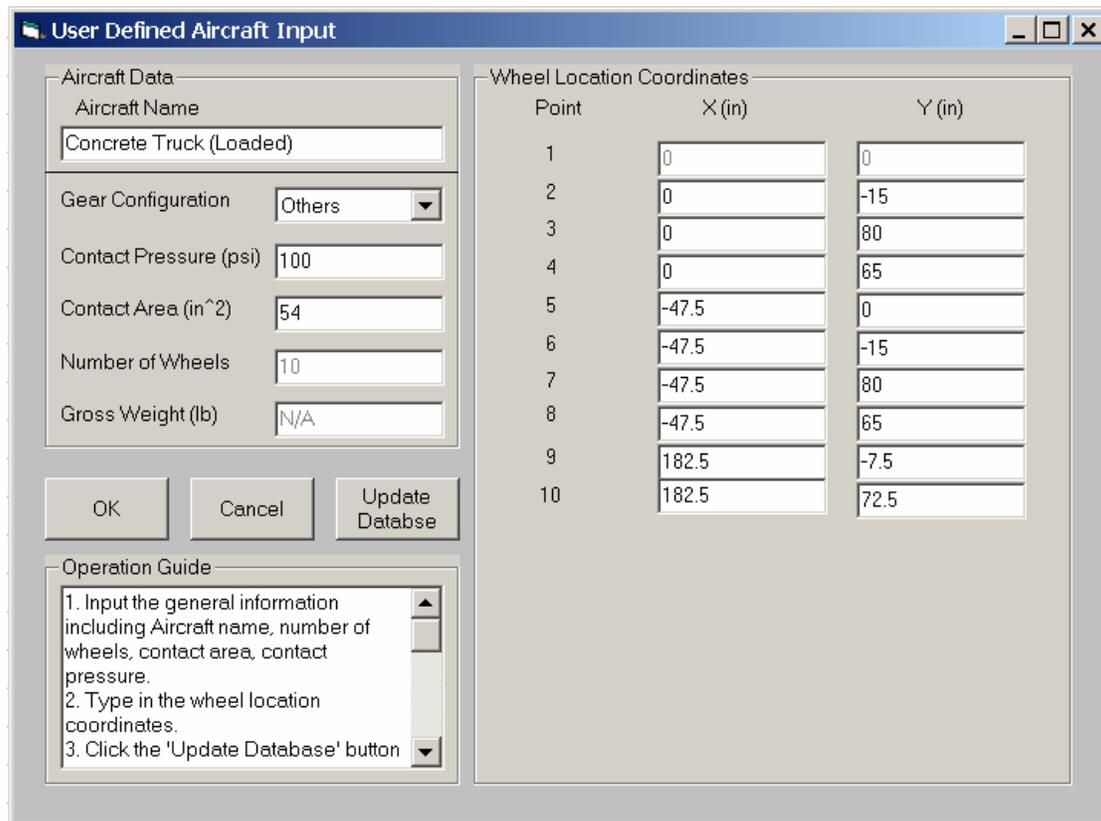


Figure 15.3 – Example AirPave “User Defined Aircraft Input” Screen

Pavement Evaluation Report

GENERAL DESIGN INFORMATION

Project ID: Concrete Truck Operator:
Run Date: 12/10/2005

GENERAL DESIGN INPUT

Slab Thickness: 16.0 Inches
Unit: US Units

USER DEFINED INPUT

Design Vehicle/Aircraft: Concrete Truck 1
Gear_Configuration: Others Pavement Type: PCC
Modulus of Elasticity (E): 4 million psi
Modulus of Rupture (MR): 700 psi
Modulus Subgrade Reaction (k): 500 pci
Computation Method: With Axle Rotation Loading Condition: Interior Loading
Number of Wheels: 10 Contact Area: 54 in^2
Contact Pressure: 100 psi
Total Load: 54000 lbf

COMPUTATION RESULT

X_Max: 0.5 Inches
Y_Max: 1.4 Inches
Maximum Angle: 165.5 Degrees
Maximum Stress: 54 psi
Stress Ratio: 0.076

OUTPUT

Allowable Total Repetitions: unlimited

WHEEL COORDINATES Inches

x:	0	0	-47.5	-47.5	0	0	-47.5	-47.5
y:	0	-15	-15	0	65	80	80	65
	182.5	182.5						
	-7.5	72.5						

Figure 15.4 – Example AirPave Pavement Evaluation Report

16. Appendix F – Example Edge-Stress Calculations using ACPA's AirPave Software

The following examples demonstrate the use of ACPA's AirPave software to calculate the maximum edge stresses applied by various types of equipment based on the hypothetical example detailed in Section 10. The following assumptions are used for these example calculations:

- Slab thickness, h , equals 16 inches;
- Modulus of subgrade reaction, k , equals 500 psi/in.
- Concrete modulus of elasticity (Young's modulus), E , equals 4×10^6 psi.

In addition, the following vehicle configurations are considered:

- Slipform paver
 - Gross weight = 136,000 pounds distributed equally over four identical tracks.
 - Each track has a contact area of 18" x 72", or 1,296 in².
 - Total contact area = $4 \times 1,296 \text{ in}^2 = 5,184 \text{ in}^2$.
 - Contact pressure = 136,000 pounds / $5,184 \text{ in}^2 = 26.2 \text{ psi}$.
 - Longitudinal center-to-center spacing between tracks = 286 in.
- Tandem-axle dump truck loaded with 9 CY of concrete
 - Gross weight = 54,000 pounds distributed equally over ten tires.
 - Each tire has a contact area of 10" x 5.4", or 54 in².
 - Total contact area = $10 \times 54 \text{ in}^2 = 540 \text{ in}^2$.
 - Contact pressure = 54,000 pounds / $540 \text{ in}^2 = 100 \text{ psi}$.
 - Wheelbase = 235 in.
 - Spacing between tandem axles = 50 in.
 - Wheel spacing = 81 in.
- 1-ton dually pickup truck
 - Gross weight = 12,000 pounds distributed equally over six tires.
 - Each tire has a contact area of 9" x 5.4", or 48.6 in².
 - Total contact area = $6 \times 48.6 \text{ in}^2 = 291.6 \text{ in}^2$.
 - Contact pressure = 12,000 pounds / $291.6 \text{ in}^2 = 41.2 \text{ psi}$.
 - Wheelbase = 180 in.
 - Wheel spacing = 80 in.
- ½-ton pickup truck
 - Gross weight = 6,700 pounds distributed equally over four tires.
 - Each tire has a contact area of 9" x 5.4", or 48.6 in².
 - Total contact area = $4 \times 48.6 \text{ in}^2 = 194.4 \text{ in}^2$.
 - Contact pressure = 6,700 pounds / $194.4 \text{ in}^2 = 34.5 \text{ psi}$.
 - Wheelbase = 150 in.
 - Wheel spacing = 70 in.

For the slipform paver, the influence chart calculations proceed as follows:

1. Launch the AirPave software.
2. In the <Airport Pavement Evaluation> <Loading Condition> area, verify that the <Interior Loading> option button is selected.
3. In the <General Design Input> area, enter “16” in the <Slab Thickness (inches)> text box.
4. In the <User Defined Input> area
 - a. Click on the <Modulus of Elasticity (E)> button and enter “4” in the <Modulus of Elasticity (million psi)> text box.
 - b. Click on the <Modulus of Rupture (MR)> button and enter “700” in the <Modulus of Rupture, MR (psi)> text box. (NOTE: This value is not used in the stress calculation. However, the software will not compute the stress without a value being entered.)
 - c. Click on the <Modulus of Subgrade Reaction (k)> button and enter “500” in the <Modulus of Subgrade Reaction, k (pci)> text box.
5. In the <User Defined Input> area, click on the <Aircraft Loading> to bring up the Aircraft screen.
 - a. Click the <User Defined> button under the <Aircraft> area.
 - b. In the <Aircraft Data> area:
 1. In the <Aircraft Name> text box, type in the name of the equipment (e.g. “Terex/CMI SF6004”).
 2. Using the <Gear Configuration> drop-down box, select “Others” then enter “2” in the input box (this is because only 2 of the 4 tracks will be on the pavement slab; the other 2 tracks will either be on the ground or on a completely different slab).
 3. In the <Contact Pressure (psi)> text box, enter “27”, which is the contact pressure for each track ($27 = 26.2$ psi rounded up to the nearest whole number).
 4. In the <Contact Area (in²)> text box, enter “1296”, which is the contact area for each track.
 - c. In the <Wheel Location Coordinates> area, enter the following “X” and “Y” coordinates for the following points:
 1. X = 0; Y = 0.
 2. X = 286; Y = 0.
 - d. Click <OK> to return to the main input screen.
6. In the <Operation Command Buttons> area of the main input screen, click the <Compute> button, then click <Yes> to review the report.
7. On the resulting “Pavement Evaluation Report”

- a. Under the “GENERAL DESIGN INPUT” heading, verify that pavement thickness is “16.0 Inches”.
 - b. Under the “USER DEFINED INPUT” heading, verify the following:
 1. Modulus of Elasticity (E) = “4 million psi”.
 2. Modulus of Subgrade Reaction (k) = “500 pci”.
 3. Loading Condition = “Interior Loading”.
 4. Number of Wheels = “2”
 5. Contact Area = “1296 in²”.
 6. Contact Pressure = “27 psi”.
 7. Total Load = “69984 lbf”.
 - c. Under the “COMPUTATION RESULT” heading, record the “Maximum Stress” value, which is “104 psi”. This is the maximum calculated INTERIOR stress (σ_{int}). This is the value shown circled on Figure 16.1.
8. Convert the calculated maximum interior stress (σ_{int}) to an estimated maximum edge stress (σ_{edge}) using Equation 15.1.

$$\sigma_{edge} = \frac{104 \text{ psi}}{0.75} = 138.7 \text{ psi} \quad (\text{from Eq. 15.1})$$

This calculation yields a maximum edge stress equal to 138.7 psi. This value represents the maximum stress applied to the 16-inch concrete slab by a 136,000-pound slipform paver positioned directly at the edge of the slab.

Similar calculations can be performed on the remaining vehicles. For this example, the following maximum edge stresses are expected:

- Slipform paver
 - 138.7 psi
- Tandem-axle dump truck loaded with 9 CY of concrete
 - 72.0 psi
- 1-ton dually pickup truck
 - 26.7 psi
- ½-ton pickup truck
 - 14.7 psi

Pavement Evaluation Report

GENERAL DESIGN INFORMATION

Project ID: Slipform Paver Operator:
Run Date: 12/15/2005

GENERAL DESIGN INPUT

Slab Thickness: 18.0 Inches
Unit: US Units

USER DEFINED INPUT

Design Vehicle/Aircraft: Slipform Paver
Gear_Configuration: Others Pavement Type: PCC
Modulus of Elasticity (E): 4 million psi
Modulus of Rupture (MR): 700 psi
Modulus Subgrade Reaction (k): 500 pci
Computation Method: With Axle Rotation Loading Condition: Interior Loading
Number of Wheels: 2 Contact Area: 1286 in^2
Contact Pressure: 27 psi
Total Load: 69984 lbf

COMPUTATION RESULT

X_Max: 0 Inches
Y_Max: 0 Inches
Maximum Angle: 90 Degrees
Maximum Stress: 104 psi
Stress Ratio: 0.149

OUTPUT

Allowable Total Repetitions: unlimited

WHEEL COORDINATES Inches

x: 0 286
y: 0 0

Figure 16.1 – AirPave Pavement Evaluation Report for Slipform Paver

17. Appendix G – Documented Problems with Maturity Systems

- **Moisture** in the external maturity meter.
“Reasons for lost readings included moisture in the meters” --TxDOT (2002)
- **Theft** of the external maturity meter.
“Several maturity meters were stolen in the field during the field monitoring phase of the project. Therefore, it is recommended that they be either secured or disguised to prevent theft.” --University of Texas-Austin (1998)
“Reasons for lost readings included ... theft” --TxDOT (2002)
- **Damage** to the external maturity meter.
“Reasons for lost readings included ... direct damage or destruction” --TxDOT (2002)
- **Battery failure** of the external maturity meter.
“The data from set six was lost due to meter malfunction. The battery from the Logic Beach system expired (sets 4 and 5) after day three, and power was not restored until day 10.” -Pennsylvania State University (2001)
“Reasons for lost readings included ... failure of the rechargeable batteries to hold adequate charge” --TxDOT (2002)
- External maturity meter malfunction due to **electrical** and/or **magnetic interference**.
“Reasons for lost readings included ... interference from external sources of electricity or magnetism,” --TxDOT (2002)
- **Chemical discoloration** of the external maturity meter’s display cover.
“Reasons for lost readings included ... chemical discoloration of the LCD cover.” --TxDOT (2002)
- Inability to read the external maturity meter’s LCD display due to exposure to **sunlight**.
“Care must be taken in the field to ensure that over exposure to the sun does not occur and prevent the Inspector from being able to read the LCD display.” --University of Texas-Austin (1998)
- Thermocouple **wires breaking** during concrete placement.
“three of the seven [thermocouple] wires broke during concrete placement.” --Pennsylvania State University (2001)
“Reasons for lost readings included ... broken or faulty thermocouple wires” --TxDOT (2002)
- Thermocouple wires **improperly connected** to the external maturity meter.
“Reasons for lost readings included ... improper or loose connections at the meter” --TxDOT (2002)

- Thermocouple ends **separating** after concrete placement.
 “Wyoming DOT officials report that they believe that the temperature rise in the concrete during hydration caused twisted thermocouple wires to expand and become unconnected during field trials conducted in Wyoming. Consequently, critical temperature was lost.” --Pennsylvania State University (2001)
- Improper thermocouple readings due to **galvanic action**
 “The dyes used in some thermocouple insulation will form an electrolyte in the presence of water. This creates a galvanic action, with a resultant output hundreds of times greater than the Seebeck effect. Precautions should be taken to **shield thermocouple wires from all harsh atmospheres and liquids.**” --OMEGA (2002)
<http://www.omega.com/temperature/Z/pdf/z021-032.pdf>
- Biased thermocouple readings due to **decalibration** and/or system inaccuracies
 “Temperatures outputted from the [thermocouple] device were approximately 1 to 2 °C lower than from the other devices tested.” --Pennsylvania State University (2001)
 “the thermocouple systems would sometimes show temperature differences in excess of 5 °C at ambient conditions.” --TxDOT (2002)
 “Decalibration is a far more serious fault condition than the open thermocouple because it can result in a temperature reading that appears to be correct. Decalibration describes the process of unintentionally altering the physical makeup of the thermocouple wire so that it no longer conforms to the NBS polynomial within specified limits. Decalibration can result from diffusion of atmospheric particles into the metal caused by temperature extremes. It can be caused by high temperature annealing or by cold-working the metal, an effect that can occur when the wire is drawn through a conduit or **strained by rough handling or vibration.** Annealing can occur within the section of wire that undergoes a temperature gradient.” --OMEGA (2002)
<http://www.omega.com/temperature/Z/pdf/z021-032.pdf>

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19. Appendix I – Sample Guide Specification

ITEM P-XXX MAKING OPEN-TO-TRAFFIC DECISIONS AND IMPLEMENTING QUALITY CONTROL FOR PORTLAND CEMENT CONCRETE PAVEMENTS USING MATURITY METHODS

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GENERAL NOTES TO ENGINEER:

Prior to using this guide specification, additional resources should be consulted so that the user thoroughly understands the concrete maturity method and its inherent limitations and potential sources of error.

This guide specification is provided as a guide only. The user is responsible for verifying all details, procedures, and protocols and their suitability for use on a given project.

1. DESCRIPTION

1.1. SCOPE

This test method outlines procedures for determining mix-specific strength-maturity relationships, determining concrete strength in the field using strength-maturity relationship data, facilitating staged opening to traffic decisions, and implementing a maturity-based quality control program.

1.2. REFERENCES

1.2.1. ASTM International (ASTM) Standards

- C31 Making and Curing Concrete Test Specimens in the Field
- C39 Compressive Strength of Cylindrical Concrete Specimens
- C78 Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
- C138 Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
- C173 Air Content of Freshly Mixed Concrete by the Volumetric Method
- C192 Making and Curing Concrete Test Specimens in the Laboratory
- C231 Air Content of Freshly Mixed Concrete by the Pressure Method
- C496 Splitting Tensile Strength of Cylindrical Concrete Specimens
- C900 Pullout Strength of Hardened Concrete
- C1074-04 Estimating Concrete Strength by the Maturity Method
- C1583 Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)

1.3. SIGNIFICANCE AND USE

This test method provides a procedure for determining mix-specific strength-maturity relationship curves and a procedure for determining concrete strength in the field using strength-maturity relationship data. In addition, this specification provides guidelines for initiating a robust quality control program for concrete strength using strength-maturity relationship data.

1.4. SUBMISSION AND ACCEPTANCE

Strength-maturity relationship data, field maturity data, maturity quality control reports, and supporting documentation shall be reported as specified herein and in accordance with the approved Contractor Quality Control Program.

1.5. CONTRACTOR QUALITY CONTROL PROGRAM

A comprehensive Contractor Quality Control Program shall be instituted as specified in *Section 100 – Contractor Quality Control Program*.

1.5.1. Concrete Quality Control Plan

Whereas reliable determinations of concrete strength using maturity methods depend heavily upon the consistent implementation of adequate process- and quality-control procedures throughout the concrete production, placement, and curing operations, a comprehensive Concrete Quality Control Plan shall be incorporated into the Contractor's Quality Control Program.

1.5.2. Concrete Maturity Implementation

A comprehensive section governing the implementation of maturity for the project shall be incorporated into the Contractor's Concrete Quality Control Plan.

1.5.2.1. Strength-Maturity Relationships

A comprehensive section detailing the procedures for determining, reporting, and documenting strength-maturity relationships shall be incorporated into the Contractor's Concrete Quality Control Plan. The section shall specifically detail the actions that will be taken to ensure that any testing errors are spread evenly across all maturity levels during establishment of strength-maturity relationships.

1.5.2.2. In-Place Flexural Strength Determination

A comprehensive section detailing the procedures for determining, reporting, and documenting in-place flexural strength using maturity shall be incorporated into the Contractor's Concrete Quality Control Plan.

1.5.2.3. Maturity as a Quality Control Tool / Concrete Mix Verification

A comprehensive section on the use of concrete maturity as a means for quality control shall be incorporated into the Contractor's Concrete Quality Control Plan. The section shall detail the frequency and conditions under which mix verification testing will be performed. The section shall include procedures detailing the specific

evaluation criteria to be applied to verification test results to determine whether or not investigative or corrective actions will be required. In addition, the section shall categorize and describe the specific investigative and corrective actions that will be taken for each of the aforementioned criteria. Investigative actions shall focus on determining the root cause of any observed deficiencies. Corrective actions shall emphasize and favor process-based changes or improvements over mere inspection-based solutions.

1.5.2.4. Strength-Maturity Relationship Validation

A comprehensive section on the validation of strength-maturity relationships shall be incorporated into the Contractor's Concrete Quality Control Plan. The section shall detail the frequency with which periodic strength-maturity relationship validation testing will occur as well as the conditions under which non-scheduled validation testing will be required, such as whenever intentional or unintentional mix changes occur or are anticipated. The section shall detail, in the event a strength-maturity relationship is deemed invalid, the interim procedures that will govern until such time as a new strength-maturity relationship can be established.

1.5.2.5. Compensating for Sources of Error

The Contractor's Concrete Quality Control Plan shall include discussion recognizing the following sources of error and identifying specific actions that will be taken to minimize their influence on the strength-maturity relationships and subsequent strength-from-maturity determinations.

- Errors due to Elevated In-Place Temperatures
- Batching Errors and Inconsistencies
- Changes in Raw Material Characteristics
- Testing Errors during Calibration
- Human Errors when Collecting Maturity Data or Calculating Strength from Maturity

2. EQUIPMENT

2.1. MATURITY CALCULATIONS

2.1.1. Nurse-Saul Equation

Concrete maturity systems shall utilize the Nurse-Saul maturity equation as follows:

$$M = \sum_0^t [\max[0, (T - T_o)]] \cdot \Delta t$$

where

M = concrete maturity expressed as temperature-time factor (TTF) (in °C-Hours)

T = average concrete temperature (in °C) during time interval Δt .

T_o = datum temperature (in °C)

Δt = length of time interval (in hours)

2.1.2. Datum Temperature

Maturity equipment shall either be pre-programmed to use 5 °C as the datum temperature or shall include datum temperature as a user-selectable parameter.

Systems that allow the user to enter or select the datum temperature shall require that the user confirm the datum temperature each time prior to beginning maturity calculations and shall prominently display the datum temperature any time a maturity value is displayed or reported.

2.2. UNITS OF MEASURE

Systems for calculating concrete maturity shall include units with all displayed or printed maturity values. The units of measure shall be °C-Hours. Abbreviated unit notations, such as “CH” or “°C-H”, are acceptable.

2.3. TEMPERATURE PRECISION AND BIAS

Systems for determining maturity shall measure temperature to a precision and bias of plus-or-minus 1 °C (1.8 °F) (or better) at a resolution of 1 °C (2 °F) or better across an operating range of -10 °C (14 °F) to 85 °C (185 °F).

Thermocouple-based systems shall, as a minimum, be recalibrated for each new spool of thermocouple wire and for each channel for multi-channel systems.

2.4. BATTERY LIFE

Systems for determining maturity shall be powered by a reliable AC power source and/or shall have adequate battery power to last at least twice as long as the time anticipated for determining flexural strength from maturity.

2.5. [DATA SECURITY AND INTEGRITY

Systems for determining maturity shall be capable of providing historical maturity data in a secure, tamper-proof format. As a minimum, the following data shall be provided:

2.5.1. Serial number of the embedded sensor

2.5.2. Calendar date and time when the sensor was activated

2.5.3. Historical temperature data

Historical temperature data shall be recorded at a minimum frequency of [once every 15 minutes].

2.5.4. Historical maturity data

Historical maturity data shall be recorded at a minimum frequency of [once every 15 minutes].

2.5.5. Datum temperature

2.5.6. [Date- and time-stamped event logs

Date- and time-stamped event logs shall be provided to securely document each of the following events:

- [Open-to-traffic, including equipment category and required threshold]
- [_____]

]

]

NOTE TO ENGINEER: Add this section on Data Security and Integrity if the needs of the project warrant a requirement for verifiable documentation with respect to in-place strength determinations. The Engineer shall specify the frequency with which historical data must be recorded and whether or not additional verifiable event-specific data logs will be required.

3. ESTABLISHING THE MIX-SPECIFIC STRENGTH-MATURITY RELATIONSHIP FOR A CONCRETE MIX

3.1. MIX DESIGN & MIXTURE COMPONENTS

Concrete mix designs shall be performed and submitted for approval as specified in P-501. Concrete mixture components and admixtures shall be as specified in P-501. Whenever raw material sources change and/or material proportions are adjusted beyond specified batching tolerances, the strength-maturity relationship shall be validated as detailed in the Contractor’s Concrete Quality Control Plan.

3.2. DATUM TEMPERATURE

Datum temperature (T_0) shall be 5 °C.

3.3. DATA POINTS FOR ESTABLISHING A STRENGTH-MATURITY RELATIONSHIP

NOTES TO ENGINEER:

ASTM C1074-04 states (in paragraph 8.7),

Measure flexural strength in accordance with Test Method C78 at time intervals of 1, 3, 7, 14 and 28 days, or as specified otherwise

then goes on to state (in NOTE 4),

For concrete mixtures with rapid strength development, or when strength estimates are to be made at low values of maturity index, tests should begin as soon as practicable. Subsequent tests should be scheduled to result in approximately equal increments of strength gain between test ages. At least five test ages should be used.

Three key issues need to be considered when making this determination:

- 1. Collect multiple data points along the steep part of the strength-maturity relationship curve. The actual ages for this will depend upon how quickly the given mix design gains strength.**
- 2. Collect data such that the “required” strength values (e.g. opening to light vehicle traffic through opening to loaded concrete truck traffic, and/or paving equipment) are in the middle of the data set.**
- 3. NEVER EXTRAPOLATE beyond the maturity levels included in the strength-maturity relationship data. As such, make certain that the strength at the last maturity age to be tested will have exceeded the maximum strength to be measured via maturity. No strength determinations should be made beyond the final maturity level tested.**

Develop a minimum of [five (5)] [six (6)] strength-maturity relationship points at the following ages: [roughly 30%, 60%, 90%, 120% and 240% of the maturity values corresponding to the anticipated required strength values] [1, 3, 5, 7, 14 and 28 days]. Each strength-maturity relationship point shall be the average strength of [three (3)] specimens plotted in relation to the average maturity of one specimen instrumented with [two (2)] maturity sensors. The specimens tested for maturity shall have been cured under identical conditions as the specimens tested for strength.

The Engineer shall specify the maturity ages at which the strength-maturity relationship shall be established, the number of specimens to be tested at each maturity age, and the number of specimens to be instrumented with maturity sensors.

ASTM C1074-04 recommends the following (in paragraph 8.7):

Test two specimens at each age and compute the average strength. If the range of flexural strength of the two specimens exceeds 15% of their average strength, test another beam and compute the average of the three tests. If a low test result is due to an obviously defective specimen, discard the low test result.

However, taking the average of at least three specimens at each maturity level is desirable. This is due to the following:

- ALL future determinations of in-place flexural strength will rely upon the strength-maturity relationship established during this calibration process,**
- As such, testing error should be minimized during this procedure as much as possible, and**
- Although taking the average of two specimens reduces the testing error by nearly 30% (compared to relying upon a single specimen), taking the average of three reduces this error by 42%. Taking the average of four reduces the error by 50%.**

3.4. PREPARING SPECIMENS

3.4.1. Number and Numbering of Specimens

The minimum number of test specimens shall be [sixteen (16)], [one (1)] of which shall be instrumented with [two (2)] maturity sensors. Each specimen shall be uniquely numbered and documented concerning the batch of origin.

The Engineer shall specify the total number of specimens to be cast, the number of specimens to be instrumented with maturity sensors, and the number of maturity sensors. Whereas the resulting strength-maturity relationship will be null and void if a maturity sensor failure occurs during the calibration process, it is generally prudent to require redundancy (i.e. two or more maturity sensors).

3.4.2. Casting Specimens

Specimens to be tested for strength shall be cast in accordance with [ASTM C31] [ASTM C192].

The Engineer shall specify whether the calibration specimens shall be cast in the laboratory (ASTM C192) or in the field (ASTM C31).

ASTM C1074-04 assumes that concrete specimens will be cast in a laboratory setting when establishing strength-maturity relationships. However, distinct advantages are gained when the actual production batching and mixing equipment is utilized and when the specimens are cast under field conditions. Regardless of how the specimens cast, they should be stored and cured in accordance with ASTM C192 as detailed below.

3.4.3. Instrumenting Specimens with Maturity Sensors

Specimens to be instrumented with maturity sensors shall be identical to and cast at the same time as those to be tested for strength. As soon as practicable after casting [(i.e. **within fifteen minutes or less**)], the specimens shall be instrumented with maturity sensors. Maturity sensors in beam specimens shall be placed approximately 75 mm (3 in.) from each end, midway between the longitudinal sides of the beam mold and at mid-depth, [**two (2)**] per specimen. Maturity sensors shall be activated to begin calculating or recording within [**fifteen minutes**] after placement in the specimens.

The Engineer shall specify the allowable time delay between casting the specimens and instrumenting them with maturity sensors, the number of maturity sensors per instrumented specimen, the number of instrumented specimens, and the allowable time delay between sensor placement and commencement of temperature recordings or maturity calculations.

ASTM C1074-04 states, “Embed temperature sensors in two specimens, one from each batch if two batches are made.”

3.4.4. Curing Specimens

Specimens shall be cured in accordance with ASTM C192.

3.5. TESTING

3.5.1. Maturity

Maturity readings shall be taken immediately *after* the corresponding specimens are tested for strength. The maturity and internal temperature of the concrete specimens shall be recorded along with the specimen identification number, the serial number of

the maturity sensor and the date, actual time and elapsed time when the readings were taken.

3.5.2. Strength

[Compressive strength testing shall conform to ASTM C39.] Flexural strength testing shall conform to ASTM C78. [Splitting tensile strength testing shall conform to ASTM C496.] [Pullout testing shall conform to ASTM C900.] [Direct tension testing shall conform to ASTM C1583.]

The Engineer shall specify which strength tests, if any, will be performed in addition to flexural strength. Supplemental strength tests may be used for validation or verification purposes.

3.6. VALIDATING THE STRENGTH-MATURITY RELATIONSHIP

Each strength-maturity relationship shall be periodically validated as detailed in the Contractor's Concrete Quality Control Plan.

Whenever intentional changes are made to a concrete mix design, or when unintentional changes are suspected, the strength-maturity relationship shall be validated as detailed in the Contractor's Concrete Quality Control Plan.

4. ESTIMATING IN-PLACE FLEXURAL STRENGTH

4.1. MIX-SPECIFIC STRENGTH-MATURITY RELATIONSHIPS

A strength-maturity relationship shall be established for each mix design for which strength-from-maturity determinations are to be made. Strength-maturity relationships shall be established in accordance with Part 3.

4.2. LOCATION AND PLACEMENT OF MATURITY SENSORS

Maturity sensors shall be placed at the beginning and end of each pavement extent for which maturity-based open-to-traffic decisions will be made.

Maturity sensors shall be placed at mid-depth in the pavement.

4.3. DATUM TEMPERATURE

Datum temperature (T_0) shall be 5 °C.

4.4. DETERMINING IN-PLACE FLEXURAL STRENGTH USING MATURITY

Field determinations of strength using the maturity method shall not be made without an approved CONCRETE QUALITY CONTROL PLAN and a valid, up-to-date

strength-maturity relationship for each mix design for which the strength-from-maturity determinations are to be made.

Procedures for obtaining in-place flexural strength measurements using maturity shall be as detailed in the Contractor's Concrete Quality Control Plan.

4.5. OPEN-TO-TRAFFIC CRITERIA

4.5.1. Determining Equipment Categories and Maximum Edge Stresses

The Contractor shall submit the following for each equipment category for which separate open-to-traffic criteria are desired:

- Detailed information for each vehicle, including
 - Manufacturer, make, and model,
 - Maximum fully-loaded gross vehicle weight,
 - Complete contact footprint with dimensions, and
 - Average contact pressure;
- Identification of which vehicle or piece of equipment produces the maximum edge stress;
- Calculated maximum edge stress for the each equipment category and each pavement thickness and support condition;
- Assumptions used during the calculation of maximum edge stresses, such as:
 - Pavement thickness,
 - Support conditions (e.g. k-value),
 - Total contact area,
 - Contact pressure, and
 - Location and orientation on the slab; and
- Detailed calculations and/or supporting documentation concerning the method used to determine the maximum edge stress(es).
- Signature and seal of a Licensed Professional Engineer affirming the veracity of the reported maximum edge stresses.

4.5.2. Open-to-Traffic Summary Report by Pavement Section

The Contractor shall submit a summary report for each pavement thickness and support condition containing the following:

- Pavement section (thickness, base type and thickness, etc.),
- For each equipment category:
 - List of vehicles included in the category (manufacturer, make, model, and gross vehicle weight),

- Calculated maximum edge stress,
- Required open-to-traffic modulus of rupture threshold (based on the criteria presented in Paragraph 4.5.3 below),
- [Required open-to-traffic maturity threshold,]
- Concrete mix design identifier,
- [Plot of the required open-to-traffic strength and maturity thresholds for each equipment category superimposed upon the strength-maturity relationship curve for the referenced concrete mix design.]

]

The Engineer shall specify whether or not maturity threshold values will be allowed as the criteria for open-to-traffic decisions in lieu of a strength (from maturity) threshold values. If so, the above-referenced plot is meaningful. If not, the plot is not meaningful and should not be required.

NOTE: If option three from Paragraph 4.5.3 below is chosen, a maturity threshold value cannot be used. In that instance, maturity must be converted to strength, then corrected strength, then the corrected strength must be compared to the threshold strength for each equipment category.

4.5.3. Determining Open-to-Traffic Flexural-Strength Thresholds

The following method shall be used to determine threshold open-to-traffic strength values for each equipment category:

Option One: Factor of Safety Multiplier Only

[
$$MR_T = ES_{MAX} \cdot FS_M$$

where

MR_T = modulus of rupture threshold value (psi) for a given equipment category and pavement section

ES_{MAX} = maximum edge stress (psi) for a given equipment category and pavement section

FS_M = factor of safety multiplier = [2.5] [3] [____]

]

Option Two: Factor of Safety Multiplier with Factor of Safety Offset

[$MR_{TC} = ES_{MAX} \cdot FS_M + FS_O$

Where

MR_{TC} = temperature-corrected modulus of rupture threshold value (psi) for a given equipment category and pavement section

ES_{MAX} = maximum edge stress (psi) for a given equipment category and pavement section

FS_M = factor of safety multiplier = [2.5] [3] [____]

FS_O = factor of safety offset = [50] [75] [100] [150] [____] psi

]

Option Three: Factor of Safety Multiplier with Temperature Correction Factor

[$MR_T = MR_{UC} - \Delta T \cdot TCF$

$MR_{UC} = ES_{MAX} \cdot FS_M$

where

MR_T = modulus of rupture threshold value (psi) for a given equipment category, pavement section, and in-place pavement temperature

MR_{UC} = uncorrected modulus of rupture threshold value (psi) for a given equipment category and pavement section

ΔT = temperature difference between the in-place concrete pavement and the beam specimens used to establish the strength-maturity relationship (°F)

TCF = temperature-correction factor = [2] [3] [5] [____] psi / °F

ES_{MAX} = maximum edge stress (psi) for a given equipment category and pavement section

FS_M = factor of safety multiplier = [2.5] [3] [____]

]

[____]

The Engineer shall specify which method shall be used to calculate the required strength threshold for each equipment category.

With respect to the factor of safety multiplier, FS_M , conventional wisdom holds that a 2x factor of safety will allow infinite repetitions to the concrete pavement with zero fatigue damage to the pavement. For open-to-traffic decisions using concrete maturity methods, the Federal Aviation Administration recommends a minimum factor of safety multiplier of 2.5. One method of compensating for errors due to elevated in-place temperatures is to simply increase the factor of safety multiplier from 2.5 to some higher value. This method is identified as “Option One” above.

“Option Two” above incorporates a factor of safety offset, FS_O , to compensate for elevated temperature errors.

“Option Three” above provides attempts to correct for rather than merely compensate for errors due to elevated (and depressed) in-place temperatures. As such, during seasons where the average in-place temperature is below the calibration-specimen temperatures, a net increase in strength will be calculated. This method requires an assumption as to the temperature sensitivity of the modulus of rupture (a.k.a. flexural strength). An unintended consequence arising from this method involves the situation wherein the temperature rise in a pavement from early morning to mid-day could quite possibly result in a more rapid *decrease* in in-place strength than the corresponding *increase* in “uncorrected” strength (due to continued hydration). This method also negates the use of a *maturity* threshold value as the open-to-traffic criterion (because in-place maturity AND current in-place temperature must be evaluated together before an estimate of in-place strength can be made). (The other two methods still allow a one-time conversion from required strength to required maturity for a given equipment category and pavement section.

4.6. VERIFYING THE CONCRETE MIX IN THE FIELD USING THE STRENGTH-MATURITY RELATIONSHIP

The concrete supplied to the project shall be frequently verified as detailed in the Contractor’s Concrete Quality Control Plan.