Tennessee Evaluation of New Maturity Technology: Laboratory Investigation

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Abstract

A project was conducted to evaluate the ability of new maturity technology to predict compressive strength development of Tennessee rigid pavements. The information generated in the project will assist the Tennessee Department of Transportation (TDOT) in making a decision on allowing the new maturity technology to be used in lieu of cylinder compressive strength results for opening new PCC pavements to traffic.

In the laboratory portion of the evaluation, one-hundred-twenty (4 groups of 30 each) 6- by 12-inch (152- by 305-mm) cylinders cured at different temperatures were used to validate the maturity relationship over the range of TDOT Portland Cement Concrete (PCC) temperature specifications for curing. The difference between compressive strengths of 6- by 12-inch (152- by 305-mm) cylinders cured in the laboratory at the same maturity index for curing temperatures between 45 and 90°F (7 and 32°C) is in the range of 3.8 to 12.5 percent for maturity indices of 2,400 to 22,000°C-hours. At lower maturity indices, the compressive strength difference in percent was much greater (29.7 to 60.7).

Introduction

The Tennessee Department of Transportation Materials and Tests Division is considering allowing the new maturity technology to be used in lieu of cylinder compressive strength results for opening new PCC pavements to traffic. The objective of the project was to evaluate the ability of a new maturity system to predict compressive strength development of Tennessee PCC pavements. The information generated in the project will assist TDOT in making a decision. The maturity evaluation was co-sponsored by the Tennessee Concrete Association and benefited from extensive technical assistance from the Tennessee representative of the American Concrete Pavement Association.

Two extensive field investigations were conducted, one in Nashville on Interstate 65 and one near Chattanooga on Interstate 75. These investigations were respectively performed in the Fall of 2002 and the Summer of 2003 to determine how accurately the new maturity technology was able to predict compressive strength development in rigid pavements.

This paper covers the laboratory portion of the evaluation using one-hundred-twenty 6- by 12-inch (152- by 305-mm) cylinders of TDOT Class A PCC cured at different temperatures to validate the maturity relationship. The temperature range selected for the laboratory investigation was 45°F (7°C, lowest allowable TDOT curing temperature for first 120 hours) to 90°F (32°C, maximum allowable TDOT placement temperature). Compressive strengths were measured at pre-determined maturity indices to determine the effect of curing temperature on the maturity-compressive strength relationship.

Maturity Background

PCC gains strength and durability from reactions between Portland cement, supplementary cementing materials and water. The continuation of the chemical reactions is commonly termed curing. Curing progress is most commonly measured with compressive strength development. Curing progress is a function of time, temperature, and moisture conditions. Provided that adequate moisture is available, curing progress is a function of time and temperature.

Just as depressing the accelerator on a vehicle makes it speed up, increasing the curing temperature makes the chemical reactions in PCC increase. To continue the analogy, the maturity index measures the progress of curing like mile markers on an interstate measure the distance the vehicle has traveled. The maturity index is simply an alternative to compressive strength development for measuring the progress of PCC curing.

The TDOT Materials and Tests Division wanted to determine if the compressive strength-maturity relationship was valid from 7°C (45°F) [*1*] to 32°C (90°F) [*2*]. A literature search was also conducted to aid in the determination.

Literature Review

In 1915, McDaniel [*3*] published a bulletin for the University of Illinois to furnish some information concerning the influence of temperature on concrete compressive strength. He stated:

> "*The general use of concrete in various kinds of construction and at all seasons of the year renders important, a knowledge of the effect of temperature upon the strength of this material. It is of special economic importance to the contractor or the builder to be informed concerning the strength of concrete at early ages under different temperature conditions so that he may know when to remove forms and what loads may be safely applied to the different parts of a structure.*"

McDaniel's research consisted of curing sixty 8- by 16-inch (203- by 406-mm) cylindrical specimens at various temperatures. The cylinders were split into four sets and cured at average mean temperatures of 90.6, 71.2, 34.7, and 26.5°F (32.6, 21.8, 1.5, and –3.1°C). Three cylinders from each set were tested for compressive strength at 3, 7, 10, 14, and 28 days, and the following conclusions were drawn:

- For any temperature, the rate of (compressive strength) increase decreases with the age of the specimen; this rate of increase is less at lower temperature conditions.
- Concrete, which is maintained at a temperature of 60 to 70°F (15.6 to 21.1°C) will, at the age of one week, have practically double the strength of the same material, which is kept at a temperature of 32 to 40°F (0.0 to 4.4°C).

In 1928, Wiley [*4*] studied the effect of temperature on hardening rate of concrete using ninety 152 by 305-mm (6- by 12-inch)cylinders. The cylinders were cast and had an initial curing period of twenty-four hours at room temperature. After the initial curing period, the cylinders were removed from the steel molds, placed into five sets and cured at approximately 205, 100, 70, 35, and 5°F (96.1, 37.8, 21.1, 1.7, and -15°C). Enough cylinders were cast to ensure that at least three cylinders from each set could be tested for compressive strength at 3, 5, 7, 14, and 28 days. A graph was constructed and the following conclusions were drawn:

- With temperatures between 35 and 100°F (1.7 and 37.8°C), the hardening of concrete proceeded in the same manner, but at different rates.
- At a temperature of 100°F (37.8°C), the same strength was obtained in approximately one-half the time as at 70°F (21.1°C).
- At a temperature of 35°F (1.7°C), something more than twice the time was required to gain the same strength as at 70°F (21.1°C).
- If the curing period is based on the strength when cured at 70°F (21.1°C), the period can be materially reduced for higher temperatures and must be correspondingly increased for lower temperatures.
- Frozen concrete showed practically no gain in strength. No dependence whatsoever should be placed on a gain in strength of concrete while frozen.

In 1934, Timms and Withey [*5*] investigated initial curing conditions with regards to winter concreting. Several hundred 3- by 6-inch (76- by 152-mm) specimens were cast in paraffin-treated cardboard molds, cured initially at 70°F (21.1°C)and subsequently cured at temperatures ranging from 16 to 70°F (-8.9 to 21.1°C). The initial curing periods ranged from one-quarter (¼) to 3 days, and the cylinders were tested for compressive strengths at 3, 7, 28, and 90 days. Timms and Withey concluded the following:

> *"The rate of hardening of the concrete following a given initial treatment was dependent on the temperature of exposure. The 28-day strengths obtained with storage temperatures of 50 and 33°F (10 and 0.6°C) were in general, from 50 to 75 percent of those obtained with concrete moist-cured at 70°F (21.1°C). The rate of gain in strength with age was less for concrete exposed to 33°F (0.6°C) than to 50°F (10°C). Even at 16°F (–8.9°C), the richest mix concrete showed a definite gain in strength."*

In 1949, Nurse [*6*] was also performing curing tests on concrete by steaming. In regards to industrial methods, he stated:

> *"In the modern factory production of concrete products, it is frequently desirable to hasten the curing process. This necessity arises generally for two reasons: firstly to release moulds and pallets as quickly as possible and secondly to put the finished article on the market as soon as feasible to avoid having to provide extensive storage space. Although some acceleration of setting and hardening can be achieved by chemical means, steam curing is more effective and more susceptible to accurate control"*

He performed flexural and compressive strength tests on 2- by 2- by 8-inch (51- by 51- by 203-mm) prisms steam-cured at 100, 80, 60, and 40°C (212, 176, 140, and 104°F) and control specimens moist-cured at 18°C (64.4°F). Similar to McIntosh, Nurse introduced a time-temperature function with the datum temperature set to 0°C (32°F). This function was also the product of the time and temperature above this datum temperature. It was used to calculate the time for steam-cured concrete specimens to attain the same time-temperature product as concrete moist-cured at three days. The compressive strengths of the specimens in each group were compared and found to be similar.

In 1951, Saul [*7*], based on the earlier work of McIntosh and Nurse, introduced the term “maturity” and defined it as follows:

> *“The ‘maturity’ of concrete may thus be defined as its age multiplied by the average temperature above freezing which it has maintained.”*

Saul also stated that the centigrade scale is very convenient when determining the “maturity” of concrete and it should be expressed in degree Celsius-hours (°C·Hrs). He also pointed out that the datum temperature should be taken to be -10°C (14°F). He then proceeded to present the “law” of gain of strength with maturity 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.”*

More specifically, Saul stated that under different (changing) curing conditions, the maturity of the concrete could be represented by the area beneath the curve of time plotted against temperature. The Nurse-Saul maturity function (shown below) was used during Saul’s research for the first time.

$$M = \sum_{0}^{t} (T - T_0)\Delta t$$

Where:
- M = maturity index
- T = average concrete temperature during time Δt
- T_0 = datum temperature (usually -10°C (14°F))
- t = elapsed time hours
- Δt = time interval (hours)

Although most mixtures tested obeyed the law of maturity, some limitations were noted:

- The concrete must not reach 50°C (122°F) prior to 1½ to 2 hours after mixing.
- The concrete must not reach 100°C (212°F) prior to 5 to 6 hours after mixing.

Saul states that if the concrete being monitored exceeds these temperatures before the times listed that it will fail to obey the law of gain of strength; this will adversely affect the latter strength of the concrete. He concludes that the higher the initial temperature gradient, the greater the adverse effect will be on compressive strength development.

In 1962, Alexander and Taplin [*8*] checked the validity of the Nurse-Saul maturity function by using two different water-cement ratios, 0.35 and 0.55. They cast concrete beams with dimensions of 3- by 3- by 11-inch (76- by 76- by 279-mm) into steel molds and immediately exposed the specimens to either 5, 21, or 42°C (41, 69.8, or 107.6°F) curing conditions. They concluded the following:

- At early maturities, for both the higher and lower water-cement ratios, the Nurse-Saul function greatly underestimated the influence of temperature on strength gain of concrete.
- By the time that the maturities equivalent to 28 days curing at 21°C (69.8°F) had been obtained, the position had changed considerably. For the mixtures with lower water-cement ratios, the Nurse-Saul function now overestimated the influence of temperature on strength gain. The mixtures with higher water-cement ratios overestimated the influence of temperature, but it was far less pronounced when compared to the mixtures with lower ratios.

A laboratory experiment was organized and conducted to resolve the inconsistencies in the literature findings.

Equipment

The new maturity technology virtually eliminates the problems of vandalism, theft, and accidental damage associated with traditional field maturity meters. The new maturity technology uses an independent embedded microprocessor (logger) that requires no permanent external connection. A maturity logger is a combination of 6 things:

1. Thermometer
2. Stop Watch
3. Calculator – has a memory
4. Battery
5. Hard-shell case – to carry and protect the other components
6. Wires – for communication with a reader

The logger calculates a new maturity index every 15 minutes. The logger stores the maturity history as well as maximum and minimum temperatures.

A maturity reader is a communications device (similar to a telephone) for obtaining information from the maturity logger. By pressing the right sequence of keys, the user is allowed to view / store specific information from the logger. The reader unit downloads maturity index values as well as maximum and minimum temperatures when connected to a logger. One reader unit can be used in conjunction with an unlimited number of independent embedded loggers, but it may only store two hundred data sets at one time. Logger data transferred to the reader can be downloaded to a personal computer in two formats: text and secure [*9*].

Materials and Procedure

The validity of the maturity relationship was evaluated by casting one-hundred-twenty 6- by 12-inch (152 by 305-mm) cylinders [*10*] from approximately one cubic yard of TDOT Class A PCC delivered in a ready mix truck and curing them at different temperatures encompassing the TDOT specified limits [*1*,*2*]. Plastic properties of the PCC are shown in Table 1. Immediately after casting, the cylinders were placed into respective storage tanks and the loggers were activated. The limewater level in the tanks was elevated to the tops of the cylinder molds to ensure acclimation to the desired curing temperature as quickly as possible. At approximately 800°C·Hrs, the molds were removed and the limewater level was elevated to completely immerse all specimens within each tank.

The three curing temperatures used were 32, 23, and 7°C (90, 73.4 and 45°F). Thirty of the 120 cylinders were cured at each temperature. The remaining thirty cylinders began in the 32°C bath and changed curing tanks approximately every 8 hours as shown in Figure 1. The rotation of cylinders in different curing temperature tanks was intended to simulate a daily cycle of temperature changes.

Testing protocol and approximate test ages in days, were estimated using the Nurse-Saul equation with a datum temperature of -10°C (14°F) and are shown in Table 2. The predetermined maturity indices for compressive strength testing were based on standard curing [*11*] for 1, 2, 3, 4, 5, 7, 14 and 28 days. Two 6- by 12-inch (152- by 305-mm) cylinders in each group contained maturity loggers and two of each group contained temperature loggers. Actual maturity indices for compressive strength testing were determined by averaging the values from the two maturity loggers. During the experiment, one maturity logger failed to perform and those logger values were no longer recorded for experimental use.

The laboratory storage tanks were insulated on all surfaces to retain the desired temperature and equipped with two circulation pumps in either end. Each tank was also equipped with a steel grate placed upon bricks to keep the cylinders exposed to the limewater conditions on all surfaces. A single tank heater in each tank provided the heat for the 32°C and 23°C tanks, while the installation of a circulation chiller was required for the 7°C tank. The chiller circulated a mixture of antifreeze and water through copper piping directly beneath the steel grating.

Results

A summary of the results of the laboratory evaluation of the new maturity technology are shown in Table 3 and Figure 2. Temperature profiles for first 144 hours of the constant temperature and variable temperature cylinders are shown in Figures 3 and 4, respectively.

Analysis of Results

The agreement between average compressive strengths obtained at various maturity indices from different curing regimes is shown in Table 4. The difference between compressive strengths of 6- by 12-inch (152- by 305-mm) cylinders cured in a laboratory at temperatures between 7 and 32°C is in the range of 3.8 to 12.5 percent for maturities greater than or equal to 2400°C-hours. At lower maturity indices the difference is much greater.

Conclusions

Based on the available data and literature, the following conclusions can be drawn:

1. Saul [*7*] was correct for maturity indices of 2,400 to 22,000°C-hours. The difference between compressive strengths of 6- by 12-inch (152- by 305-mm) cylinders lab-cured at the same maturity index for curing temperatures between 7 and 32°C is in the range of 3.8 to 12.5 percent.

2. Alexander and Taplin [*8*] were also correct. At low maturity indices, the Nurse-Saul function greatly underestimates the influence of temperature on strength gain of concrete. The difference in compressive strengths at maturity indices less than 2,400°C-hours was in the range of 29.7 to 60.7 percent.

3. The maturity relationship used by the new maturity technology is valid between TDOT's minimum curing and maximum placement temperatures at maturity indices greater than or equal to 2400°C-hours.

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Table 1. Plastic Properties of the Laboratory Evaluation Mixture

Property	Result	TDOT Specification [*16*]
Slump [*12*]	2-inch (51-mm)	0.5 - 2.0 inches (12.5 – 51 mm)
Air Content [*13*]	6.1%	3-8%
Unit Weight [*14*]	143.2-pcf (2291 kg/m^3)	No requirement
Temperature [*15*]	43°F (6.1 °C)	50 - 90°F (10 - 32°C)

Table 2. Testing Schedule for Laboratory Experiment

Approximate Maturity Index (°C·Hrs)	Neoprene Durometer	Approximate Age of Hot (32 +/- 1.6 °C) Cure Tank Specimens (Days)	Approximate Age of Standard (23 +/- 1.6 °C) Cure Tank Specimens (Days)	Approximate Age of Cold (7 +/- 1.6 °C) Cure Tank Specimens (Days)	Specimens Tested from each curing condition
800	50	0.8	1	2	2
1600	50	1.6	2	4	2
2400	60	2.4	3	6	3
3200	60	3.2	4	7.8	3
4000	60	3.9	5	9.7	3
5500	60	5.4	7	13.3	4
11000	60	10.9	14	26.6	3
22000	60	21.7	28	53.3	6

Table 3. Average Compressive Strengths for Each Approximate Maturity Index

Approximate Maturity Level (°C-hours)	7°C Cylinders TDOT Lower Curing Temperature Limit (MPa)	23°C Cylinders AASHTO Standard Curing Temperature (MPa)	32°C Cylinders TDOT Upper Placement Temperature Limit (MPa)	Variable Temperature Cylinders (MPa)
800	7.23	11.07	14.12	12.96
1600	13.58	18.69	17.91	18.65
2400	20.15	20.93	20.86	20.77
3200	22.26	23.75	22.21	24.08
4000	25.90	24.60	24.79	25.77
5500	29.57	26.10	27.10	28.26
11000	35.80	33.35	34.85	32.70
22000	42.40	39.15	42.28	41.47

Table 4. Comparison of Average Strengths at Each Approximate Maturity Level

Approximate Maturity Index (°C-hours)	Range (High Result – Low Result) (MPa)	Range as a Percent of the Mean Result
800	6.89	60.7
1600	5.11	29.7
2400	0.78	3.8
3200	1.87	8.1
4000	1.30	5.1
5500	3.47	12.5
11000	3.10	9.1
22000	3.25	7.9

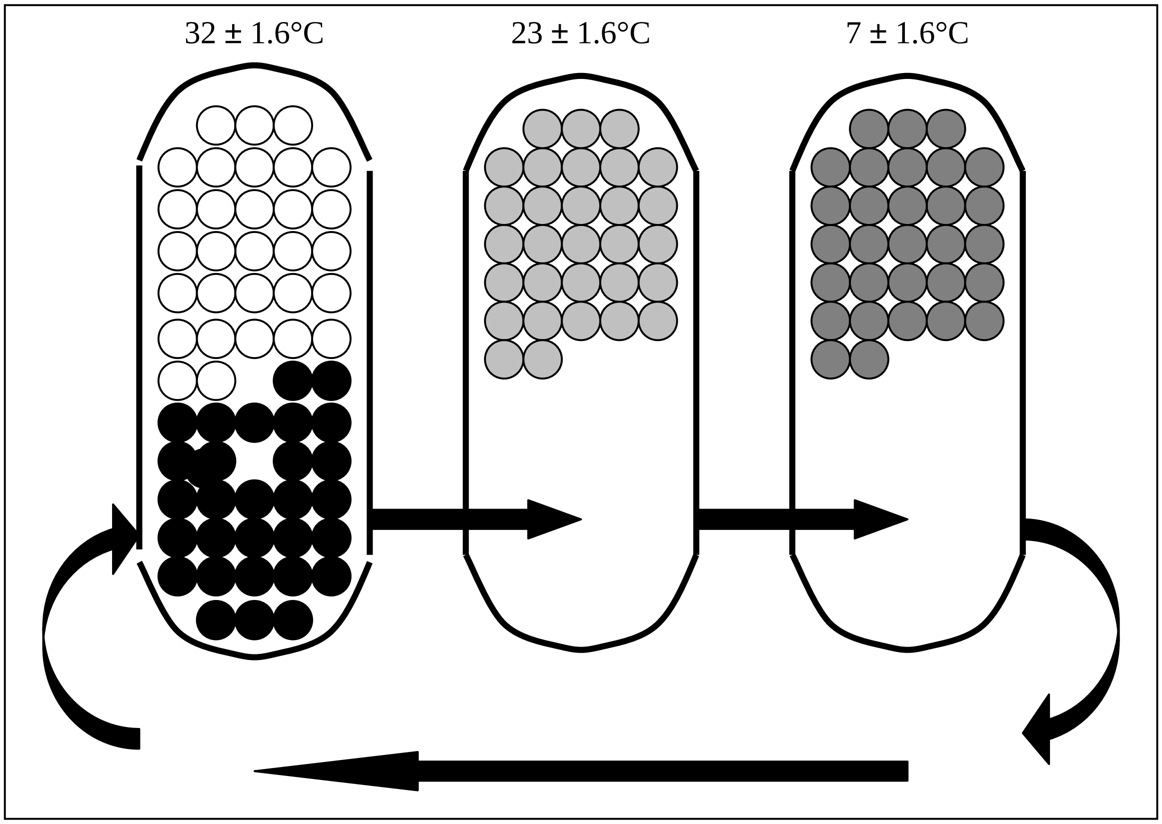

Figure 1. Schematic of Curing Tank Set-up and Rotation of Variable Cylinders

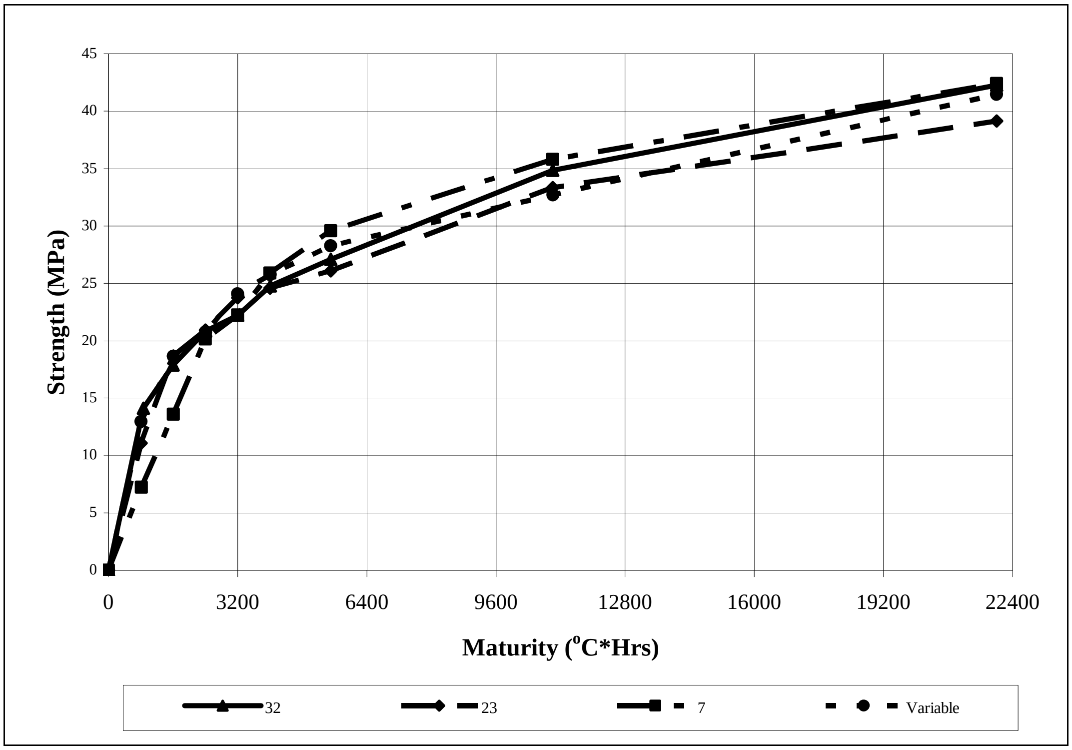

Figure 2. Compressive Strength vs. Maturity at Various Curing Temperatures

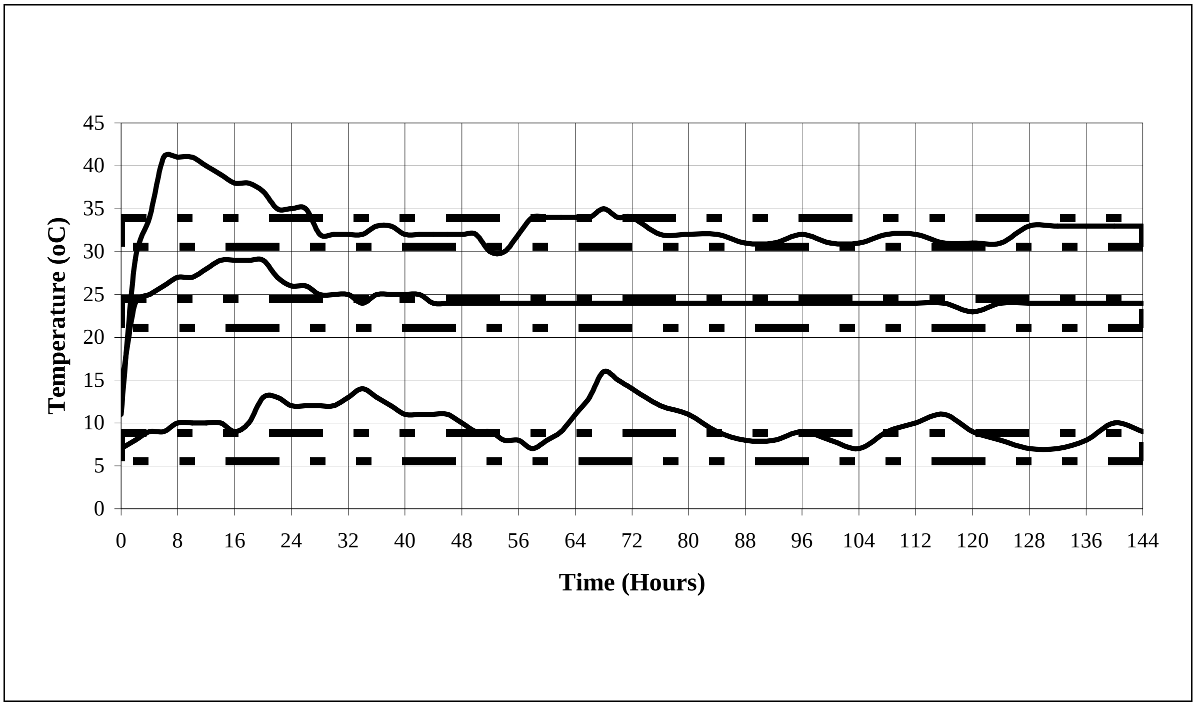

Figure 3. Temperature Logger Profiles for 32, 23, and 7° C Cylinders

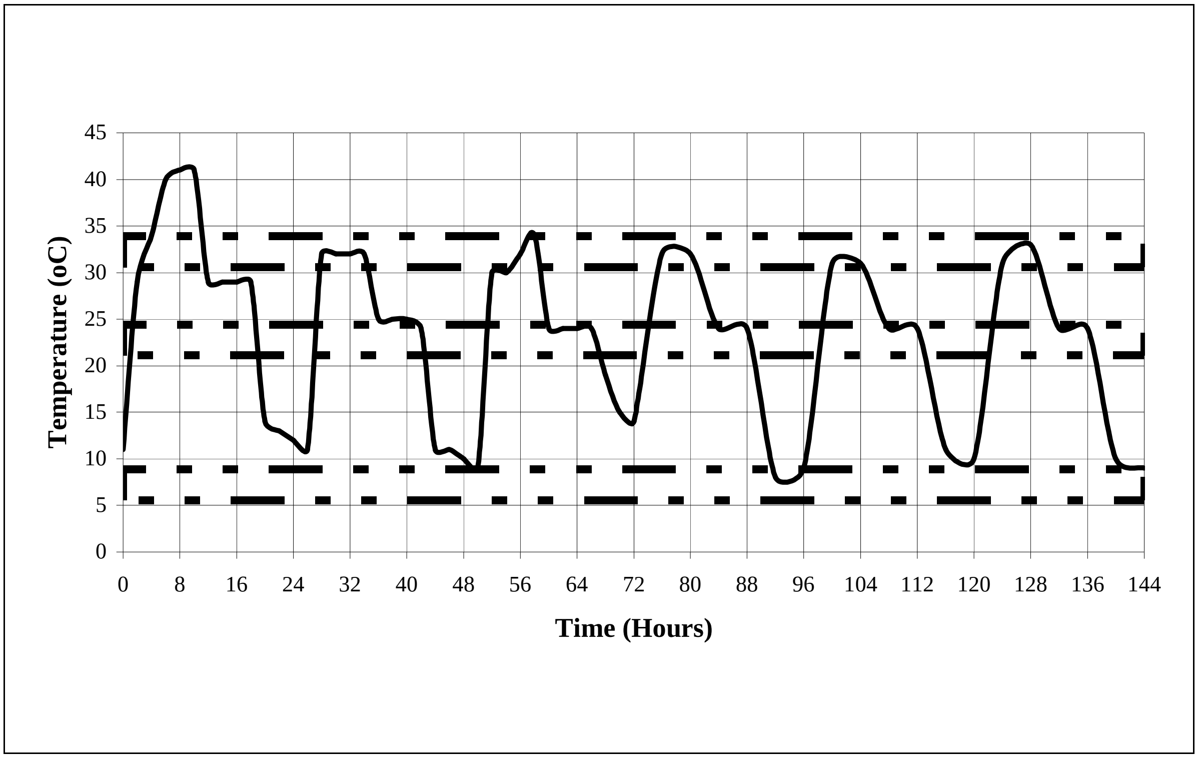

Figure 4. Temperature Logger Profiles for Variable Temperature Cylinders