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Development of Maturity Protocol for Construction of NJDOT Concrete Structures

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16. Abstract

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Introduction

For years, 28-day cylinder tests have been employed during the construction in order to estimate the compressive strength of concrete. Compression test is not intended for determining the in-place strength of concrete, since it makes no allowance for the effects of placing, compaction, or curing. For example, it is unusual for the concrete in a structure to have the same properties as a standard-cured cylinder at the same test age. In addition, since standard-cured cylinders are usually tested at an age of 28 days, they cannot be used to determine whether adequate strength exists at earlier ages for safe removal of formwork, shoring or the application of the post-tensioning.

Nondestructive in-place test methods have been developed for estimating the compressive strength of concrete in structures. These tests are essential for realistic depiction of the in-place strength in concrete elements. One of the techniques for estimating the strength gain of in-place concrete is the maturity method. This technique is based upon the measured temperature history of concrete during the curing period. The combined effects of time and temperature lead to a single parameter termed maturity. Accordingly, samples of the same concrete whether in the cylinder or in the structure will be assumed to have acquired equal strengths provided that they have equal maturities. This is irrespective of the thermal history differences in the cylinder and the structure. Application of the maturity method for estimation of in-place strength requires determination of strength-maturity relationship from cylinder tests, measurement of in-place concrete temperatures, and estimation of in-place strength based on the strength-maturity relationship.

In summary, Fig.1 depicts the concept pertaining to the application of the maturity method, which encompasses laboratory testing, and field measurement of the in-place temperature history. The laboratory testing establishes the relationship between the compressive strength and the maturity for concrete. In-place maturity of concrete is determined through field measurements of temperature by way of thermocouples or maturity meters. The in-place maturity can be employed in conjunction with the laboratory determined compressive strength-maturity relationship to estimate in-place compressive strength of concrete as it exists in the structure. This reduces the number of cylinder tests during construction. It is imperative to understand that sufficient moisture has to be provided for proper curing of concrete for laboratory specimens as well as the concrete in the structure. Otherwise, gain in strength ceases due to insufficient moisture necessary for hydration reactions to continue.

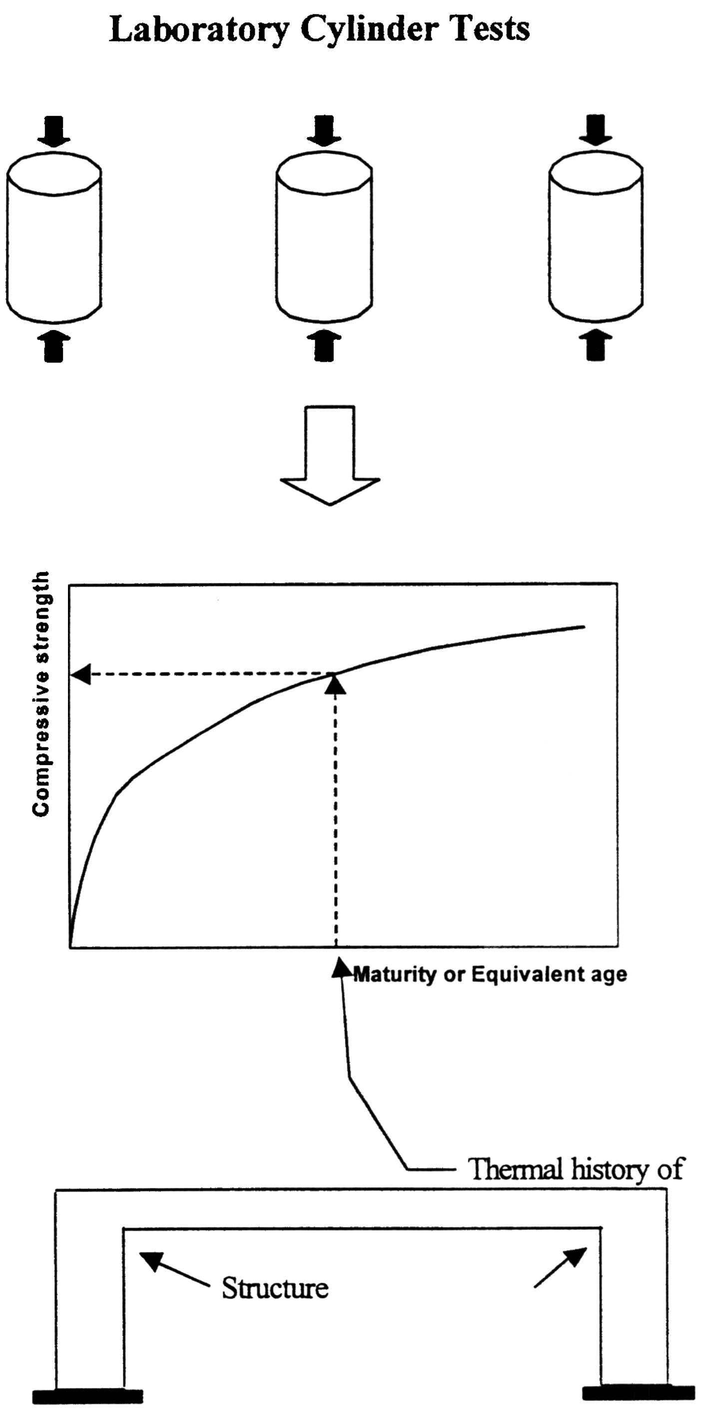

Fig.1 Basic concept of the maturity method in structural applications.

Research Objectives

The objectives for the research reported here were to develop laboratory and field testing protocols for the use of maturity concepts in NJDOT concretes. Employment of the maturity method in NJDOT projects will be cost effective. The number of cylinders tested during construction will be reduced by 75%, and the construction time for future NJDOT projects will be reduced by 30 to 50 percent. The maturity levels will be checked at early ages in order to make deterministic decisions for removal of shoring, and formwork for rapid construction of pavements, bridges and other types of highway construction.

Investigative Approach

The investigation encompassed a rigorous experimental program involving determination of maturity constants for typical NJDOT concretes. As it will be explained in later sections of this report, typical NJDOT concrete mixtures were prepared in the laboratory as per ASTM C 1074. Strength maturity parameters including the datum temperature, the activation energy, as well as the strength maturity, and strength age correlation relationships were developed in the laboratory.

Field and laboratory maturity computations and data acquisition process were automated to facilitate establishment of real-time temperature-age data, and strength-maturity correlation relationships. Field maturity operation protocols, i.e. thermocouple placement techniques, and requirements for various structural elements (columns, beams, slabs, footings, walls, etc) were established for use by field personnel. Field data was analyzed, and comparisons between cylinder maturity strength and the estimated maturity of the concrete in the structure were made. Data was collected from several elements of the structure, i.e. pier caps, footings, and columns, and their maturities were compared.

NJDOT personnel were trained during a workshop at NJDOT in order to develop an understanding as to the basics of the maturity principle. This workshop was intended to provide the NJDOT personnel with basic computations skills in order to establish correlation relationships between the maturity and the in-place compressive strength in structures. A suitable NJDOT construction project was identified, and the laboratory established mix design and the correlation relationships were employed in the estimation of in-place compressive strength for the concrete provided by the contractor for the project.

Maturity Concept

After initial setting, concrete gains strength over time. The higher the temperature during the early life of the concrete, the faster it gains strength; the lower the temperature, the slower it gains strength. At a very low temperature, generally in the range of 10^0F to 14^0F (-12^0C to -10^0C), hydration, and therefore strength gain ceases. The exact temperature at which strength gain ceases for each concrete mix depends on its composition and the properties of the cementitious materials and chemical admixtures used. The maturity method is a technique to account for the combined effects of time and temperature on the strength development of concrete. By measuring the temperature of concrete during curing period, it is possible to estimate the strength at any particular age. The temperature history is used to calculate a maturity index which can be related to compressive strength by a strength-maturity curve.

The maturity index is calculated from the temperature history by a maturity function. The maturity function used in the United States, the Temperature-Time factor, computes the product of time and temperature and it is expressed in degree-hours. In Europe, the equivalent age principle is used, which is the age at a standard temperature that results in the same strength as under the nonstandard condition. The maturity function used to compute the temperature- time factor is given below:

$$M(t) = \sum (T_a - T_0)\Delta t \qquad (1)$$

Where:

$M(t)$ = The temperature-time factor, or maturity, at age t, degree-days or degree-hours,

Δt = Time interval, days or hours,

T_a = Average concrete temperature during time interval, Δt, ^{0}C, and

T_0 = Datum temperature, ^{0}C

In the Equivalent age approach the maturity function employed in computing the equivalent age at a specified temperature is given in the following format:

$$t_e = \sum e^{-[Q((1/T_a)-(1/T_s))]} \Delta t \qquad (2)$$

Where:

t_e = Equivalent age at a specified temperature, T_s, days or hours,

Q = Activation energy divided by the gas constant (8.31 J/(mol-K)), ^{0}K,

T_a = Average temperature of concrete during time interval Δt, ^{0}K,

T_s = Specified temperature, ^{0}K, and

Δt = Time interval, days or hours

The Equivalent age is not popular in U.S., since it is more difficult to interpret the results. The Equivalent age may be interpreted as the number of days or hours at a specified temperature required to produce maturity value equal to the value achieved by a curing period at temperatures different from the specified temperature. The strength versus equivalent age relationships established in the laboratory is used in the field. Field thermal history data is converted to equivalent age, and is employed in the strength equivalent-age relationship obtained in the laboratory to determine strength at the age of testing in the field.

The main maturity parameter involved in the time-temperature factor is the datum temperature. On the other hand, in the equivalent age approach, the key parameter is the activation energy. Nominal datum temperature and activation energy values are given in ASTM C1074. However, more accurate strength predictions are achieved if these parameters are evaluated for specific cement brands and types as well as the admixture types employed in the mixture. Both the datum temperature as well as the activation energy for a typical NJDOT mixture has been developed through rigorous experimental investigation. These parameters can be employed for both NJDOT class A and B concretes. The experimental procedures and computations necessary for achieving these results are given, in case NJDOT personnel needed to evaluate maturity parameters for entirely new class of concretes.

Although, activation energy values are evaluated, however, the laboratory and field computations involved the temperature-time maturity approach as opposed to the equivalent age approach. This was mainly due to simplicity involved in the application of the maturity principle, therefore rendering it more practical for widespread usage by NJDOT personnel.

Determination of Datum Temperature and Activation Energy

The procedure described here is taken from ASTM C1074. This procedure was employed in order to determine the maturity parameters for the NJDOT concrete mixtures.

General procedure

The testing required for experimental determination of datum temperature can be performed with mortar specimens, and results are applicable to concrete made with the same mortar composition. The procedure is as follows:

1) Proportion a mortar mixture similar to the mortar in the concrete that is to be used. The mortar shall include the appropriate quantities of admixtures that will be used in the concrete.

2) Prepare three sets of mortar specimens (18 cubes per set)) using the container specified in the ASTM Test Method C 403[1]. Carefully submerge each specimen into temperature-controlled water baths. Two of the baths shall be at the maximum and minimum concrete temperatures expected for the in-place concrete during the time the strength predictions will be made. The third bath temperature shall be midway between the two extremes.

3) Using Test Method C 403, determine the time of the final setting for each temperature. The specimens are removed from the water baths and the excess water is removed prior to making penetration measurements.

4) Prepare three sets of 50-mm mortar cubes. Each set comprising of 18 cubes. Mold the cubes in accordance with Test Method C 109[2] and carefully submerge each set into the temperature-controlled baths used in step 2 above. For each set, remove the molds and return the specimens to their respective baths 1-hour before the first series of compression tests.

5) For each set of cubes, determine the compressive strength of three cubes in accordance with Test Method C 109 at an age that is approximately twice the age to reach the final setting. Perform subsequent tests with three cubes from each set at ages that are approximately twice the age of the previous tests. For example, if the final set for a particular mortar was 12 hours, then compressive tests would be performed at 24, 48, 120, 355, and 672 hours respectively.

6) For each curing temperature, plot the reciprocal of the average cube strength along the y-axis and the reciprocal of the age, beyond the time of final set along the x-axis (Fig.2).

7) Determine the slope and the intercept of the best-fitting straight line through the data for each curing temperature.

8) For each straight line, divide the value of the intercept by the value of the slope. These quotients, or K-values, are used to calculate the datum temperature and the activation energy.

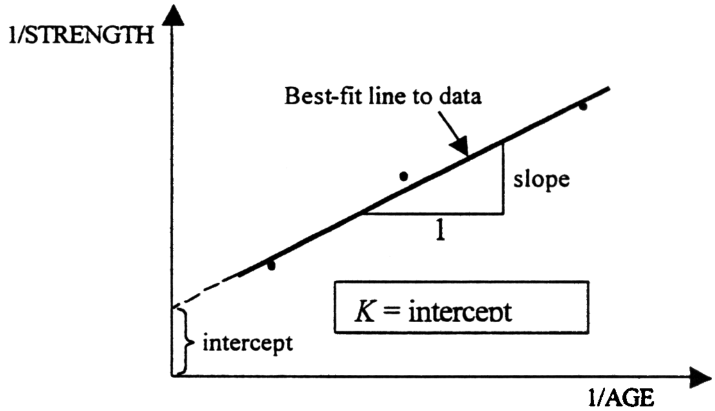

Fig.2 Schematic representation of the relationship between the inverse of strength and the age of concrete

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[1] ASTM C-403 "Test Method for Time of Set of Concrete Mixtures by Penetration Resistance"
[2] ASTM C-409 "Test Method for Compressive Strength of Hydraulic Cement Mortars"

Determination of Datum Temperature

Plot the quotients (K-values) from step 8 above as a function of the water bath temperature. Determine the best-fitting straight line through the three points and determine the intercept of the line with the temperature axis. This intercept is the datum temperature, T_0, that is to be used in computing temperature-time factor according to Eq.(1).

Determination of Activation Energy

Calculate the natural logarithm of the quotients (K-values) in step 8 above and determine the absolute temperatures (in Kelvin) of the water baths. Plot the natural logarithm of the quotients (k-values) as a function of the reciprocal absolute temperature. Determine the best-fitting straight line through the three points. The slope of the line is the value of the activation energy divided by the gas constant, Q that is to be used in computing equivalent age according to Eq (2).

Datum Temperature and Activation Energy for NJDOT Concrete

According to the testing procedures described in the foregoing section, three sets of 50-mm mortar cubes, each set comprising of 18 cubes were prepared. The mortar cubes were cured in three temperature-controlled water baths, whose temperatures were fixed at 10 ^{0}C, 22 ^{0}C, 33 ^{0}C respectively. The mortars in these experiments were extracted, through sieving, from a typical NJDOT concrete mix (Class A, Serial No. 563510 M1). The sieving process involved passing the plastic (fresh) concrete through a No.4 sieve (square openings). *This procedure assured production of mortar specimens with exact mixture proportions as the class A concrete.* For each set, compressive strengths at ages 24, 48, 120, 355, and 672 hours were determined. Average of three cubes per testing age was computed. The reciprocal of the average cube strength is plotted against the reciprocal of the age beyond the time of final setting as shown in Fig.3.

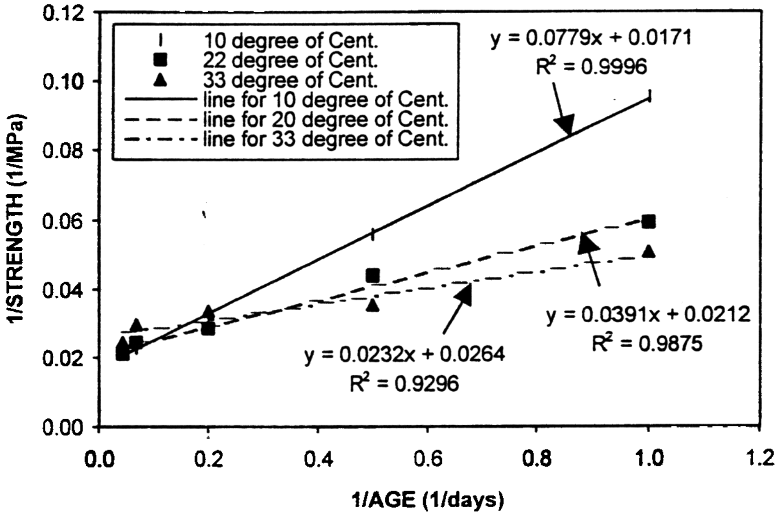

Fig.3 Reciprocal of strength versus reciprocal of age beyond time of final setting

As shown in Fig.3, at each curing temperature, the best-fit straight line is drawn through the data. The quotients or *K*-values are obtained by dividing the value of intercept by the value of the slope. *K*-values are plotted against the curing temperatures in Fig.4. The datum temperature is obtained by evaluating the intercept of the best-fit line to the data in Fig.4. Results from this evaluation yields an intercept of 5.7 ^{0}C, which is the datum temperature, T_0 for the NJDOT mixture.

Activation energy is obtained from the slope of the best-fit line to the data points corresponding to the natural logarithm of the quotients (*K*-values) and the reciprocal of the curing temperatures (in degrees-Kelvin). This is shown in Fig.5, where the slope, Q , is the activation energy divided by the gas constant (gas constant is 8.3144J/mol·K), and therefore, the activation energy for the NJDOT concrete is E_a = 51.537 kJ/mol.

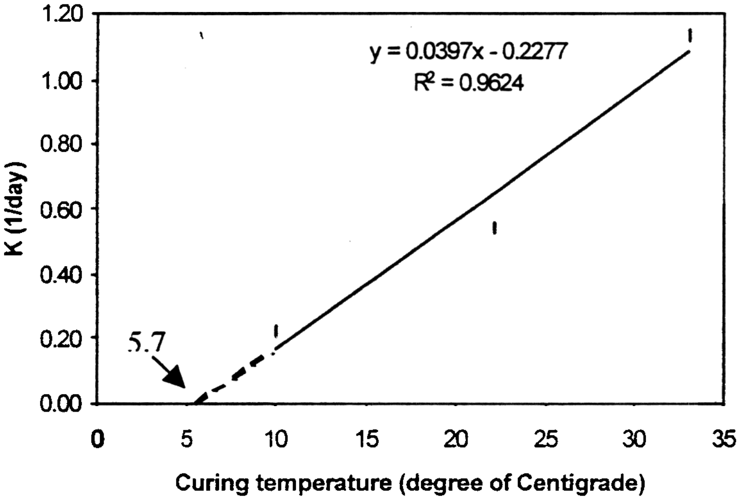

Fig.4 K-Values versus curing temperature for determining the datum temperature

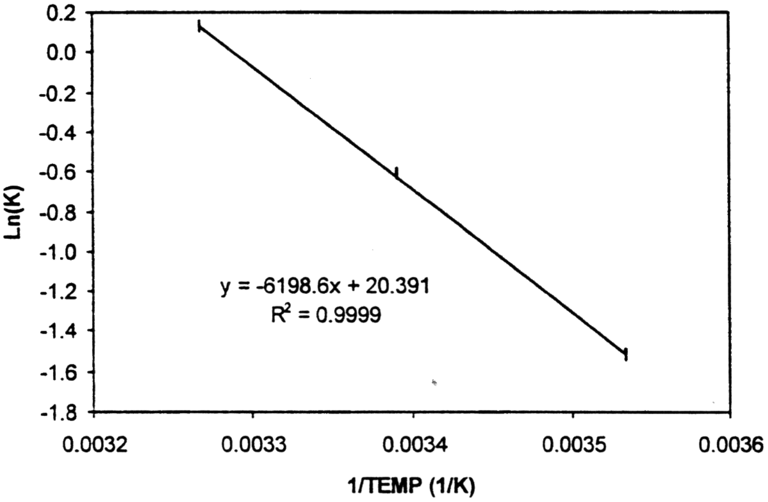

Fig.5 Natural logarithm of K-values versus the inverse absolute temperature

Procedures to Develop Strength-Maturity Relationships in the Laboratory

Prior to the field application of the maturity method, laboratory tests need to be implemented in order to establish a relationship between the maturity and the compressive strength. The laboratory testing shall be performed on concretes with the same constituents and mixture proportions as those to be placed in the field. The procedure described below outlines the ASTM C-1074[3] requirements, and those implemented here for NJDOT concretes.

1) Prepare at least 15 cylindrical specimens according to Practice C 192[4] using the mixture proportions and constituents, including admixtures, of the concrete whose strength-maturity relationship is to be developed.
2) Embed temperature sensors (thermocouples) at the centers of at least two specimens. Connect the sensors to maturity instruments or to temperature-recording devices such as computer data acquisition systems, data-loggers or strip-chart recorders.
3) Moist cure the specimens in a water bath or in a moist curing room meeting the requirements of specification ASTM C-511[5].
4) Perform compression tests at the ages of 1, 3, 7, 14 and 28 days in accordance with test method ASTM C-39[6]. Test at least three specimens at each age.
5) At each test age, record the average maturity value for the instrumented specimens. If maturity instruments are used, record the average of the displayed values. If temperature recorders are used, evaluate the maturity according to Eq (1). Use a time interval of ½hour or less or the first 48 hours of the temperature record. Larger time intervals may be used for the relatively constant portion of the subsequent temperature record.
6) Create a spreadsheet similar to the one in ASTM C-1074, plot the average compressive strength as a function of the average maturity value. Draw a best-fit curve through the data. The resulting curve is the strength-maturity relationship to

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[3] ASTM C-1074 "Practice for Estimating Concrete Strength by the Maturity Method"

[4] ASTM C-192 "Practice for Making and Curing Concrete Test Specimens in the Laboratory"

[5] ASTM C-511 "Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes"

be used for estimating the strength of concrete mixture cured under other temperature conditions, such as those in the structure (Fig.6).

7) Estimate from the curve, the maturity necessary to create the required strength.

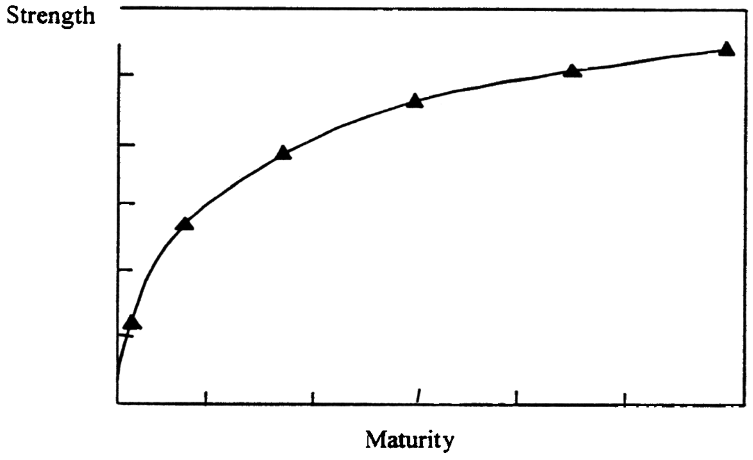

Fig.6 Schematic representation of a typical Strength-Maturity relationship.

Example for calculation of Maturity index from Time and Temperature Data

This example is aimed at demonstrating calculation of maturity values from age versus temperature data. Data corresponds to only first 2.5 hours of test. These maturity calculations are applicable to laboratory as well as field temperature readings. At desired maturity values cylinders can be tested to establish strength maturity data.

Example: Given the Age vs. Concrete Temperature data in the first two columns of the table below, and a datum temperature, $T_0=5.7^0C$, compute maturity (it is also called time-temperature factor).

In the table below (Table-1), t-T refers to time- temperature factor or maturity.

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[6] ASTM C-39 "Test Method for Compressive Strength of Cylindrical Concrete Specimens"

Table-1 Example for the computation of maturity values ($T_0 = 5.7\ ^0$C)

1	2	3	4	5	6
Age (hrs)	Temperature T, (^{0}C)	Age Incr. (hrs)	Avg. T_a (^{0}C)	Maturity Incr. (^{0}C-hrs)	Maturity (^{0}C-hrs)
0.0	20				0.00
0.5	18	0.5	19.0	6.65	6.65
1.0	17	0.5	17.5	5.90	12.55
1.5	16	0.5	16.5	5.40	17.95
2.0	15	0.5	15.5	4.90	22.85
2.5	15	0.5	15.0	4.65	27.50

The following relationship (Eq.1) is used to compute maturity values:

$$M(t) = \Sigma(T_a - T_0)\Delta t \qquad \text{(Eq. 1)}$$

Age increments between temperature readings are given in Column 3. In this case, since data was acquired at 0.5 hour intervals, then all the values in column 3 are 0.5 hours. Column 4 corresponds to the average temperature readings between subsequent intervals. For instance, the average temperature during the first 0.5 hours is: $\frac{20+18}{2} = 19^\circ C$, and the average temperature between the 0.5 and 1 hour readings is: $\frac{18+17}{2} = 17.5^\circ C$, and similar computations can be made for the rest of the time intervals. Eq.(1) is employed for evaluation of maturity within each time interval of 0.5 hours. For instance, during the time 0 to 0.5 hours, $\Delta t = 0.5$ hours, T_a= 19 ^{0}C, and T_0=5.7^{0}C. Therefore:

During the first time period 0 to 0.5, T_a= 19 ^{0}C

M_1= 0.5 (19-5.7)= 6.65 ^{0}C-hr.

During the next time period 0.5 to 1, $T_a=17.5^0C$, and the increment in maturity is:

$M_2 = 0.5\ (17.5 - 5.7) = 5.9\ ^0C\text{-hr}.$

Maturity after 1-hour is cumulative and it is: $M_{\text{after 1-hr}} = M_1 + M_2 = 6.65 + 5.9 = 12.55^0C$
The same pattern of computations is performed for the subsequent intervals. Laboratory strength-maturity relationships for NJDOT mixtures are described next.

Strength-Maturity Relationship for NJDOT Concrete

The construction site chosen for this project was a highway bridge located near Newark airport at the intersection of I-78 and NJ routes 1&9 and 21. The mix designs were provided by the contractor as per NJDOT specifications. All the laboratory samples were prepared according to this mix design. Cylindrical specimens (4x8 inch) were prepared for the determination of strength at 5 different ages of 1, 3, 7, 14, and 28 days. Three specimens were instrumented with thermocouples to measure the temperature changes in the specimens. The thermocouples were placed into approximate half-height of the cylinder through the top of the cylinder. All these samples were cured under moist cure condition in the curing room. At each test age, three replicate specimens were tested and the average compressive strength was obtained. At the same time, an average maturity value based on results from the three-instrumented cylinders was also computed.

The average compressive strength as a function of the average maturity value for the NJDOT concrete is plotted in Fig.7. The best-fit curve to the data was obtained through nonlinear regression analysis of data. The following relationship is the result of the nonlinear regression analysis and represents the relationship between the maturity and the compressive strength of the concrete to be used in the construction site:

$$S = 622.06 \ln(M) - 1340.5 \tag{3}$$

Where S and M denote the strength (psi) and maturity (^0C-hours unit) respectively.

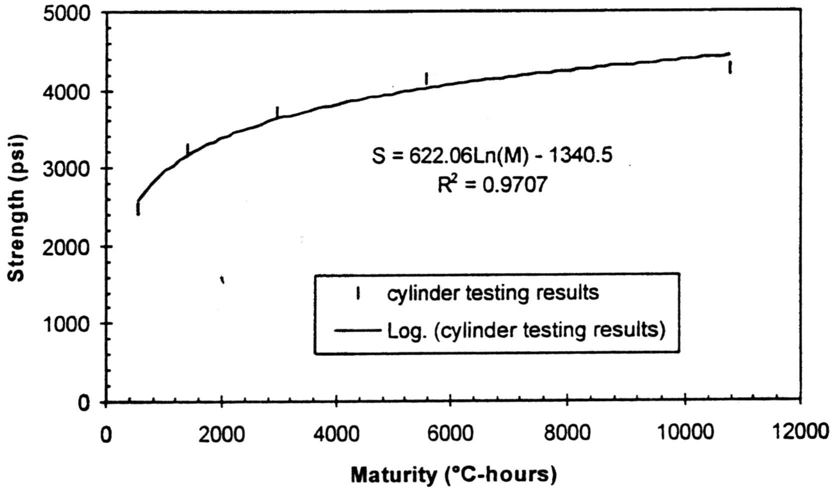

Fig. 7 Strength-Maturity Relationship (S and M in the regression relationship correspond to Strength and Maturity respectively)

The strength-maturity correlation relationship in Eq.(3) or Fig.7 is used in conjunction with the concrete specifically developed for this project. The materials and mixture proportions employed in the laboratory mimicked the mixture design provided by the contractor for the field application. In future NJDOT projects, strength-maturity correlation relationships need to be developed for concretes to be used in the field. The datum temperature developed here (5.7^{0}C) can be used for a crude estimation of NJDOT concrete strengths. However, it is important to note that, accurate results require determination of datum temperature for each cement type, brand, and concrete mixture prior to the use of maturity method in the field. Procedures employed in this report and stipulated in ASTM C-1074 can be used for this purpose. Field instrumentation details and construction procedures will be given next.

Field Implementation of the Maturity Method

Maturity method is a nondestructive testing method that provides an estimate of concrete strength for new construction. Unlike other NDT methods, there are no compressive strength limitations, and the maturity method can be employed for all the strength levels. Prior to description of the field tests performed during this project, it is imperative to provide the NJDOT personnel with general guidelines regarding field operations. These guidelines will be useful for future application of the technique by NJDOT personnel.

Planning for In-Place Testing

During a pre construction-planning meeting between NJDOT, contractor, supplier of the concrete, and the formwork contractor, the following items need to be discussed:

- The specifics concerning the maturity test to be performed, compressive strength tests at specific ages of concrete, number and locations of tests, and the assistance to be provided by the contractors in preparing and protecting test locations and testing equipment.
- The criterion for acceptable test results, i.e. strength levels, for performing critical operations, such as form removal, post-tensioning, removal of re-shores, or termination of curing.
- Procedures for providing access and any modifications to formwork required to facilitate testing.
- Procedures and responsibilities for placement of testing hardware, where required, and protection of test sites.
- Procedures for execution and timing of testing.
- Reporting procedures to provide timely information to site personnel.
- Approval procedures to allow construction operations to proceed if adequate strength is shown to have been achieved.
- Procedures to be followed if adequate strength is not shown to have been achieved.

Number of test locations (locations at which temperature to be measured) in the structure depends on the structural element type and the quantity of concrete employed. As a general rule, the following guidelines extracted from the report of ACI Committee 228 may be recommended:

For slabs, and shear walls, the minimum number of test locations for the first 100 yd^3 to be 5, and add 2 test locations for each additional 20 yd^3.

- In vertical elements such as columns, concrete in the lower (bottom) portion of the column gains higher compressive strength than the top layers (top-to-bottom effect).

This is mainly due to better consolidation and lower water-to-cement ratios in the lower levels. For individual columns, use at least five (5) test locations. Divide the column lengthwise into three portions, top, middle, and bottom. Use two, and preferably three thermocouples on the top and middle portions. Use one and preferably two thermocouples in the bottom section. For columns with spandrel beams use five (5) test locations per every 50 yd^3 of concrete.

- For wing walls, abutments, and bridge decks follow the guidelines for slabs.
- For footings and pier caps prepare two sets of thermocouples (three thermocouples in each set). Place one set along the edge and the other within the middle section of the element (Figs. 8, and 10). Distribute the three thermocouples in each set on top, middle, and bottom layer of the footing or the pier cap.

For thermocouples with wires as sensors, the wires are fastened to reinforcing bars before concreting. After testing is completed, the wires are cut flush with the concrete surface, and the remaining wires can be prepared for reuse. The number of test points suggested here are only advisory. It is recommended to use test points in addition to those recommended here for better statistical analysis of data.

Field Tests

As per foregoing discussions, the construction site chosen for this project was a highway bridge located near Newark airport at the intersection of I-78 and NJ routes 1&9 and 21. The structural elements chosen for instrumentation comprised of a column, a footing, and a pier cap. The concrete employed in this project contained the mixture proportions and materials for which the strength-maturity relationships were previously developed in the laboratory. Thermocouples were fastened to the reinforcing bars prior to concreting operations. Locations of the thermocouples in these structural elements are shown in Figs. 8, 9, and 10. Six thermocouples were placed in each of the individual structural elements comprising a total of 18 thermocouples. Immediately after concreting operations, the thermocouples were connected to the electronic maturity meter. Field cylinders were also prepared and instrumented. The compressive strength of cylinders were determined at the ages of 1, 2, 3, 7 and 28 days respectively. Forty-five field cylinders were prepared comprising of fifteen cylinders per structural element (pier cap, column, and footing). Averages of three cylinders per testing age were employed in the determination of the compressive strength. The cylinders were instrumented with thermocouple and transported to the laboratory for curing 24 hours after they were cast.

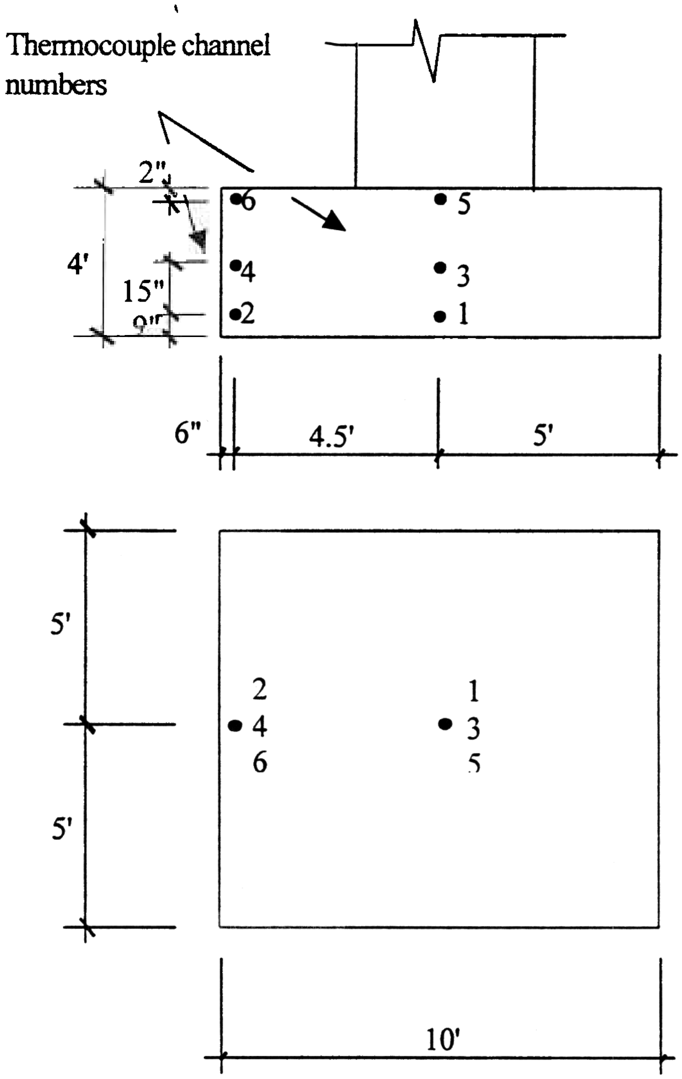

Fig.8 Location of thermocouples in Footing E8

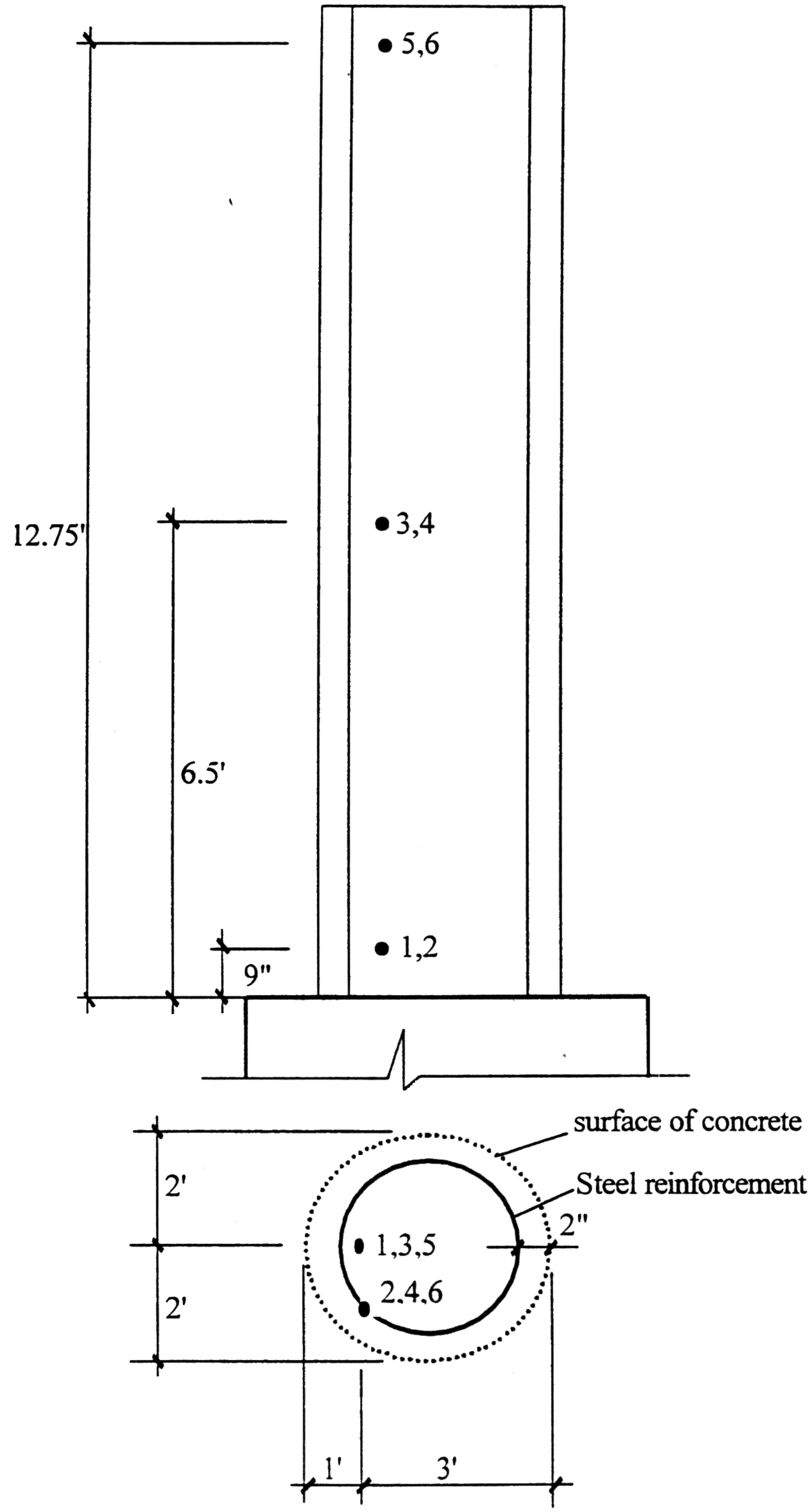

Fig.9 Location of thermocouples in Column E1

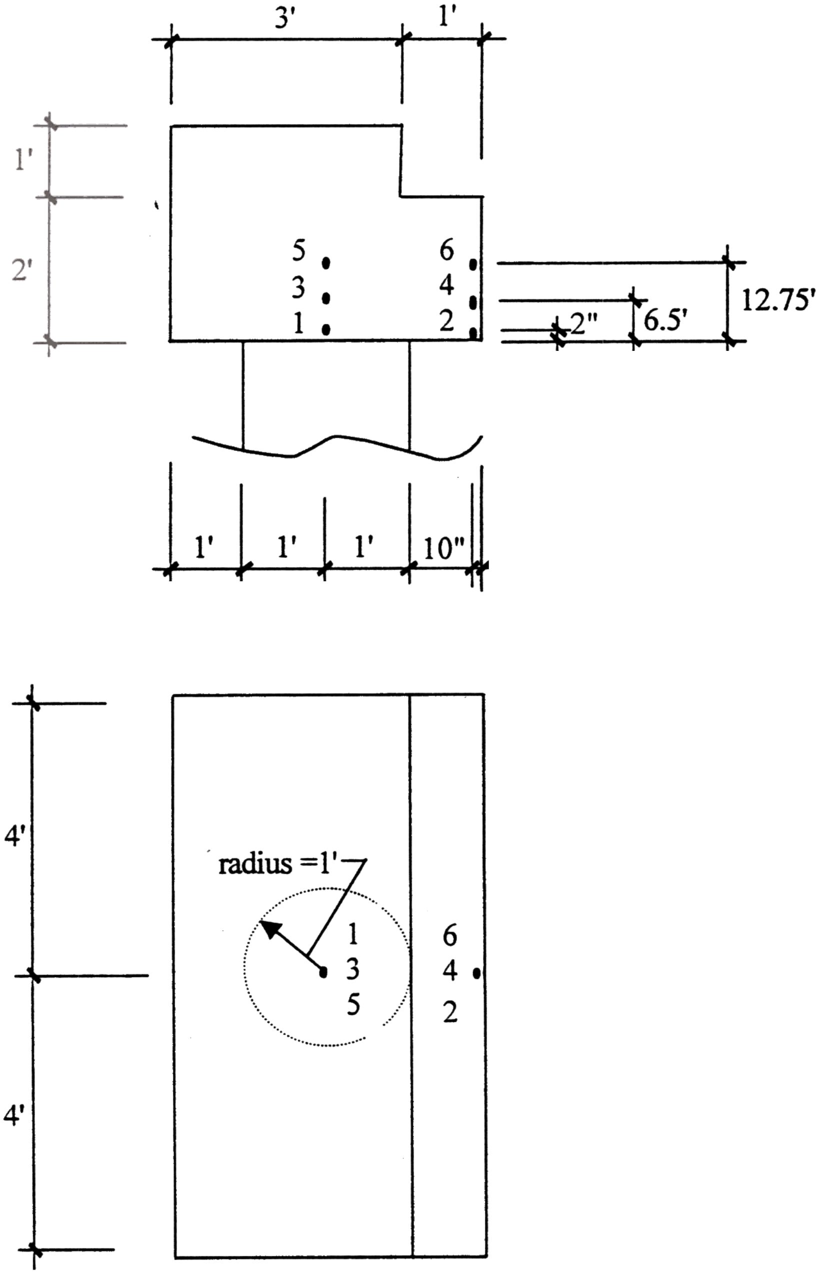

Fig.10 Location of thermocouples in Pier-Cap 3W

Maturity Development in the Structures

Temperature development in the structural elements as per data from the thermocouple channels were analyzed and converted to maturity values according to Eq.(1). Figs. 11 through 13 pertain to the maturity development of the concrete as a function of time in the footing, column and the pier cap respectively. Channels 2, and 3 corresponding to two of the thermocouples in the column malfunctioned and therefore data in Fig. 12 corresponds to channels 1, 4,5, and 6. In a similar manner, the thermocouple pertaining to channel 6 in the pier cap malfunctioned and is not shown in Fig.13. As shown in these figures, there is quite a variation in the maturity of concrete even within the same structural element. This is due to differences in the thermal history since thermocouples were intentionally placed at various locations in the structural elements in order to record various exposure conditions. Interpretation of these results will be given in the following section of this report.

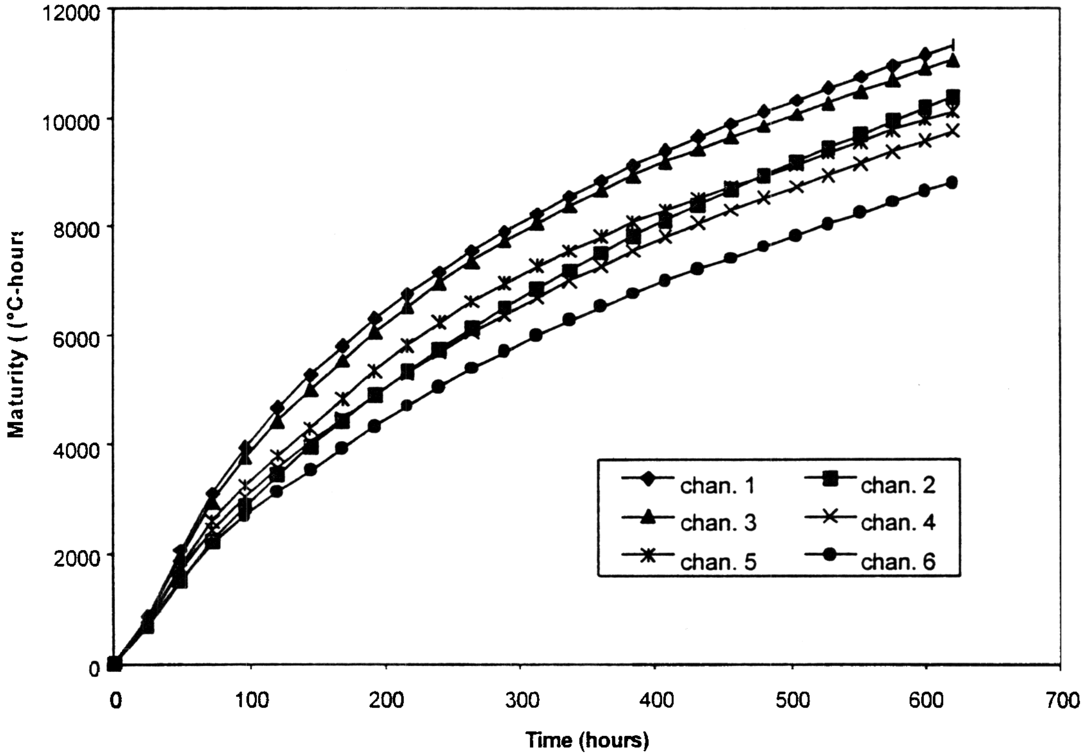

Fig.11 Development of concrete maturity in Footing E8

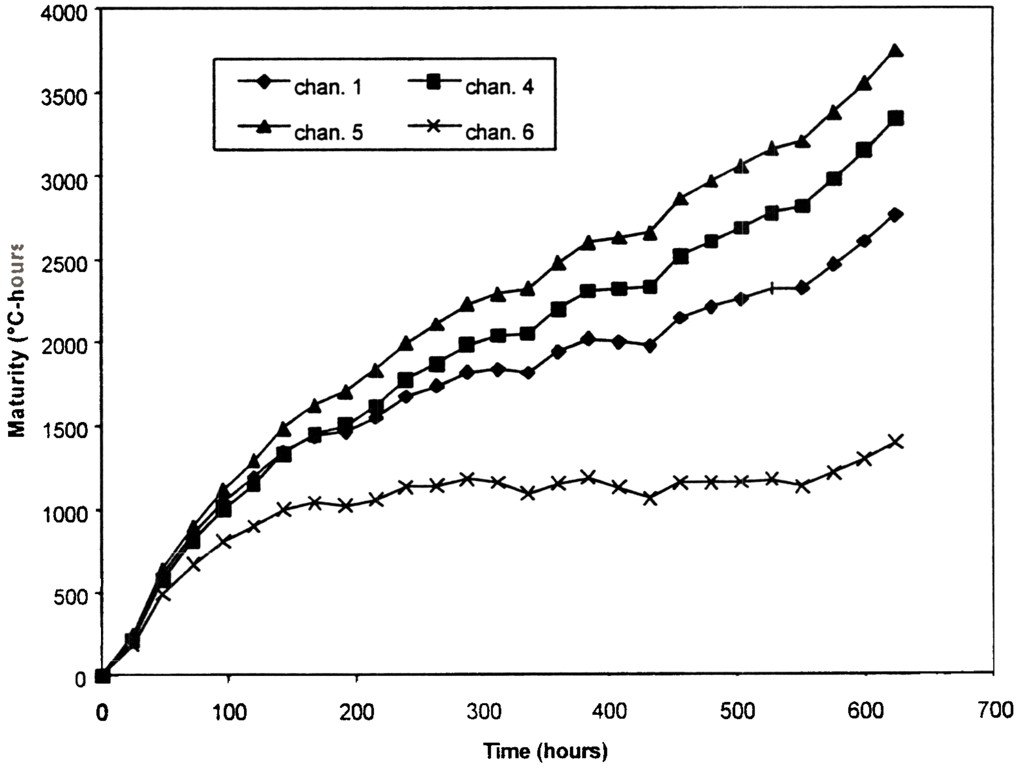

Fig.12 Development of concrete maturity in Column E1

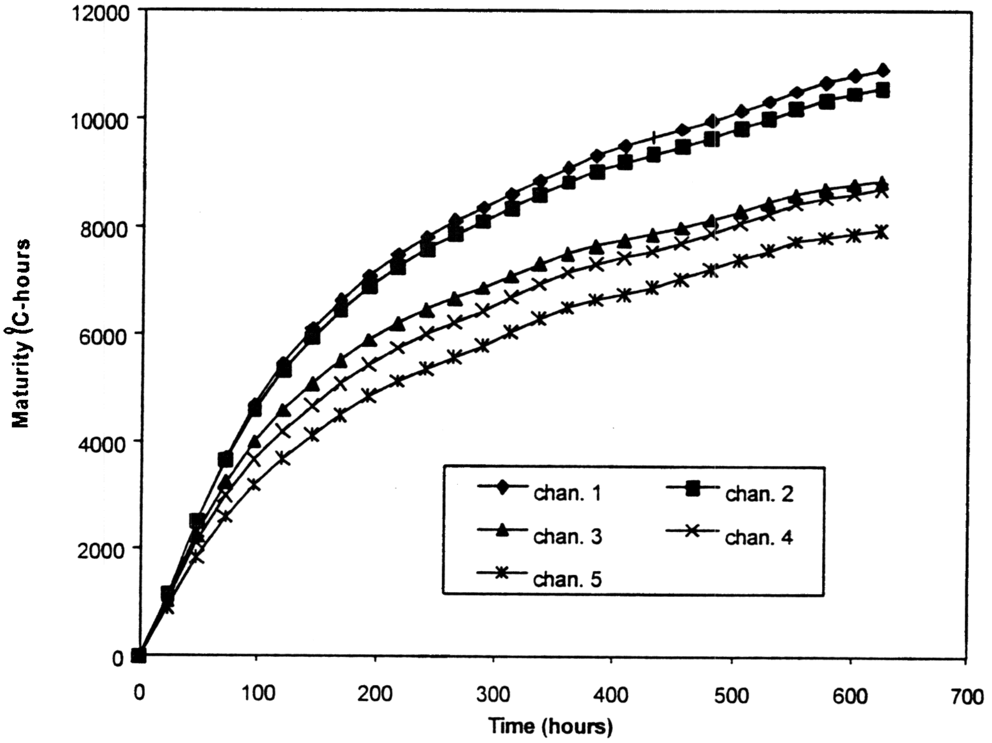

Fig.13 Development of concrete maturity in Pier Cap 3W

Reporting of the Results

Interpretation of in-place tests, i.e. maturity, pullout, pulse velocity, etc. should be made by using standard statistical procedures. It is not sufficient to simply average the values of the in-place test results and then compute the equivalent compressive strength by means of the previously established strength relationship. It is necessary to account for the uncertainties that exist. While no procedure has yet been agreed upon for determining the tenth-percentile in-place strength based on the results of in-place tests, proponents of in-place testing have developed and are using statistically based interpretations. One of those procedures has been employed for the determination of in-place strengths based on maturity values. This technique was employed due to simplicity, and it only requires tabulated statistical factors and a calculator. More sophisticated techniques are also available and the report by ACI committee 228 decribes them in detail[*]

Interpretation of the Results

To estimate in-place strength, maturity of the structural elements are acquired as per the procedures described earlier and the correlation relationship is used to convert the test results to a compressive strength value. To judge whether sufficient strength has been attained, the estimated compressive strength is compared with the required strength in the project documents. However, to provide for a margin of safety, the maturity results should be treated statistically, and then compared with the required strength as called for by the project.

In assessing the safety of a structure, the ***'specified'*** or ***'characteristic'*** concrete strength is used in the design equations to calculate member resistances. The specified strength is the strength that is expected to be exceeded by a large proportion of the concrete in the structure. In the North American practice, this proportion (or fraction) is about 90%. Alternatively, it is expected that 10% of the predicted concrete strength in the structure will be lower than the specified strength (Fig.14). Therefore, in interpreting test

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[*] ACI 228.1R-95, " In-Place Methods to Estimate Concrete Strength," Reported by ACI Committee 228, American Concrete Institute, PP. 41.

results, the characteristic strength should be calculated from the maturity results for comparison with the required strength.

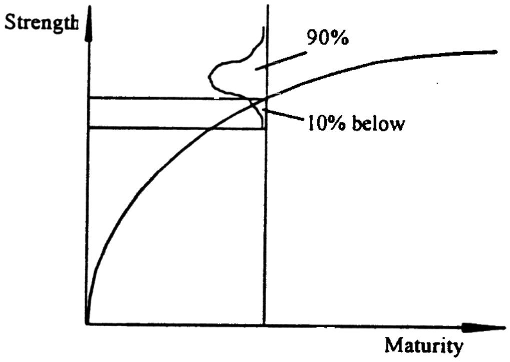

Fig.14 Statistical interpretation of the characteristic strength

The approach employed here was developed in Denmark and has been used in North America. It uses the lower tolerance limit of the in-place strength as the characteristic strength. The lower tolerance limit is a statistical term, which represents the value that is expected to be exceeded by a certain fraction of the population with certain degree of confidence (or probability level). It is calculated by subtracting the product of the standard deviation and the appropriate tolerance factor from the average value. In applying this approach for the in-place determination of compressive strength by the maturity method in this project, the following procedure was employed:

1) Maturity tests were performed in the field and the maturity values were obtained from thermal history data as in Figs. 11, 12, and 13.
2) Compressive strength at the ages of 1, 3, 7, 14, 28 days are determined by using the strength-maturity correlation relationship developed in the laboratory (Fig.7 or Eq.3).

3) At the desired ages (1,3,7,14 and 28 days), the average maturity values and the predicted strengths are evaluated.

4) A spread sheet operation or the following equation can be employed for the determination of standard deviation of the predicted strength at the individual ages of 1, 3, 7, and 28 days:

$$sd = \sqrt{\frac{n\sum\sigma^2 - \left(\sum\sigma\right)^2}{n^2}} \qquad (4)$$

Where,

s_d = The standard deviation of the predicted strength

σ = The predicted strength

n = Number of samples

(5) Compute the **specified** or the **characteristic** strength by the following equation:

$$\sigma_{0.} = \bar{\sigma} - ks_d \qquad (5)$$

Where,

$\sigma_{0.1}$ = The specified strength, i.e., the strength not expected to be exceeded by 10% of the predicted strength

$\bar{\sigma}$ = Average predicted strength based on the test results (based on the Strength-Maturity relationship)

k = one-sided tolerance factor

The tolerance factor value depends on the number of tests and the confidence level. A confidence level of 0.75 is usually used [*]. Table-2 lists the one-sided tolerance factors for an under-strength fraction of 10%. Depending on the particular sequences of construction in a project, the statistical procedure is applied either for estimation of compressive strength in individual structural elements, i.e. a footing, or collectively for the entire structure, i.e. footings, columns, and pier caps. To illustrate this, computations are made for both cases. Case-1 corresponds to the determination of characteristic strengths at different ages for the entire structure. This means that the statistical averages were made considering the maturity values of the column, footing, and the pier caps collectively according to the computation steps 1 through 5. Results are shown in Table-3. In Fig. 15, the specified strengths are compared against the field cylinder data as well as the strengths directly evaluated from the strength- maturity relationship. As it can be observed, the statistical procedure provides a more conservative approach in the estimation of the in-place strength as compared to the results directly obtained from the strength-maturity relationship. Field cylinder data, which were cured, out-side of the structure exhibit large strengths and do not represent the compressive strength of the concrete in the structural element.

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[*] Carette,G.C., and Malhotra,V.M.," In situ Tests: Variability and Strength Prediction at Early Ages," in ACI-SP-82, In Situ Nondestructive Testing of Concrete, Malhotra., Ed., ACI, Detroit, MI, 1984, pp. 111.

Table-2 One-sided tolerance factor for ten percent defective level*

Number of tests, n	Confidence level		
	75%	90%	95%
3	2.501	4.258	6.158
4	2.134	3.187	4.163
5	1.961	2.742	3.407
6	1.860	2.494	3.006
7	1.791	2.333	2.755
8	1.740	2.219	2.582
9	1.702	2.133	2.454
10	1.671	2.065	2.355
11	1.646	2.012	2.275
12	1.624	1.966	2.210
13	1.606	1.928	2.155
14	1.591	1.895	2.108
15	1.577	1.866	2.068
20	1.528	1.765	1.926
25	1.496	1.702	1.838
30	1.475	1.657	1.778
35	1.458	1.623	1.732
40	1.445	1.598	1.697
50	1.426	1.560	1.646

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* Natrella,M., "Experimental Statistics, Handbook No. 91, National Institute of Standards and Technology,"U.S. Govt. Printing Office, Washington, D.C., October 1966.

Table-3 Specified and predicted compressive strengths based on Maturity.

Age (day)	Averaged maturity (°C-hours)	Averaged strength (psi)	Standard deviation (psi)	Specified Strength (psi)	Predicted strength by lab strength-maturity (Eq.3) (psi)
0	0	0	0	0	0
1	710.17578	2614.25	474.8752	1865.372	2737.12
2	1604.832	3242.891	416.5286	2586.025	3340.05
3	2327.1261	3512.399	429.4929	2835.089	3614.88
7	4178.2892	3938.804	447.9831	3232.335	4047.71
26	7981.2469	4419.225	459.1883	3695.085	4526.35

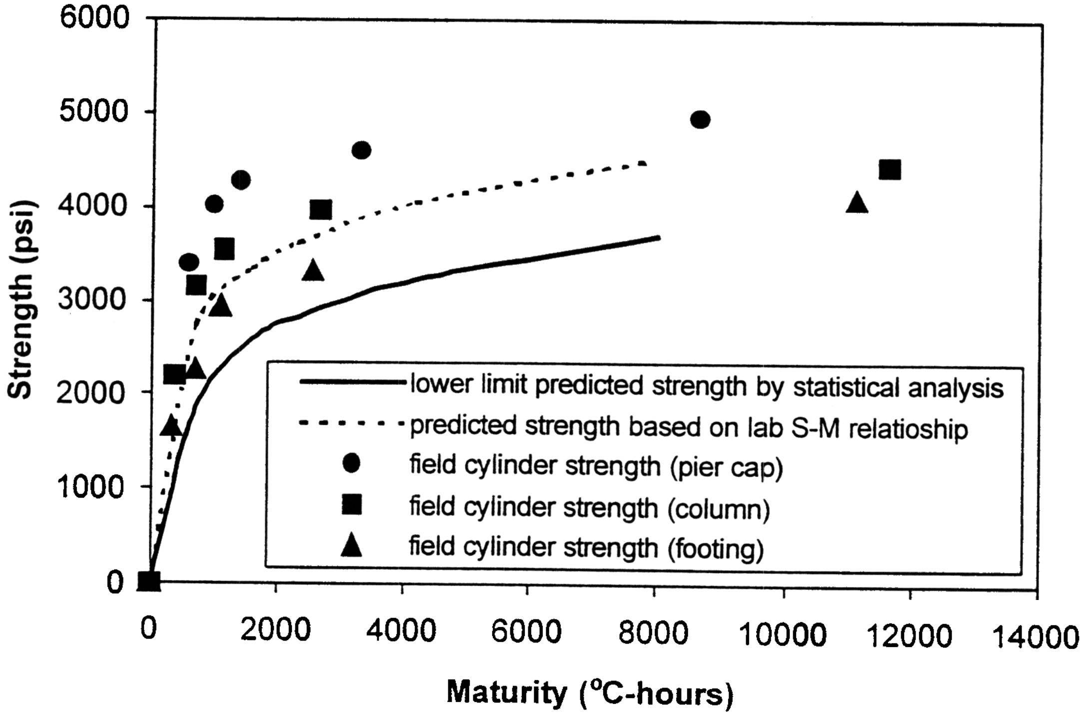

Fig.15 Comparison of compressive strengths by various methods

Alternatively, it may be desired to estimate the strength of individual members. In case-2, computations involve statistical analysis based on maturity values from the individual structural elements. In figs. 16 through 18 the specified strengths and the field cylinder data as well as the strengths directly evaluated from the strength-maturity relationships are compared. Fig. 16 corresponds to the pier-cap strengths, whereas, figs. 17 and 18 pertains to the footing, and the column strength predictions.

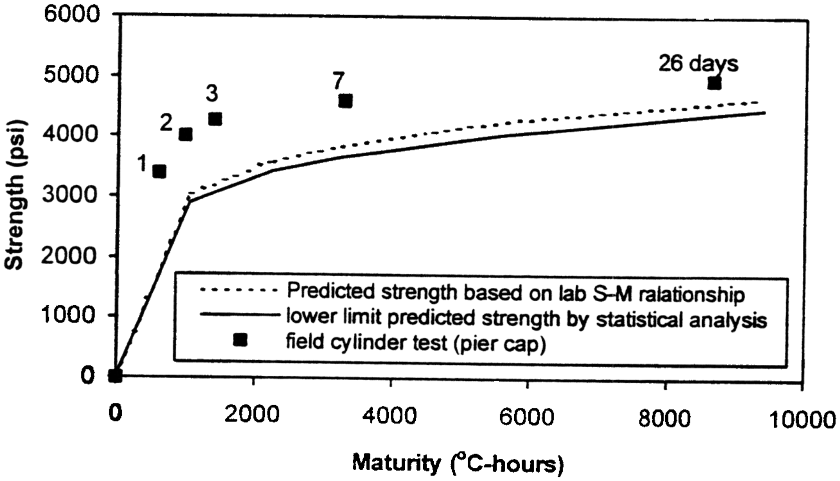

Fig.16 Comparison of compressive strengths for the pier-cap by various methods

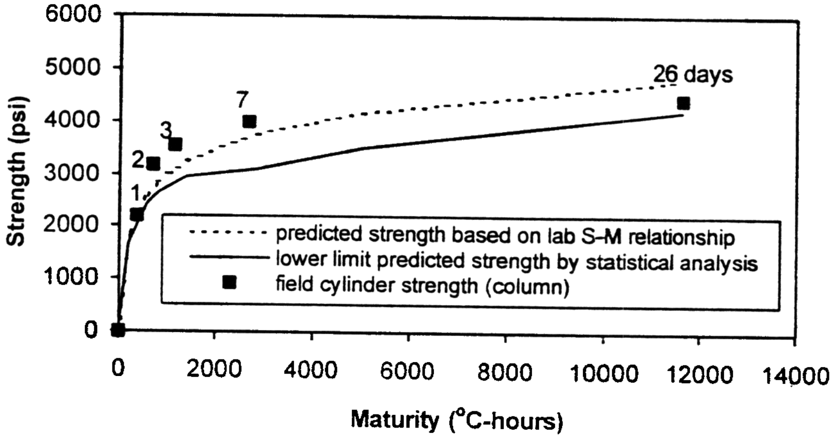

Fig.17 Comparison of compressive strengths for the column by various methods

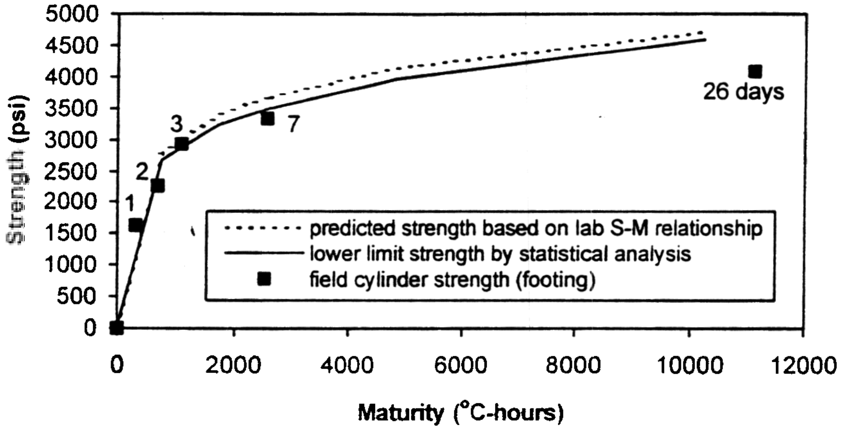

Fig.18 Comparison of compressive strengths for the footing by various methods

Conclusions

This report summarizes a comprehensive program of research pertaining to the development of maturity protocols to facilitate in-place estimation of compressive strength for NJDOT concretes. This report is intended as a guide for NJDOT personnel for procedures and computations regarding the application of maturity method to NJDOT construction projects. Maturity parameters, i.e. the activation energy and the datum temperature for NJDOT concretes were determined through laboratory experiments. Experiments pertained to monitoring of thermal history for concrete mixtures cured under three curing temperatures. Compressive strengths of these samples were determined through uniaxial compression tests. Laboratory strength-maturity-correlation relationship for a typical construction project was developed. The construction site at the intersection of I-78, and routes 1&9, and 21 was chosen for field studies. Thermal history of a pier-cap, a footing, and a column was recorded via electronic maturity meters. Statistical analysis of data was carried out, and a method introduced for the interpretation of maturity data.

In-place tests results are more representative of concrete strength as it exists in the structure. They reduce the number of cylinders to be tested and facilitate the construction project. However, their results shall be checked against other in-place test methods, i.e. pull-out inserts, etc. in order to assure safe construction procedures. Moreover, companion cylinder tests need to accompany the maturity test data for comparison and as an aid for making decisive actions regarding the construction sequence.