The Application of Maturity Method on Whitetopping Construction

By

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ABSTRACT
The primary objective of this study was to assess the use of the maturity method to determine the joint sawing time and the traffic opening time on whitetopping construction in Korea. The Nurse-Saul function and the Arrhenius equation accepted by ASTM were examined and compared in the research. To determine joint sawing time, it was necessary to find the minimum strength not to cause raveling and to identify the time to the occurrence of drying shrinkage. Through the analysis of concrete deformation and laboratory experiments at early concrete age, this study found that the minimum compressive strength for joint sawing was 4.41MPa (45kg/cm²) and drying shrinkage occurred just after the concrete temperature reached at the peak. To develop the relationship between compressive strength and maturity values, thermachron i-buttons were inserted into the top and mid-depth of the fresh concrete in the test slabs. In-place strength was then estimated from a pre-established relationship between maturity values and compressive strength. The results of the laboratory tests indicated that the Arrhenius equation better fitted the relationship between the compressive strength and maturity values than did the Nurse-Saul equation. However, the Nurse-Saul function estimated in-place strength quite well in this study. Therefore, the Nurse-Saul equation was used to determine the joint sawing time and the traffic opening time for whitetopping construction. Another finding was that high temperature with strong solar radiation had a significant effect on developing concrete strength. In this condition, very close attention should be placed when maturity method is used.

Keyword: maturity, Nurse-Saul function, Arrhenius equation, whitetopping
INTRODUCTION

It is well known that asphalt pavements have problems such as severe rutting and shoving due to frequent stop and go traffic at intersections. Whitetopping can be one of best alternative methods to eliminate these distress types and to open traffic to public at the earliest possible time. The advantage of the whitetopping overlay is sawn into a block system that was design to reduce the curling and warping stresses that the concrete pavement experiences while curing and in-service (1). With regard to quality control of whitetopping construction, this study has been conducted to examine the proper use and applicability of the maturity method to whitetopping construction in Korea.

The maturity method provides a reliable technique for continuously monitoring of concrete strength gain for determining the proper joint sawing time and opening traffic to public without delay (2,3). This technique is a non-destructive test method for estimating in-place concrete strength as a function of temperature and time. The advantages of this technique does not require as much conventional field testing of concrete specimens and improves safety by reducing the exposure time of work zone area to traffic (3). There are currently two maturity methods accepted by ASTM; the Nurse-Saul Function and the Arrhenius Equation.

This technique was first applied to whitetopping construction in Korea. Therefore, the laboratory test plan and pilot field application are established after extensive literature review. Based on the results of the laboratory tests, a maturity values for joint sawing time and traffic opening times are calculated at desired times. In-place concrete strengths of whitetopping sections at intersections on National Highway 2 and 17 are then estimated from a pre-established relationship between maturity values (or equivalent age) and the concrete compressive strengths. This study also conducts to analyze and compare the differences between in-place concrete strength and estimated strength from two maturity methods.

OBJECTIVES OF THE STUDY

The primary objective of this study is to apply maturity methods for determining joint sawing time and traffic opening time on whitetopping construction in Korea. Another objective is to examine and compare two maturity methods.

THEORY OF MATURITY METHOD

As well known, the strength of a given concrete mixture, which has been properly placed, consolidated, and cured, is a function of its time and temperature history (2,3,4). The combined effects of time and temperature on strength gain are quantified by means of a maturity function. Two maturity methods accepted by ASTM are used to predict the strength of concrete using time and temperature history. The
first is the Nurse-Saul function, which uses simple linear integration of the age and temperature. The output of the function is a time-temperature factor (TTF). The datum temperature is the temperature at which the concrete ceases to gain strength and is commonly taken as somewhere between -10°C and 0°C (5,6). Saul suggested that datum temperature is -10°C (2,7). The datum temperature being used in this study is -10°C recommended by Sargand for a fast set (8). The Nurse-Saul function is as follows:

\[
M(t) = (T - T_0) \times \Delta T
\]  

(1)

Where,  
\( M(t) \): maturity at age \( t \), or time-temperature factor (TTF) at age \( t \)  
\( \Delta T \): time interval, day or hours  
\( T \): average concrete temperature during time interval, °C  
\( T_0 \): datum temperature, °C

The Second method is the Arrhenious method proposed by Freiesleben Hansen and Pederson, which uses the reaction rate of cement to compute an equivalent age from the recorded temperature history of the concrete (2,6,7). The equivalent age (\( t_e \)) can be defined as the amount of time it would take concrete hydrating at the reference temperature (\( T_r \)) to achieve the same maturity that the measured concrete has obtained at the time of calculation. The activation energy of concrete varies with the type, water/cement ratio, and admixtures. For type I cement with no admixtures, the activation energy varies between 40,000 and 45,000 J/mol (5,6). Table 1 shows activation energy values based on compressive strength tests of concrete cylinders and mortar cubs (2). Based on water-cement ratio and admixture as shown in Table 1, the activation energy used in this study was 44,600 J/mol.

The reference temperature is usually taken as 20°C or 23°C because much standard curing is done at those temperatures but other temperature can be used (2,5). The reference temperature used in this study was 20°C. The equation is as follows:

\[
t_e = \sum_0^t e^{-\frac{E}{R T} \left( \frac{1}{T} - \frac{1}{T_r} \right) \times \Delta T}
\]  

(2)

Where,  
\( t_e \): equivalent age at a reference temperature \( T_r \)  
\( T \): average concrete temperature during time interval \( \Delta T \), °K  
\( T_r \): reference temperature, °K  
\( \Delta T \): time interval, day or hours  
\( E \): activation energy  
\( R \): the gas constant, 8.3144 J/(mol K)
The Nurse-Saul function assumes a log-linear relationship between maturity and temperature, while the Arrhenius function uses an exponential relationship. Previous studies have shown that the Nurse-Saul function is inferior to Arrhenius function (2,5,6). However, the Nurse-Saul function is widely used because of its simplicity (5,6).

MIX DESIGN AND CONSTRUCTION SEQUENCE

In the July of 2003, whitetopping construction projects at two intersections on National Highway 2 and 17 in Korea were scheduled for rehabilitation. Lane closure was only feasible during one day. A mix was required to provide high early strength with sufficient workability. The mix containing type III Portland cement was designed to attain a 22.5 MPa compressive strength for early traffic opening to the public within 24 hours. Table 2 shows information on the mix proportions. The mix design was determined after a lot of laboratory tests were performed, which was considered an early concrete strength and deliver time to field.

Figure 1 shows the layout of 100m-whitetopping section for each direction of National Highway 2 and 17. The average daily traffics at both National Highways were around 40,000 vehicles with 40 percent of truck ratio. The average rutting of both intersections was 40~50 mm, but the result of FWD test indicated good support of asphalt layer, exhibiting 216 micron of maximum deflection. After milling off the surface of distressed asphalt, the design included the overlay of 150mm-thick concrete with 1.8m of joint spacing. Paving operation on the eastbound and the westbound of National Highway 17 started at 4 p.m. and completed at 8 p.m. On the following day, paving operation on the eastbound and the westbound of National Highway 2 started at 3 p.m. and completed at 5 p.m., and started 7 p.m. and continued until 9 p.m., respectively.

LABORATORY TEST

The Determination of Sawing Time and Strength

The concrete must be sawn at the appropriate time because sawing too early will cause excessive reveling and may result in a marred pavement surface, while sawing too late will not provide the weak plane in time to guide the concrete to crack at that location and may bring out random creaking in the pavement (9). To determine appropriate joint sawing time, it was necessary to find and identify the minimum strength that does not cause raveling and the time to the occurrence of drying shrinkage.

The test slabs (0.9m ×0.9m×0.1m) were fabricated to find the minimum strength and to identify the time to the occurrence of drying shrinkage. Thermachron i-buttons and strain gages also were inserted into the top and the mid-depth of fresh concrete to monitor concrete temperature and initial behavior of concrete. Figure 2 shows the test slab temperature, cylinder temperature, ambient (air) temperature, and
the concrete deformations at the top of the test slab with time. The rate of strength development for the test slab is expected to be higher because the slab temperature is higher than cylinder temperature. The ambient (or air) temperature kept 20°C as a reference temperature. As seen Figure 2, the concrete deformation curve can be divided into four phases: AB, BC, CD, and DE. At early concrete age, thermal deformation and autogenous shrinkage occur simultaneously. This thermal deformation results from the temperature rise caused by hydration and is proportional to the thermal dilation coefficient of cement paste (10). When no additional water is added to the concrete through curing, the concrete begins to chemically consume the water from the capillary pores during the hydration (10,11,12).

In the first phase (AB), slight initial expansion was observed up to 2 hours. The dry cement first comes into contact with water and the rate of evolution of heat is very high, which corresponds to the initial hydration at the surface of the cement particles, largely involving C₃A (12). Therefore, it seems that slight initial expansion of the concrete occurred during this phase. Since the concrete temperature is constant during BC phase, concrete deformation, especially autogenous shrinkage, starts and continues until concrete temperature begins to increase. During the CD phase, there is almost no deformation until maximum concrete temperature. Generally, autogenous shrinkage dominantly occurs until maximum concrete temperature, but thermal deformations compensate for autogenous shrinkage (10). After the cooling period (DF), drying shrinkage begins to take place just after maximum concrete temperature (11). Therefore, random cracks may occur if the concrete is not sawn until the beginning of the DE phase.

As mentioned earlier, sawing too early causes excessive raveling. To identify the minimum concrete strength for joint sawing time, test slabs were cut and compressive strengths were measured per every 20-minute after 4 hours since the concrete was placed. Aggregates did not pop out after 6 hours since the concrete was placed. The compressive strength at this time was 4.41MPa (45kg/cm²). Therefore, the appropriate sawing time ranged 6 to 9 hours for this mix at 20°C.

To develop the relationship between maturity and concrete strength, three cylinders (150mmx300mm) were tested after 6,8,10,12,15,21, and 24 hours of wet curing. Guideline procedures for maturity testing are given in ASTM C 1074-98 (13).

Figure 3 shows the relationship of compressive strength and maturity using the Nurse-Saul function. The datum temperature was used to -10°C due to high amount of type III cement. ACPA (American Concrete Pavement Association) recommends that decisions regarding joint sawing and traffic opening times should be based on data from a test probe at the top (within 25mm) and at the mid-depth of concrete, respectively (3). The coefficients of determination (R-square) were 0.96 for the top and the mid-depth.
These values are satisfied with ACPA’s recommendation (higher r-square of 0.95). Two maturity curves are not much different as shown in Figure 4. Based on the equations in Figure 4, joint sawing can start at 190°C-hour and should be completed at 310°C-hour. Traffic opening time was after maturity values reached at 390°C-hour.

**Arrhenius Equation**

The reference temperature and the activation energy were taken as 20°C and 44,600 J/mol for this study. For the strength-maturity relationship, the hyperbolic prediction model is more accurate than the logarithmic prediction model (2,14). The following hyperbolic equation was used to estimate the strength gain up to 24 hours at 20°C for this study:

\[
\frac{S}{S_\infty} = \frac{k_T(t_e - t_0)}{1 + k_T(t_e - t_0)}
\]

Where,  
- \( S \): strength at time \( t \), MPa  
- \( S_\infty \): the limiting strength  
- \( k_T \): value of the rate constant at the curing temperature  
- \( t_0 \): age at the start of strength development, hours

The age at the start of strength development is the age at the time of final setting (8). This was found to be 5.83 hour through penetrometer test according to ASTM C-403. The values for \( S_\infty \) and \( k \) were fitted using non-linear regression technique. The results of \( S_\infty \) and \( k \) were 61.68MPa and 0.066 for the top, and 64.99MPa and 0.052 for the mid-depth of test slab, respectively. The coefficients of determination (R-square) were 0.990 for the top and 0.986 for the mid-depth. Figure 4 describes the relationship between the compressive strength and the equivalent age at top and mid-depth of test slab. The equivalent age at the top of test slab is lower due to the difference of temperatures. However, two curves were not much different as found in the Nurse-Saul function. According to the determined hyperbolic prediction equations, the range of joint sawing time was from equivalent age of 7 to equivalent age of 12 and traffic opening time was after the equivalent of 16.

**FIELD APPLICATION**

**The Case of National Highway 17**

Figure 5 shows the concrete temperature at the top and the mid-depth of the slab, air temperature, and concrete deformation of the top of the slab at National Highway 17. Weather condition was heavily
cloudy and average temperature was around 25°C. The peak concrete temperature for both the top and mid-depth of slab appeared about 7.5 hours since the concrete was placed. The trend of concrete deformation curve was similar to that of the laboratory tests except for deformation at later age. Figure 6 shows the comparison between predicted strength-maturity and in-situ strength-maturity for the Nurse-Saul function. During early period, the Nurse-Saul function predicted in-place strength quite well, but it overestimated in-place strength during later period. Figure 7 shows the comparison between predicted strength-maturity and in-place strength-maturity for the Arrhenius equation. The Arrhenius equation overestimated in-place strength.

**Determination of Joint Sawing Time and Traffic Opening Time**

After two maturity methods were compared, joint sawing time and traffic opening time were determined using the Nurse-Saul function. Joint sawing started at 220°C-hour and completed at 270°C-hour (the range of actual time was 5 to 6 hour) and traffic opening was achieved at TTF of 470°C-hour after 10 hours since the concrete was placed. ACPA recommends that in-place compressive strength be placed within 3.4MPa (500psi) of the original maturity curve at the TTF (3). In the case of National Highway 17, this condition was satisfied. Condition survey was conducted after a year and these sections did not exhibit any distresses including raveling at joint.

**The Case of National Highway 2**

Figure 8 shows the concrete temperature and ambient temperature at both directions of National Highway 2. The weather condition was sunny and the maximum daily temperature of 35°C. The eastbound was constructed before sunset, while the westbound of this highway was constructed after sunset. Even though both average daily air temperatures were about 25°C, the peak concrete temperature at the westbound came 2 hours faster and was higher 5°C than those of the eastbound.

The Nurse-Saul function predicted concrete strength well for the westbound and it overestimated concrete strength for the eastbound as shown in Figure 9. The difference between sections was that ambient temperature was 30°C with sunshine at the eastbound and 25°C without sunshine at the westbound when the concrete was placed. Schindler et al. stated that due to hot weather condition the non-uniform distribution of pores in hardening paste and the creation of shells around the cement grains impede the development of concrete strength (15). Therefore, when a concrete pavement is constructed during high temperature with strong solar radiation, very close attention should be placed. Figure 10 delineates the comparison to the estimated concrete strengths and in-place concrete strengths along the equivalent age. The Arrhenius equation significantly overestimated in-place strength for National Highway 2.
Determination of Joint Sawing Time and Traffic Opening Time

The concrete temperature of sections on National Highway 2 was monitored at only the mid-depth of slab. Therefore, based on temperature history at the mid-depth of slab, joint sawing time and traffic opening time were determined using the Nurse-Saul Function. For the westbound, joint sawing started at 213°C-hour and completed at 260°C-hour (the range of actual time was 5 to 6 hour). Then, traffic opening was achieved at TTF of 465°C-hour after 10 hours since the concrete was placed. For the eastbound, joint sawing started at 291°C-hour and completed at 348°C-hour (the range of actual time was 6 to 7 hour) and traffic opening was achieved at TTF of 670°C-hour after 13 hours since the concrete was placed. In the case of the eastbound, joint sawing and traffic opening was delayed due to slow development of concrete strength. The section on the westbound was satisfied with ACPA’s recommendation but the section on the eastbound was failed. Condition survey was conducted after a year and the section on the eastbound exhibited a little distresses including raveling at joint.

SUMMARY AND CONCLUSION

The primary objective of this study was to determine joint sawing time and traffic opening time by using the maturity method for whitetopping construction in Korea. To determine joint sawing time, it was necessary to find the minimum strength not to be resulted in raveling and to identify the time to the occurrence of drying shrinkage. This study found that the minimum compressive strength for joint sawing was 4.41MPa (45kg/cm²) and drying shrinkage occurred just after the concrete temperature reached at the peak. For Nurse-Saul function, The range of joint sawing time was from 190°C-hour to 310°C-hour (6 to 9 hours at 20 °C) and traffic opening time was when maturity values reached at 390°C-hour after 10 hours since the concrete was placed. For Arrhenius equation, the range of joint sawing time was from equivalent age of 7 to equivalent age of 12 and traffic opening time was after the equivalent of 16. According to the results of the laboratory tests, Arrhenius equation estimated concrete strength better than did the Nurse-Saul function. However, the Arrhenius equation significantly overestimated in-place concrete strength. In this study, the Nurse-Saul function was used for determining joint sawing time and traffic opening time. The application of the Nurse-Saul function to fields was successful except for the section on the eastbound of National Highway 2. It seemed that high ambient temperature with strong solar radiation had a negative effect on developing concrete strength and increased the peak concrete temperature. Therefore, close attention should be placed in this condition when the maturity method is used.

The more detailed research on the Nurse-Saul function and the Arrhenius equation will be conducted in future study. The future study includes investigating effects of various curing conditions, seasonal temperature variation, and daily weather conditions such as wind, variation of daily temperature, and solar radiation. It is expected that the guideline for application of maturity method on whitetopping will be prepared after the completion of this project.
REFERENCES

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<table>
<thead>
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<th>Cementations Material</th>
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<tr>
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<tr>
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<tr>
<td>Type III</td>
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<td>Type I + Retarder</td>
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</table>

*Source: Carino, N.J. and Tank, R.C., ACI Mater.J., 89(2), 188, 1992*

<table>
<thead>
<tr>
<th>Mix Proportion</th>
<th>Quantity per cubic meter (kg/m³)</th>
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<tr>
<td>Slump (cm)</td>
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Figure 1. Layout of Whitetopping Sections

Figure 2. Trends of Temperatures and Concrete Deformations with Time
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Figure 10. Application of Arrhenius Equation on National Highway 2