Early Strength Testing of Concrete Cores and Cylinders

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During the 1989 construction season in Wisconsin, six projects, which were built by four different concrete paving contractors, were studied to assess the in situ early strength of concrete pavements, the early strength of lightly insulated field-cured concrete cylinders, and the 28-day strength of paving concrete. The projects were also studied to establish the relationship between cylinder and in situ strength typical on paving projects in Wisconsin. The results of testing over 1,500 individual cores and cylinders indicate that most pavements constructed in warm weather attain compressive strengths of 20.7 mPa (3,000 psi) to 24.1 mPa (3,500 psi) in 3 days or less, approximately 95 percent of the paving grade concrete has a 28-day compressive strength of more than 27.9 mPa (4,050 psi), and the compressive strength of lightly insulated cylinders cured in the field provides a reasonable measure of the in situ compressive strength of the pavement as measured in core tests.

Wisconsin Department of Transportation (WisDOT) policy in 1988 required a minimum curing period of 7 days and a minimum compressive strength of 20.7 mPa (3,000 psi) before new concrete pavements could be opened to traffic. The contractors represented by the Wisconsin Concrete Pavement Association (WCPA) requested WisDOT to consider changing this policy to allow traffic on new pavements after the required minimum compressive strength has been achieved or after a shorter minimum time requirement. WCPA believed that, with the widespread use of slipform paving and lower slump concretes, the 7-day requirement was overly restrictive causing unnecessary construction delays. The 7-day requirement also tended to inhibit the implementation of innovative methods such as fast track paving. WisDOT subsequently produced data based on an analysis of the cylinder test records for the 1988 construction season that appeared to indicate that a substantial percentage of test cylinders failed to reach the required level of strength in 7 days.

On review it was pointed out that data for high slump concrete used for purposes other than paving were included. An independent analysis of the same test records showed significantly higher average strengths when only paving concrete was included. In addition, the test cylinders were not given sufficient temperature protection to mimic the thermal mass effect of the material in the pavement slab.

The study described in this report was conducted during the 1989 construction season to address these concerns. Field work was performed by WCPA, Wisconsin Testing, and Twin City Testing Corporation. WisDOT, Wisconsin Testing, and Twin City Testing Corporation performed the laboratory testing.

The objectives of this study were to

- Assess the typical in situ compressive strength at 3, 5, and 7 days for paving-grade concretes by testing cores cut from the pavement.
- Assess the typical field-cured compressive strength at 3, 5, and 7 days for paving-grade concretes by testing cylinders cured in lightly insulated boxes.
- Assess the typical 28-day compressive strength for paving-grade concretes by testing cylinders fabricated on grade.
- Compare the results of core and cylinder tests to establish a relationship that can be used to predict in situ strength from the compressive strength of field-cured cylinders.

DESCRIPTION

Paving concretes from six separate highway projects built by four contractors were included in this study. These projects are referred to as Beaudoin-45, Cape-190, Vinton-19, Trierweiler-A, and Trierweiler-B for WisDOT grade A–FA concrete, containing fly ash (*1*). A small amount of WisDOT grade A–WR concrete, containing water reducer (*1*), was used on the Beaudoin-45 project and for the entire Vinton-29 project. The WisDOT specified mix component quantities for each grade of paving concrete are shown in Table 1.

Twelve standard 152.4-mm (6-in.) diameter by 304.8-mm (12-in.) long cylinders, in groups of three, were cast each morning for compressive strength testing at 3, 5, 7, and 28 days. A similar set of specimens was produced each afternoon. Except for the Vinton-29 project, the 3-, 5-, and 7-day cylinders were cured on grade in cardboard boxes loosely filled with vermiculite to simulate the thermal condition seen at mid-slab in the pavement. More heavily insulated curing boxes were used on the Vinton-29 project. The 28-day cylinders were cured in the same way for the first 7 days, then stored in a laboratory curing room at 23°C (73.4°F) and 100 percent relative humidity for the rest of the curing period.

Nine 101.6-mm (4 in.) diameter cores, in groups of three, were cut for each day of paving operations and tested for compressive strength at 3, 5, and 7 days. The locations of the cores were matched to a set of cylinder specimens.

The cylinders and cores were prepared and tested in accordance with established ASTM (*2*) procedures for determining the compressive strength of concrete. All the reported core strengths were adjusted for aspect ratio (*L/d*).

All specimen fabrication, curing, and testing was done by Wisconsin Testing for the Beaudoin-45 project, and by Twin City Testing Corporation for the Vinton-29 project. WCPA personnel conducted the field work on the other projects and delivered the cylinders and cores to WisDOT for compression testing. Early

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TABLE 1 WisDOT Mix Component Quantities

	WisDOT grade of concrete	
	A-FA	A-WR
Cement (N/m ^{3})	2,792	3,083
Class C Fly Ash (N/m ^{3})	640	none
Total Aggregate (N/m ^{3})	18,207	19,022
Fine Aggregate (% of total aggregate by weight)	30 - 45 %	30 - 45 %
Target Air Content	6%	6%
Typical Water/Cement Ratio	.40 - .45	.40 - .45

* To convert from N/m^3 to lb/yd^3 multiply by 0.172

efforts to break cylinders in the field with a manually actuated portable testing machine were abandoned because of erratic results.

INDIVIDUAL RESULTS BY PROJECT AND GRADE OF CONCRETE

Summaries of the results by project for WisDOT grade A–FA concrete are shown in Table 2 and for WisDOT grade A–WR concrete in Table 3. Each sample point represents the average of three individual test specimens.

COMBINED RESULTS

A summary of the results for the combined grade A–FA data is shown in Table 4. Here the tests from each project are lumped together to form one large sample. The standard deviation given thus includes the differences between the projects as well as the variability inherent in the strength on a given project. This analysis can be used to assess strength on an industrywide basis.

Each sample point represents the average of three individual test specimens. All of the grade A–FA data were used for the core strengths and data for the Trierweiler projects were excluded in the analysis of the cylinder strengths.

Sampling and testing procedures were being refined on these early projects. A portable hand-actuated hydraulic breaker was used to test the cylinders in the field. This equipment gave erratic results, as can be seen from the significantly larger coefficients of variation reported for the Trierweiler-A project (see Table 2). Only laboratory compression testing was conducted on the other projects. The sample size was also very small for both Trierweiler projects, especially Trierweiler-B (see Table 2).

The sample size for grade A–WR concrete was too small to warrant a combined analysis (see Table 3). Most of the A–WR data were from the Vinton-29 project, obtained late in the paving season when the ambient temperature was significantly lower. The cylinders on this project were also cured in more heavily insulated curing boxes, which may have accelerated strength development. This effect can be seen from the significantly higher cylinder strength, relative to core strength, for this project (see Table 3). These results were included for completeness and should not be used to characterize the typical strength of grade A–WR concrete.

POOLED RESULTS

The combined results presented in Table 4 for grade A–FA concrete include the variability between projects. This is appropriate when considering an opening criterion based on curing period alone. This criterion should be applied on an industrywide basis without any on-site testing. This lumping together of data, however, tends to exaggerate the estimate of the variability that can be anticipated on a given project.

The development of opening criteria based on cylinder testing requires an assessment of the strength without the variability between projects. Data used for this purpose should be pooled instead of combined. In the pooling process, variability is determined from the weighted average, by degrees of freedom, of the component project variances. The differences between project mean strengths are thus eliminated from the computed standard deviations.

An estimate of the strength parameters as determined from the pooled results for grade A–FA concrete is shown in Table 5. Note that the standard deviations and resultant coefficients of variation are reduced while the estimated means are unchanged. Each sample point represents the average of three individual test specimens. All of the data were pooled for the core strengths, and the data from the Trierweiler projects were excluded in the analysis of the cylinder strengths for the reasons previously stated. There were not enough data for the grade A–WR concrete to warrant a pooled analysis.

DISCUSSION OF RESULTS

The first objective of this study was to assess the typical in situ compressive strength of paving-grade concretes at 3, 5, and 7 days on an industrywide basis. Review of the core test results for the combined data (Table 4) indicates that most of the surveyed pavements using grade A–FA concrete had attained compressive strengths of 20.7 mPa (3,000 psi) to 24.1 mPa (3,500 psi) after only 3 days.

An estimate of the percentage of pavements that equal or exceed a given strength can be calculated from the mean and standard deviations shown in Table 4. The results of this analysis for strength levels of 20.7 mPa (3,000 psi) and 24.1 mPa (3,500 psi) are given in Table 6.

A picture of both the mean of and the variability in the in situ strength of the grade A–FA pavement on an industrywide basis can

TABLE 2 Summary Statistics for Individual Projects—Grade A–FA

	Average of 3 Cores			Average of 3 Cylinders			
Beaudoin - 45	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	29.9	31.9	34.8	23.2	25.3	27.6	33.9
Standard Deviation (mPa)	2.4	3.4	3.2	2.3	2.3	2.6	3.6
Coefficient of Variation	7.9%	10.6%	9.3%	9.7%	8.9%	9.5%	10.6%
Sample Size	10	10	10	17	17	17	17
95% Exceed (mPa)	26.0	26.3	29.4	19.5	21.6	23.3	28.0

	Average of 3 Cores			Average of 3 Cylinders			
Cape - I90	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	25.9	28.2	29.3	25.7	27.7	29.0	35.7
Standard Deviation (mPa)	2.2	2.5	3.0	2.2	2.1	1.9	4.0
Coefficient of Variation	8.6%	9.0%	10.1%	8.6%	7.5%	6.6%	11.2%
Sample Size	11	10	10	20	20	19	20
95% Exceed (mPa)	22.3	24.0	24.4	22.1	24.2	25.8	29.1

	Average of 3 Cores			Average of 3 Cylinders			
Vinton - 19	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	24.7	24.3	29.7	21.0	22.6	24.3	31.4
Standard Deviation (mPa)	1.9	1.9	2.4	1.3	1.5	1.4	2.0
Coefficient of Variation	7.6%	7.9%	8.2%	6.3%	6.5%	5.6%	6.2%
Sample Size	13	13	13	20	20	20	10
95% Exceed (mPa)	21.6	21.1	25.7	18.8	20.2	22.0	28.2

	Average of 3 Cores			Average of 3 Cylinders [a]			
Trierweiler - A	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	23.3	28.7	30.3	22.2	24.9	27.4	34.4
Standard Deviation (mPa)	1.9	2.8	4.4	4.1	3.5	4.1	5.6
Coefficient of Variation	8.0%	9.9%	14.5%	18.6%	14.0%	15.0%	16.3%
Sample Size	3	6	7	10	11	11	9
95% Exceed (mPa)	20.3	24.0	23.1	15.4	19.2	20.6	25.2

	Average of 3 Cores			Average of 3 Cylinders [a]			
Trierweiler - B	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	25.1	27.1	28.5	22.1	24.3	26.3	34.5
Standard Deviation (mPa)	3.3	3.9	2.6	1.6	1.2	1.4	1.5
Coefficient of Variation	13.2%	14.2%	9.0%	7.3%	5.0%	5.4%	4.2%
Sample Size	5	4	5	8	8	6	8
95% Exceed (mPa)	19.6	20.7	24.3	19.4	22.3	24.0	32.1

[a] Trierweiler cylinder data contain inconsistencies

* To convert from mPa to psi multiply by 145.14

TABLE 3 Summary Statistics for Individual Projects—Grade A–WR

	Average of 3 Cores			Average of 3 Cylinders			
Beaudoin - 45	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	26.3	27.4	31.7	23.3	25.3	26.6	30.6
Standard Deviation (mPa)	1.4	2.0	0.2	0.8	1.2	1.0	1.3
Coefficient of Variation	5.5%	7.1%	0.6%	3.2%	4.6%	3.9%	4.1%
Sample Size	2	2	2	3	3	3	3
95% Exceed (mPa)	23.9	24.2	31.4	22.0	23.4	24.9	28.5

	Average of 3 Cores			Average of 3 Cylinders			
Vinton - 29	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	18.6	22.6	26.0	24.2	28.1	29.6	35.2
Standard Deviation (mPa)	3.5	2.5	2.7	4.6	3.6	3.4	3.7
Coefficient of Variation	18.6%	10.8%	10.5%	19.1%	12.8%	11.5%	10.5%
Sample Size	8	8	8	14	14	14	14
95% Exceed (mPa)	12.9	18.6	21.5	16.6	22.2	24.0	29.1

TABLE 4 Summary Statistics for Combined Data—Grade A–FA

	Average of 3 Cores			Average of 3 Cylinders			
	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	26.2	27.8	30.7	23.3	25.2	26.9	34.1
Standard Deviation (mPa)	3.1	3.9	3.7	2.8	2.9	2.8	3.8
Coefficient of Variation	11.8%	13.9%	12.2%	11.8%	11.3%	10.5%	11.2%
Sample Size	42	43	45	57	57	56	47
95% Exceed (mPa)	21.1	21.5	24.5	18.8	20.5	22.2	27.9

* To convert from mPa to psi multiply by 145.14

TABLE 5 Estimated Process Parameters for Pooled Data—Grade A–FA

	Average of 3 Cores			Average of 3 Cylinders			
	3-day	5-day	7-day	3-day	5-day	7-day	28-day
Mean (mPa)	26.2	27.8	30.7	23.3	25.2	26.9	34.1
Standard Deviation (mPa)	2.3	2.8	3.1	2.0	2.0	2.0	3.5
Coefficient of Variation	8.7%	9.9%	10.1%	8.4%	7.7%	7.4%	10.3%

* To convert from mPa to psi multiply by 145.14

TABLE 6 Percentage of Pavements Exceeding Given Strength—Grade A–FA

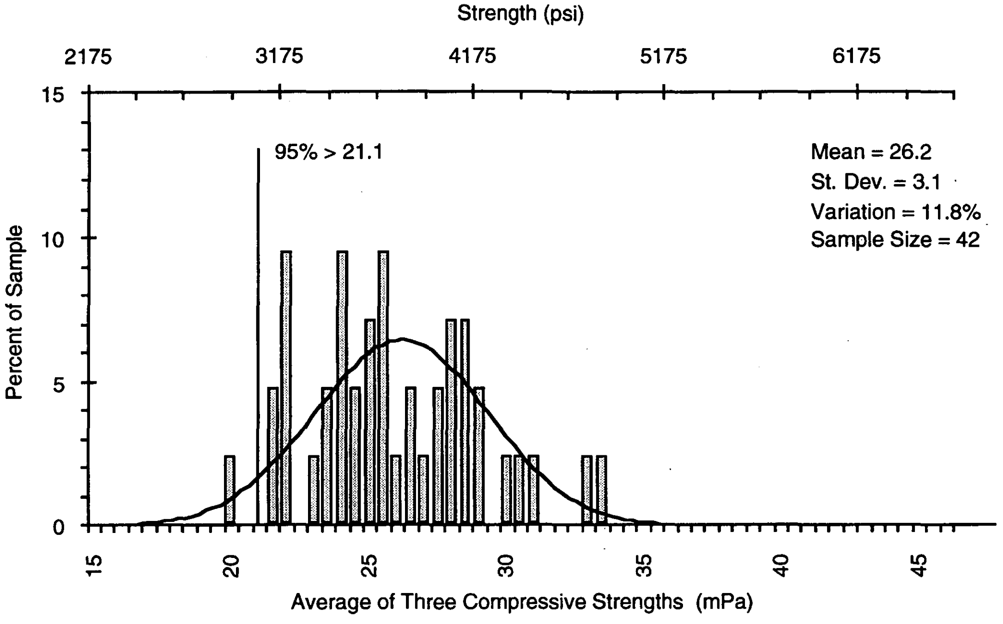
	Age of Pavement		
	3 Days	5 Days	7 Days
Predicted Strength > 20.7 mPa	96%	97%	100%
Predicted Strength > 24.1 mPa	75%	83%	96%

* To convert from mPa to psi multiply by 145.14

be obtained by examining frequency distributions, histograms, for the combined early strength core data. The histogram for the grade A–FA 3-day core strength, (Figure 1) shows the assumed normal distribution and the percentage of the sample within each 500 kPa (72.6 psi) increment.

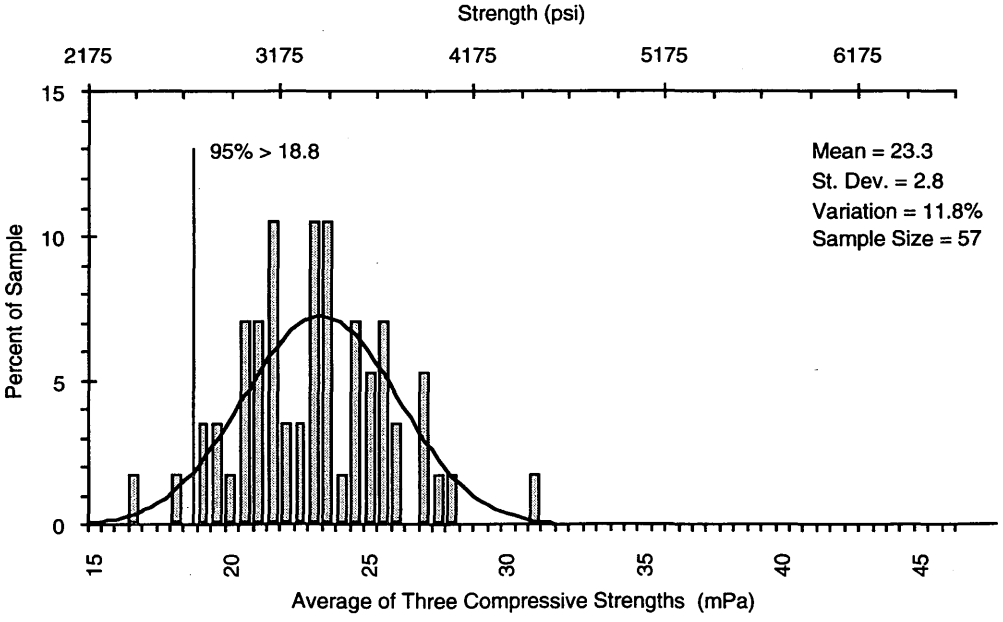
The second objective of this study was to assess the typical field-cured compressive strength of paving grade concretes at 3, 5, and 7 days for cylinders cured in lightly insulated boxes. Review of the grade A–FA combined cylinder test results (Table 4) shows a lag in strength gain with respect to the cores. It appears that the level of insulation provided was insufficient to recreate the thermal environment of the slab. The histogram for the grade A–FA 3-day cylinder strength from Table 4 is shown in Figure 2.

The third objective of this study was to assess the typical 28-day compressive strength of paving grade concretes on an industrywide basis. Review of the 28-day results for the grade A–FA combined



* To convert from mPa to psi multiply by 145.14

FIGURE 1 Histogram of combined data for 3-day cores—Grade A–FA.



* To convert from mPa to psi multiply by 145.14

FIGURE 2 Histogram of combined data for 3-day cylinders—Grade A–FA.

data (Table 4) indicates that more than 95 percent of the grade A–FA samples exceeds a strength of 27.6 mPa (4,000 psi). The histogram for grade A–FA 28-day cylinder strength from Table 4 is shown in Figure 3.

The final objective of this study was to compare the results of the core and cylinder tests to establish a relationship that can be used to predict in situ strength from the compressive strength of field-cured cylinders.

The grade A–FA core strength is plotted against the cylinder strength in Figure 4. Each pair of values was matched by location to ensure that they represent essentially the same material and curing history.

The 3-, 5-, and 7-day samples from three of the projects are shown. The data from the Trierweiler projects were excluded because of the problems with cylinder strengths previously stated.

Most of the data fall above the line of equality, indicating that core strengths generally exceed cylinder strengths. The scatter in the data, however, makes it difficult to reliably quantify that relationship.

Regression analyses were performed individually for each project and for all the data taken together. The results for grade A–FA concrete are given in Table 7.

The coefficients of determination (R^2) are very low for all cases, as was obvious from Figure 4. Despite the broad scatter, the data appear to be banded, indicating that a relationship exists. Predicting variable core strength in terms of variable cylinder strength with a high level of precision may not be possible. The equation for all the data appears reasonable on physical grounds.

Over the range of cylinder strengths of concern, 17.2 to 31 mPa (2,500 to 4,500 psi), the regression line lies above the line of equality but intersects it at about 31 mPa (4,500 psi). Cores are thus predicted to be stronger than cylinders at about 3 days, while nearly the same strength around 7 days. This makes physical sense, because higher temperatures prevail in the slab for the first day or two, but by 7 days, the relative difference in maturity between the slab and cylinders should be smaller.

Despite the lack of a good statistical fit, the regression equation for all the data can be used to derive a rough estimate of the cylinder strength that should be required. First the mean core strength necessary to equal or exceed the required strength 95 percent of the time can be computed. This value can then be used to compute the mean cylinder strength needed.

For the normal distribution, 95 percent of the strengths exceeds the mean minus 1.645 standard deviations. The average pooled standard deviation for grade A–FA core strength is about 2.7 mPa (397 psi) (see Table 5). The pooled data are used because these opening criteria will be applied on a project-by-project basis. The estimated necessary grade A–FA mean core strengths are

for 20.7 mPa (3,000 psi): $20.7 + (1.645 \times 2.7) = 25.1$ mPa (3,650 psi)

for 24.1 mPa (3,500 psi): $24.1 + (1.645 \times 2.7) = 28.5$ mPa (4,140 psi)

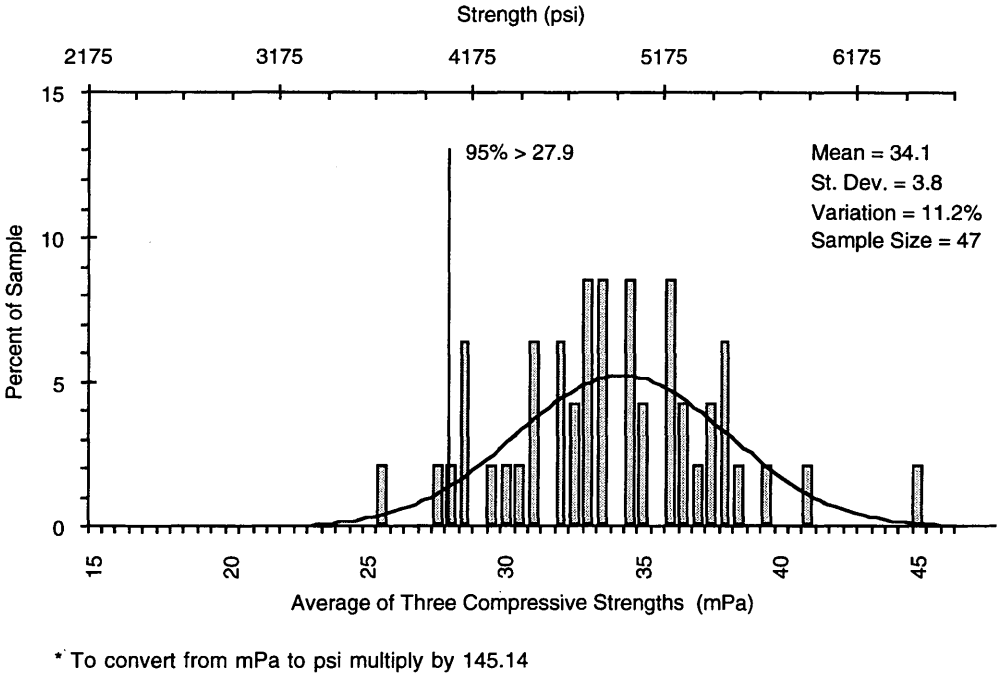
The regression equation from Figure 4 can now be applied to find the required cylinder strengths:

for 20.7 mPa (3,000 psi): $(25.1 - 16.7) \div 0.472 = 17.8$ mPa (2,580 psi)

for 24.1 mPa (3,500 psi): $(28.5 - 16.7) \div 0.472 = 25.0$ mPa (3,630 psi)

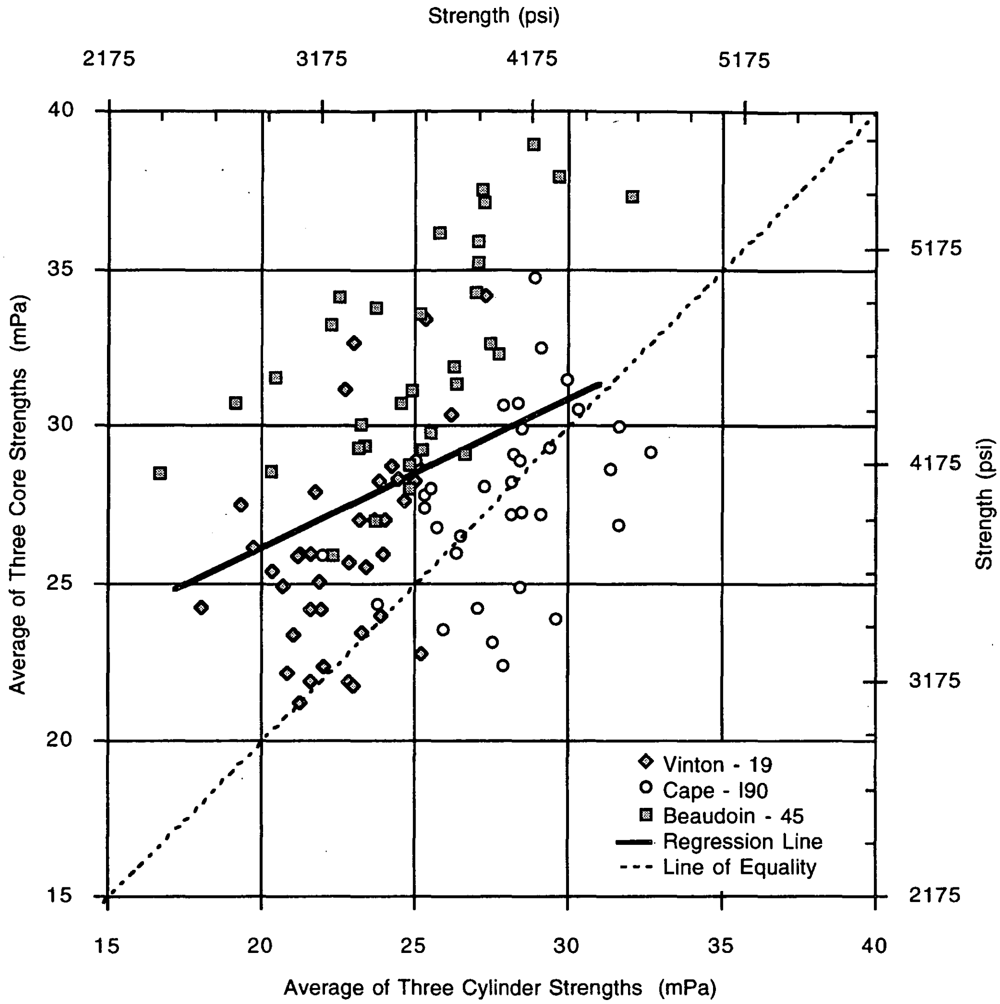
This analysis indicates that the resultant grade A–FA cylinder strengths are roughly equivalent to the required strength over the limited range under consideration. Cylinder test results should thus provide reasonable criteria for opening of concrete pavements.

In Wisconsin cylinders for opening are usually cured on grade with no insulation. Although excluded from this analysis, the grade A–WR data from the Vinton-29 project suggest that the level of insulation provided during field-curing is also important.



* To convert from mPa to psi multiply by 145.14

FIGURE 3 Histogram of combined data for 28-day cylinders—Grade A–FA.



* To convert from mPa to psi multiply by 145.14

** Core Strength = 16.7 + (0.472 x Cylinder Strength)

FIGURE 4 Comparison of core versus cylinder strengths—Grade A–FA.

CONCLUSIONS

The analysis contained in this report is based exclusively on WisDOT grade A–FA concrete placed from June through September. The average daily ambient air temperatures during this period and the construction dates for each project are shown in Figure 5. Any attempt to generalize these results beyond the scope of this analysis should be accompanied by further research. Several variables would likely affect the results to some degree. Cement content, ambient temperature, and the level of insulation or protection afforded to both cylinders and the pavement warrant consideration.

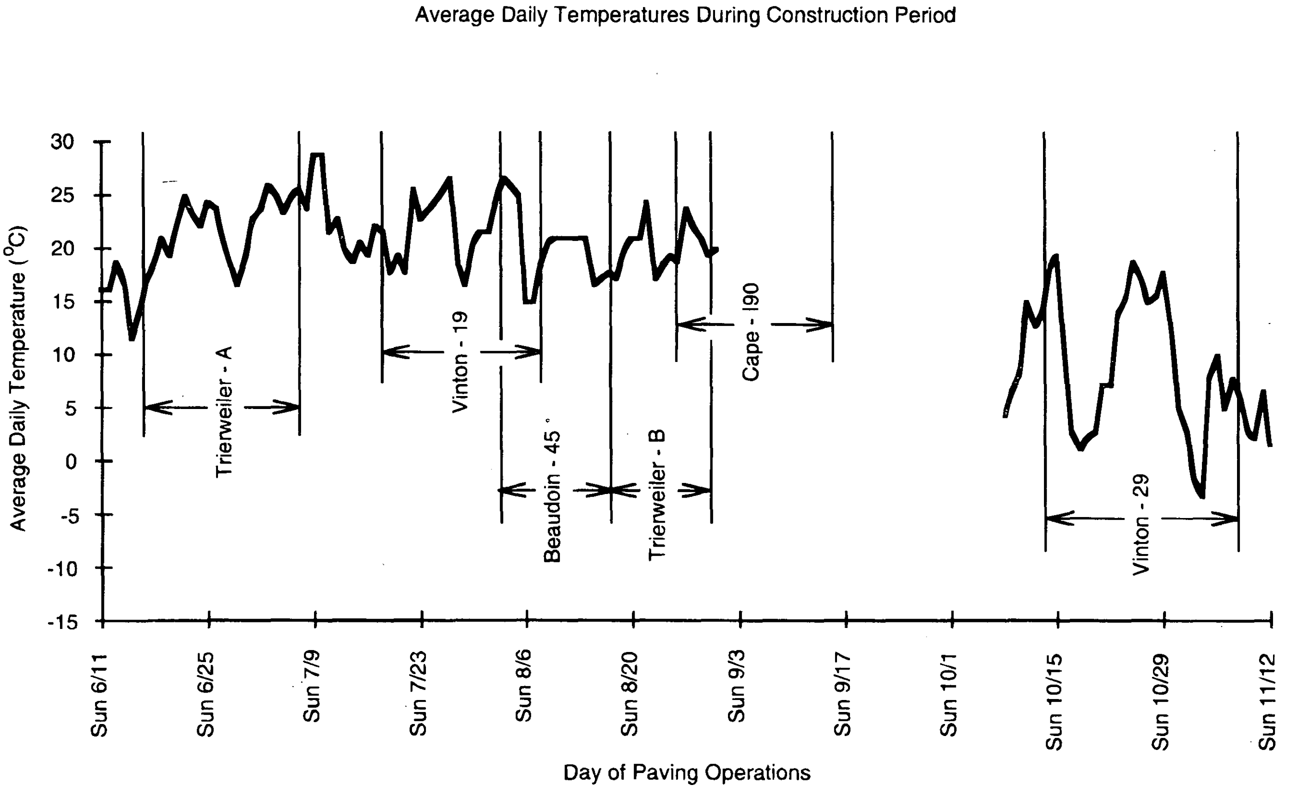
The following conclusions were drawn for WisDOT grade A–FA concrete placed during the typical warm weather portion of the Wisconsin construction season:

- Most WisDOT grade A–FA concrete pavements are attaining strengths of 20.7 mPa (3,000 psi) to 24.1 mPa (3,500 psi) in 3 days or less.

TABLE 7 Core Strength Versus Cylinder Strength Regression Analysis—Grade A–FA

	Data Set			
	Vinton - 19	Cape - I90	Beaudoin - 45	All Data
Coefficient	0.836	0.449	0.693	0.472
Intercept (mPa)	7.22	15.20	14.85	16.70
Coefficient of Determination	.26	.14	.39	.15

* To convert from mPa to psi multiply by 145.14



* To convert °C to °F multiply by 1.8 then add 32

FIGURE 5 Ambient temperatures and project construction dates.

- Approximately 95 percent of WisDOT grade A–FA paving-grade concrete has a 28-day compressive strength in excess of 27.9 mPa (4,050 psi).
- Cylinders cured in the field with light protective insulation provide a reasonable measure of the in situ compressive strength of the pavement.

ACKNOWLEDGMENT

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