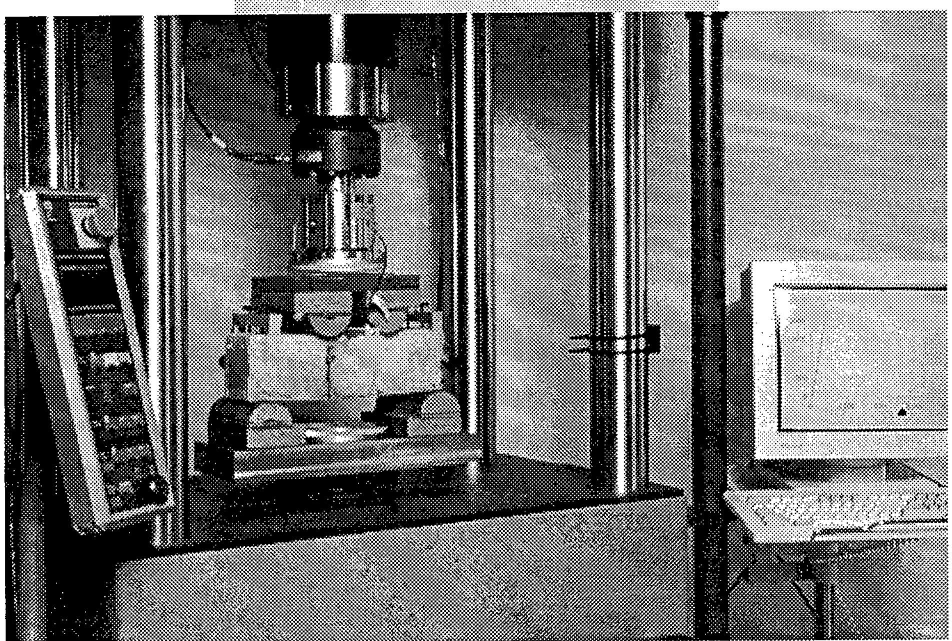
FINAL REPORT

EVALUATION OF CONCRETE CHARACTERISTICS FOR RIGID PAVEMENTS



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Supplementary Notes

Abstract

The researcher developed correlations among flexural, split tensile, and compressive strengths and ultrasonic pulse velocity from laboratory testing using materials and mix designs proposed for use in a paving project. These relationships were used to review the current VDOT specifications and quality control procedures for concrete used in the construction of rigid pavements.

Correlations between compressive and flexural strength for project-specific materials and mix designs permit the use of compressive strength cylinders rather than beams for compliance testing. The relationships also provide a means for evaluating the quality of the concrete as placed in the pavement.

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Transportation Research Council
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ABSTRACT

The researcher developed correlations among flexural, split tensile, and compressive strengths and ultrasonic pulse velocity from laboratory testing using materials and mix designs proposed for use in a paving project. These relationships were used to review the current Virginia Department of Transportation specifications and quality control procedures for concrete used in the construction of rigid pavements.

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INTRODUCTION

For rigid pavements, the Virginia Department of Transportation's (VDOT) 1993 *Road and Bridge Specifications* (VDOT 1993) specified that the concrete have a 28-day compressive strength of 20.7 MPa (3,000 psi) (20 MPa in the 1997 edition), a minimum cementitious materials content, a maximum water-cement ratio of 0.49, an air content of 6 ± 2 percent, and a slump of 0 to 76 mm (0 to 3 in). Concrete pavements are currently designed using a mean 28-day flexural strength of 4.5 MPa (650 psi) based on third-point loading (ASTM C 78). During construction, acceptance testing is often limited to measuring slump and air content and fabricating beams to test flexural strength. The beams are cured in the field, and flexural strength is determined by the center-point method (AASHTO T177). A flexural strength of 4.1 MPa (600 psi) is required to open pavement to traffic prior to 14 days after placement.

These specifications raise several issues with regard to the quality of concrete specified and the methods used to ensure compliance with the specifications. The class of concrete specified, VDOT Class A3, requires, as noted, a mixture with a 28-day compressive strength of at least 20.7 MPa (3,000 psi). Mather recommended that concrete exposed to freezing and thawing have a compressive strength of at least 27.6 MPa (4,000 psi).[1] Although the relationship between compressive and flexural strength depends on a number of mixture-specific factors, a reported general relationship exists that suggests a concrete with a compressive strength of 20.7 MPa (3,000 psi) would yield a flexural strength of 2.8 to 3.4 MPa (400 to 500 psi) by third-point loading. This does not necessarily mean that the quality of the concrete currently used is inadequate, but it does indicate inconsistent specification requirements, which could result in acceptance of a lower-quality material than is intended.

In addition, although pavements are designed based on a 28-day flexural strength of 4.5 MPa (650 psi) determined by third-point loading, the actual testing is performed by center-point loading with a criterion requiring attainment of a flexural strength of 4.1 MPa (600 psi) if the pavement is to be loaded prior to 14 days after placement. Because of the way the load is placed in the center-point test, the concrete yields a higher flexural strength than would be obtained with third-point loading.[2] As a consequence, the acceptance scheme for rigid pavements does not provide a means to determine whether the concrete meets the design requirements.

Flexural strength results are sensitive to many factors, including fabricating, curing, and loading of the beams.[3,4] Because these factors lead to high variability, the concrete industry is interested in using compressive strength rather than flexural strength tests for field quality assurance. With pavements, where flexural strength is the important design criterion, the relationship between compressive and flexural strength can be determined through trial batching the proposed concrete mixes and establishing the correlation between the two by testing, thus permitting an accurate estimation of the flexural strength of the as-delivered concrete by testing cylinders for compressive strength.[3,5]

The use of standard-cured compressive strength cylinders to estimate flexural strength in this fashion provides a means to evaluate the quality of the concrete delivered for placement. Likewise, the strength of the constructed pavement could be evaluated by testing cores removed from the pavement for compressive or tensile strength (i.e., depth-check cores) and comparing the results to the relationship developed through laboratory testing.[6] This process would provide an indication of the quality of the pavement, which relates directly to pavement performance.

Removing cores from the pavement to determine the thickness or evaluate the quality of the in-place concrete is a destructive process. Although it is, no doubt, worth its cost in the long run because of the information it provides, a nondestructive alternative may exist. It has been suggested that ultrasonic pulse velocity (UPV) measurements may permit in-situ evaluation of pavement quality if the relationship between UPV and strength (compressive/flexural) is known for the concrete mixture.[7] It is envisioned that this relationship can be developed along with the relationship among compressive, flexural, and tensile strength through laboratory testing. The application of nondestructive techniques to the quality assurance process would greatly simplify this extremely important construction task.

PROBLEM STATEMENT

Current VDOT specifications for hydraulic cement concrete used to construct rigid pavement are a blend of performance and prescriptive requirements that appear to be inconsistent. Quality assurance procedures rely primarily on flexural testing of beams by center-point loading, a test with high variability. As a consequence, the properties of the concrete used to construct the pavement are less well known than is desirable, and virtually nothing is known about the properties of the concrete actually in the pavement, which is the most crucial piece of information regarding pavement performance.

PURPOSE AND SCOPE

The objective of this project was to evaluate the strength properties of concrete paving mixtures in the laboratory to develop the relationships among compressive strength, tensile strength, flexural strength, and stress wave propagation. The ultimate goal of this research was to collect a database to develop a performance-related specification and thereby improve the specifications and quality assurance procedures for hydraulic cement concrete pavements.

RESEARCH DESIGN

Concrete batches were mixed in the laboratory using the materials proposed for a specific paving project. The mixture proportions were based on the mix designs accepted for use on the project. To develop the relationship between compressive and flexural strength, the mixtures tested should have a range of property values. For compressive strength, a minimum range of 10 to 14 MPa (1,500 to 2,000 psi) has been suggested.[5]

To ensure a wide and reasonable range in concrete properties, six mix designs with a water-cementitious material ratio (W/CM) between 0.40 and 0.52 were used. These mix designs were based on the designs accepted for use in the concrete pavement being constructed as part of the widening and rehabilitation of I-66 in VDOT's Northern Virginia District. The series accepted for use on the project consisted of six mixtures with a W/CM between 0.40 and 0.45. The maximum W/CM permitted by VDOT for paving concrete is 0.49. The cementitious material and coarse aggregate content is held constant in these mixes, and the variation in W/CM is accommodated by adjustments in the fine aggregate content. A duplicate batch for each W/CM was mixed on a separate day. The six mix designs are given in Table 1.

The materials used in the laboratory tests were from the same sources as those used in the construction project:

- portland cement: Type I (see Table 2)
- fly ash: Class F (see Table 2)
- coarse aggregate: No 57 crushed stone, diabase
- fine aggregate: quartzose natural sand.

The properties of the fresh concrete (slump, unit weight, air content) were determined for each batch, and cylindrical and beam specimens were cast for determining the properties of the hardened concrete. In addition, cubes, 150 x 150 mm, were fabricated to measure UPV. The properties of the hardened concrete were determined using specimens tested at 7, 14, and 28 days. Prior to strength testing, the UPV of the concrete was determined. Two specimens were tested, and the results averaged for each strength test at each age.

The results of these tests were analyzed to determine the relationship among flexural strength, compressive strength, tensile strength, and UPV. Cores removed to check the depth were tested for UPV and compressive or tensile strength and were used for petrographic analysis of the air-void system. The data obtained during construction were evaluated and compared to the relationships developed in the laboratory to assess the practicality of using those relationships in quality assurance operations.

Table 1. Mix Designs for Concrete Batches, m^3 (yd^3)

Batch No.	1	2	3	4	5	6
W/CM	0.52	0.49	0.47	0.45	0.43	0.40
Cement, kg (lb)	284 (479)	284 (479)	284 (479)	284 (479)	284 (479)	284 (479)
Fly ash, kg (lb)	67 (113)	67 (113)	67 (113)	67 (113)	67 (113)	67 (113)
Coarse aggregate, kg (lb)	1128 (1902)	1128 (1902)	1128 (1902)	1128 (1902)	1128 (1902)	1128 (1902)
Fine aggregate, kg (lb)	686 (1156)	714 (1203)	733 (1235)	751 (1266)	771 (1300)	799 (1347)
Water, kg (lb)	183 (308)	172 (290)	165 (278)	158 (266)	51 (255)	140 (236)
Air, %	6	6	6	6	6	6

Table 2. Chemical and Physical Analysis of Cement and Fly Ash

Parameter	Portland Cement	Parameter	Fly Ash
SiO_2	22.07%	$SiO_2 + Al_2O_3 + Fe_2O_3$	88.51%
Al_2O_3	5.34%	SO_3	0.21%
Fe_2O_3	2.47%	LOI	4.76%
CaO	65.44%	Specific gravity	2.23
MgO	3.79%	No. 325 (ret.)	25.3%
SO_3	2.87%		
Na_2O (equiv.)	0.75%		
C_3S	51.1%		
C_2S	24.7%		
C_3A	10.0%		
C_4AF	7.5%		
Fineness (cm^2/g)	3927		
LOI	0.80%		

The following test methods were used to determine the properties of the fresh and hardened concrete:

- ASTM C 192, making and curing test specimens in the laboratory
- ASTM C 138, unit weight of fresh concrete

- ASTM C 231, air content of fresh concrete, pressure method
- ASTM C 143, slump
- ASTM C 39, compressive strength
- ASTM C 78, flexural strength, third-point loading
- ASTM C 496, splitting tensile strength
- ASTM C 469, static modulus of elasticity
- ASTM C 42, obtaining and testing drilled cores
- ASTM C 597, pulse velocity through concrete
- ASTM C 457, microscopical determination of the parameters of the air-void system in hardened concrete.

RESULTS AND DISCUSSION

Laboratory Tests

Table 3 shows the results of the tests using fresh concretes. The slump for mixtures 1 through 4 exceeded the 75-mm maximum slump specified for paving concretes, and the air content of batches 1 and 5A was slightly below the minimum 4 percent.

Table 3. Test Results for Fresh Laboratory-Batched Concrete

Batch No.	Slump (mm)	Unit Weight (kg/m^3)	Air Content (%)	Temperature (C^o)
1	190	2435	3.8	26
1A	178	2416	4.0	24
2	133	2416	4.9	26
2A	165	2390	6.0	26
3	165	2364	6.5	25
3A	127	2403	5.7	24
4	102	2384	6.0	26
4A	119	2403	5.1	24
5	57	2422	5.1	26
5A	25	2467	3.8	25
6	13	2377	7.0	25
6A	25	2460	5.1	27

Table 4 shows the results of the tests using hardened concretes. Compressive strength ranged from 18.2 to 38.3 MPa (2,640 to 5,550 psi). Splitting tensile strength ranged from 2.3 to 4.4 MPa (330 to 640 psi), and third-point flexural strength from 2.8 to 5.0 MPa (410 to 725 psi). Elastic modulus ranged from 28 to 41 GPa (4.1 to 6.0 x 10^6 psi) with an average of 32 GPa (4.6 x 10^6 psi). The average 28-day modulus of elasticity of mixtures with a W/C of 0.49 or less was 34 GPa (4.9 x 10^6 psi). UPV ranged from 4,286 to 5,146 m/s.

Table 4. Test Results for Hardened Laboratory-Batched Concrete

Batch No.	Age (days)	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of Elasticity (GPa)	Ultrasonic Pulse Velocity (m/s)
1	7	18.2	2.3	2.8	30	4496
1A	7	19.9	2.7	3.1	---	4454
2	7	19.7	2.4	3.1	29	4521
2A	7	21.0	---	3.8	---	5045
3	7	19.6	3.1	3.4	28	4578
3A	7	22.3	2.9	3.6	---	4708
4	7	23.2	3.3	4.1	31	4596
4A	7	22.2	2.7	3.4	---	4469
5	7	26.5	3.6	4.1	34	4286
5A	7	30.3	3.7	---	---	4668
6	7	21.9	2.9	4.1	30	4389
6A	7	31.3	3.7	4.7	---	5146
1	14	22.6	3.4	3.2	30	4638
1A	14	23.2	3.4	3.1	---	4638
2	14	22.8	3.4	3.7	32	4496
2A	14	23.6	3.1	3.8	---	5144
3	14	24.0	3.1	3.7	30	4843
3A	14	25.7	3.3	4.2	---	4675
4	14	26.3	2.7	4.4	32	4846
4A	14	27.2	3.1	4.0	---	4480
5	14	---	3.2	4.1	---	4738
5A	14	34.3	4.0	4.4	---	4709
6	14	25.1	3.0	3.7	30	4601
6A	14	34.6	3.9	4.4	---	4856
1	28	24.4	2.9	4.0	31	4702
1A	28	27.4	3.5	3.8	30	4629
2	28	26.1	3.4	4.0	34	4793
2A	28	25.8	3.4	3.6	28	4684
3	28	26.3	3.2	3.7	32	4704
3A	28	28.8	3.6	3.9	---	4738
4	28	30.2	---	3.9	34	4643
4A	28	32.1	3.8	4.4	32	4631
5	28	33.1	3.7	5.0	37	4716
5A	28	38.3	4.2	4.6	---	4804
6	28	29.2	3.3	4.4	34	4690
6A	28	38.1	4.4	4.2	41	4774

Compressive versus Splitting Tensile Strength

Figure 1 is a plot of log compressive strength against log splitting tensile strength. Regression analysis of 33 observations yielded a correlation coefficient (r) of 0.86 with a standard error of 0.04. This regression is statistically significant at the 95 percent confidence level. From this regression, compressive strength can be predicted from splitting tensile strength using equation 1:

$$\log f_c = 1.096(\log f_t) + 0.85 \quad \text{[Eq. 1]}.$$

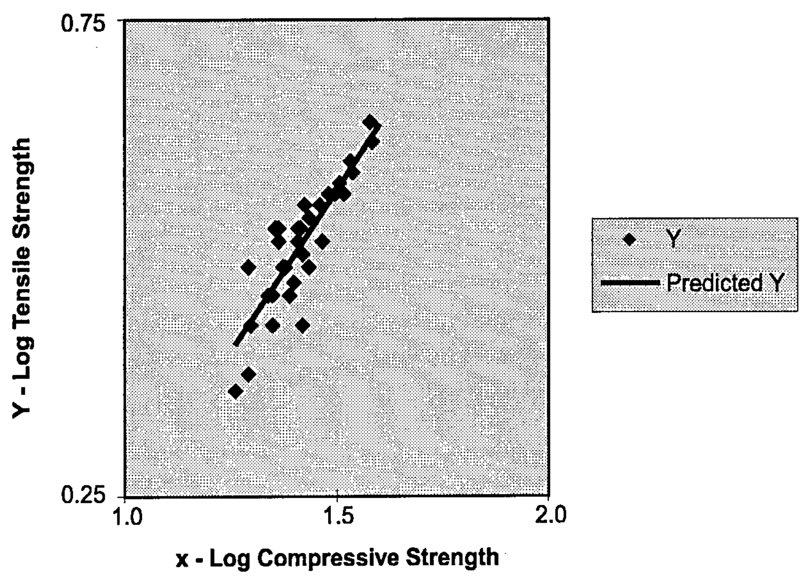

Figure 1. Compressive-Tensile Strength Line Fit Plot

Flexural versus Compressive Strength

Figure 2 is a plot of log flexural strength against log compressive strength. Again, a linear relationship is suggested. A correlation coefficient of 0.80 with a standard error of 0.04 is obtained from the analysis based on 34 observations. This relationship is significant at the 95 percent confidence level. Flexural strength can be predicted from compressive strength using equation 2:

$$\log f_f = 0.555(\log f_c) - 0.197 \quad \text{[Eq. 2]}.$$

Using equation 2, a flexural strength of 4.5 MPa (650 psi), the strength used in pavement design, corresponds to a compressive strength of 33.9 MPa (4,920 psi). In an analysis of a large block of published data from several sources, Raphael[8] found the relationship between flexural and compressive strength to be:

$$f_f = 2.3 f_c^{2/3} \text{ (in psi)}$$

$$f_f = 0.44 f_c^{2/3} \text{ (in MPa)}.$$

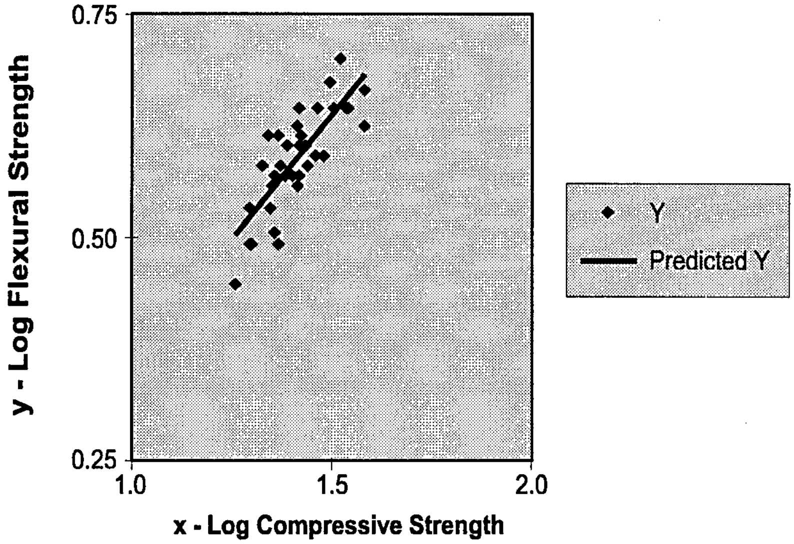

Figure 2. Compressive-Flexural Strength Line Fit Plot

This relationship is recommended by American Concrete Institute (ACI) Committee 330 for use when the relationship for specific materials is not known.[8,9] Using Raphael's relationship, a flexural strength of 4.5 MPa (650 psi) corresponds to a compressive strength of 32.8 MPa (4,760 psi).

Both the 33.9 MPa (4,920 psi) value obtained in this study and the 32.8 MPa (4,760 psi) value indicated by Raphael's work as corresponding to a flexural strength of 4.5 MPa (650 psi) are well in excess of the specified compressive strength of 20.7 MPa (3,000 psi) for Class A3 paving concrete. This has implications for both the concrete specification and pavement design calculations.

With respect to the concrete specification, prescriptive requirements for proportioning regarding the total cementitious material content and the maximum water-cement ratio virtually ensure that compressive strength should be well in excess of 20.7 MPa (3,000 psi). For instance, in these tests, the lowest 28-day strength complying with the 0.49 maximum W/C was 25.8 MPa (3,740 psi). Consequently, because testing compressive strength is the most practical means of evaluating concrete quality, post-placement evaluations of quality will rely on the specification criterion of 20.7 MPa (20 MPa in VDOT's 1997 *Road and Bride Specifications* [VDOT 1997]) for compressive strength, possibly creating a situation wherein concrete of much lower quality than intended is accepted.[10] Increasing the minimum specified compressive strength for paving concretes to at least 25 MPa (3,625 psi) would much better reflect the quality that is intended by the prescriptive specification and is needed to provide durable pavements. With such a specified minimum strength, the anticipated minimum mean 28-day strength would be about 27.5 MPa (3,990 psi), the strength needed for resistance to freezing and thawing.[1]

In designing pavements in accordance with the specifications in the 1986/1993 AASHTO guide, the mean 28-day flexural strength by third-point loading has a significant impact on the required thickness of the pavement.[11,12] In this study, the 28-day flexural strength of mixtures with a maximum W/C of 0.49 averaged 3.8 MPa (550 psi), and the average of all results for mixtures with a W/C less than 0.49 was 4.2 MPa (610 psi). These values contrast with the 4.5 MPa (650 psi) flexural strength value used in designing pavement, suggesting that the use of a design value of 4.5 MPa (650 psi) overestimates the flexural strengths actually being achieved. This could result in pavements that are thinner than they should be for their strength.

With the current VDOT prescriptive specification for paving concrete, a value of 4.0 MPa (580 psi) is more realistic for the mean 28-day flexural strength by third-point loading. Consequently, either the specified performance of paving concrete should be increased so that a mean 28-day flexural strength of 4.5 MPa (650 psi) is achieved or the design flexural strength should be reduced to 4.0 MPa (580 psi).

A 4.0 MPa (580 psi) flexural strength value corresponds to a compressive strength of 27.4 or 27.5 MPa (3,970 or 3,990 psi) based, respectively, on the relationships developed by Raphael and this study. These relationships indicate that a compressive strength of 33 MPa (4,790 psi) corresponds to a flexural strength of 4.5 MPa (650 psi). To ensure a mean 28-day compressive strength of 27.5 MPa (3,990 psi), thus achieving a mean 28-day flexural strength of 4.0 MPa (580 psi), a minimum 28-day compressive strength of 25 MPa (3625 psi) should be specified. To ensure that a concrete with a mean 28-day compressive strength of 33 MPa (4,790 psi) achieves a mean 28-day flexural strength of 4.5 MPa (650 psi), the specified minimum 28-day strength should be 30 MPa (4,350 psi). ACI Committee 325 recommends that concrete for paving have a minimum mean 28-day flexural strength of 4.5 MPa (650 psi).[10]

A flexural strength of 4.1 MPa (4.0 in VDOT 1997*)* (600 psi) by center-point loading is specified for opening pavement to traffic prior to 14 days after placement. Because of the difference in loading configuration, the center-point test yields a value approximately 1.15 that of the third-point test.[2] Thus the third-point value roughly comparable to the specified 4.1 MPa (600 psi) center-point value is 3.6 MPa (3.5 MPa, VDOT 1997) (520 psi). Corresponding compressive strengths based on Raphael and this study are 23.4 and 22.8 MPa (22.4 and 21.6 MPa in VDOT 1997) (3,400 and 3,310 psi), respectively.

For pavements with a required 4.0 MPa (580 psi) mean 28-day flexural strength by third-point loading, establishing a third-point loading flexural strength of 3.5 MPa (510 psi) or preferably its corresponding compressive strength of 22 MPa (3190 psi) as a criterion for opening pavement to traffic would provide protection equivalent to VDOT's current specification. The corresponding criterion for pavements with a flexural strength requirement of 4.5 MPa (650 psi) would be 3.9 MPa (570 psi) for flexural strength or 26 MPa (3,800 psi) for compressive strength.

Ultrasonic Pulse Velocity versus Compressive Strength

Figure 3 is a plot of UPV against compressive strength. No significant relationship is discernible in these data. This result is similar to the finding of other researchers who reported difficulties in attempting to predict compressive strength from UPV.[13]

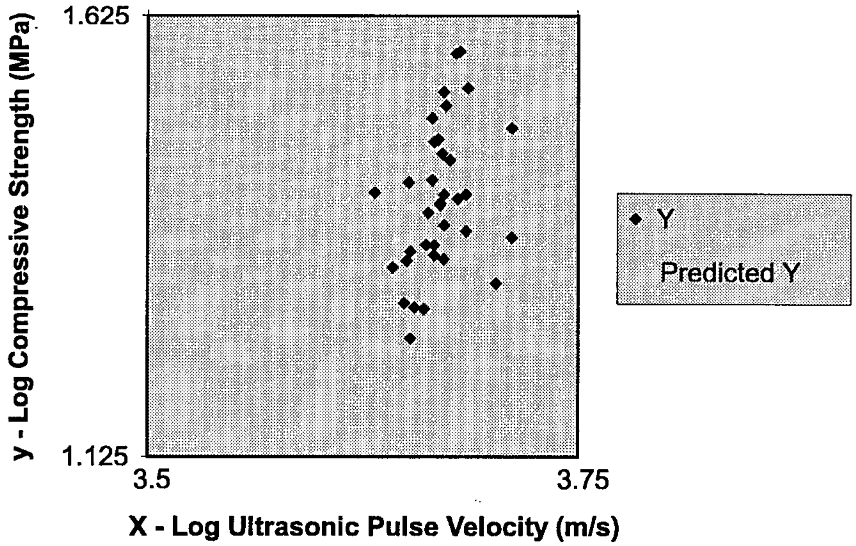

Figure 3. Ultrasonic Pulse Velocity-Compressive Strength Line Fit Plot

Pavement Tests

Table 5 shows the results of tests conducted on cores removed from the pavement. Compressive strength ranged from 28.3 to 51.6 MPa (4,100 to 7,480 psi), and splitting tensile strength ranged from 3.4 to 5.2 MPa (490 to 750 psi). The wide range in strength is attributable to fairly large differences in the age of cores when tested. UPV measurements ranged from 3,865 to 4,603 m/s.

Air-Void Parameters

Air content (Table 5) measured near the top of cores ranged from 2.9 to 9.6 percent, and near the bottom from 4.4 to 9.9 percent. The air-void spacing factors were 0.20 mm or less. A spacing factor of 0.20 mm is considered the maximum allowable to ensure resistance to freezing and thawing; consequently, given the combination of spacing factors and strengths, the concrete is considered to be resistant to freezing-thawing deterioration.[1]

Consolidation of concrete is generally considered adequate if the air content contributed by voids greater than 1 mm is less than 1.5 to 2 percent.[14] Inadequate consolidation has an adverse impact on compressive strength, durability, and, consequently, pavement performance.[15] Of the eight cores examined, the air content in large voids (>1 mm) in the top of two and the bottom of two others exceeded 2 percent. In three of these cases, the 2 percent value was only slightly exceeded. In the bottom of core P2250 (location 162+05), the air content in large voids was 4.7 percent, suggesting extremely poor consolidation near the bottom of the slab. However, the middle portion of this core was tested in compression and yielded a strength of 43.9 MPa (6,370 psi), suggesting the poor consolidation may have been a local feature. Based on the limited sampling of this study, pavement consolidation in this project appears to have been good.

Table 5. Results of Strength Tests on Pavement Cores

Core	Location	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Ultrasonic Pulse Velocity (m/s)	Air Content (%)		Spacing Factor (mm)		Voids > 1 mm (%)	
					Top	Bottom	Top	Bottom	Top	Bottom
P2220	WBL 82+16	---	---	4393	---	---	---	---	---	---
P2221	WBL 88+76	41.8	---	4603	---	---	---	---	---	---
P2222	WBL 94+69	---	5.0	4487	6.7	7.9	0.13	0.15	---	---
P2223	WBL 120+71	40.1	---	4378	---	---	---	---	---	---
P2224	WBL 191-14	48.5	---	4468	---	---	---	---	---	---
P2225	WBL 197+54	43.4	---	4202	7.6	4.4	0.12	0.19	2.6	0.5
P2226	WBL 198+28	---	---	4300	---	---	---	---	---	---
P2227	WBL 204+04	---	---	4276	9.6	5.9	0.11	0.16	2.5	0.4
P2228	WBL 277+73	---	5.1	4397	---	---	---	---	---	---
P2229	EBL 91+92	---	5.2	4292	2.9	6.7	0.12	0.16	0.4	2.3
P2230	EBL 192+32	51.6	---	4333	5.0	7.3	0.14	0.11	1.1	1.3
P2247	WBL 153+07 (HOV)	45.0	---	4346	4.1	5.7	0.17	0.20	1.2	1.8
P2248	156+03	---	---	4152	---	---	---	---	---	---
P2249	156+14 (HOV)	---	4.0	4064	---	---	---	---	---	---
P2250	162+05	43.9	---	4410	4.9	9.9	0.16	0.17	1.1	4.7
P2251	WBL 270+23	---	---	4068	---	---	---	---	---	---
P2252	WBL 277+50	---	3.8	4215	---	---	---	---	---	---
P2253	WBL 277+54	---	---	4343	6.1	6.4	0.12	0.18	1.6	1.7
P2254	281+46	33.8	---	4005	---	---	---	---	---	---
P2255	282+98	---	3.4	4099	---	---	---	---	---	---
P2256	287+67	28.3	---	3865	8.5	7.8	0.10	0.07	2.0	0.5

Strength Testing

Table 6 provides the third-point flexural strength of the pavement concrete predicted from core strength. The flexural strength is predicted either from the core compressive strength using equation 2 or Raphael's equation or indirectly from the core splitting tensile strength using equation 1 to obtain a compressive strength and then using equation 2 or Raphael's equation for the corresponding flexural strength.[8] Because many of the cores were tested at ages much later than 28 days, their strength exceeded the maximum strengths on which equations 1 and 2 were developed. The affected values are noted by parentheses in Table 2 and are consequently subject to increased uncertainty. In spite of this problem, the results do serve to indicate that the flexural strength in the pavement was quite high and well in excess of anticipated design strengths. Similar problems in future work can be avoided by including 56-day tests in the development of laboratory correlations and testing pavement cores in a timely fashion.

Table 6. Flexural Strength of Pavement Concrete Predicted from Cores

Core	Location	Flexural Strength (MPa)		Third-Point Predicted	
		From compressive strength using Eq. 2	From splitting tensile strength using Eqs. 1 & 2	From compressive strength using Raphael[8]	From splitting tensile strength using Eq. 1 & Raphael[8]
P2221	WBL 88+76	(5.04)	---	5.3	---
P2222	WBL 94+69	---	(5.01)	---	(5.3)
P2223	WBL 120+71	(4.92)	---	5.2	---
P2224	WBL 191-14	(5.47)	---	5.9	---
P2225	WBL 197+54	(5.14)	---	5.4	---
P2228	WBL 277+73	---	(5.07)	---	(5.3)
P2229	EBL 91+92	---	(5.13)	---	(5.4)
P2230	EBL 192+32	(5.66)	---	6.1	---
P2247	WBL 153+07 (HOV)	(5.25)	---	5.6	---
P2249	156+14 (HOV)	---	4.38	---	4.5
P2250	162+05	(5.18)	---	5.5	---
P2252	WBL 277+50	---	4.24	---	4.3
P2254	281+46	4.48	---	4.6	---
P2255	282+98	---	3.96	---	4.0
P2256	287+67	4.06	---	4.1	---

Note: (values) used in Eqs. 1 or 2 are beyond the range of the data on which the equations were based.

For the group tested at later ages, flexural strengths predicted from equations 1 and 2 or 2 ranged from 4.9 to 5.7 MPa (710 to 825 psi). Predictions using Raphael's equation were slightly higher. Flexural strength for the group tested at earlier ages ranged from 4.0 to 5.2 MPa (580 to 750 psi) using equations 1 and 2 or 2. Because of the later-age strength gain potential of fly ash concretes, it is anticipated that those sections tested at an earlier age will ultimately have a strength at least equivalent to that of the group tested at later ages. These predicted flexural strengths indicate that the strengths of the pavement slab meet or exceed design expectations.

CONCLUSIONS

- Correlations among compressive, flexural (third-point), and splitting tensile strength can be developed in the laboratory for mixtures proposed for use in hydraulic cement concrete paving projects. UPV and strength are not correlated. VDOT prescriptive requirements for paving concrete should yield concretes with a compressive strength that greatly exceeds the specified design value of 20.1 MPa (3000 psi) (20 MPa, VDOT 1997).

- Current procedures for rigid pavement design assume a mean 28-day flexural strength by third-point loading of 4.5 MPa (650 psi). Correlations developed in this study and by Raphael indicate that achieving this strength would require a mean 28-day compressive strength of about 33 to 34 MPa (4,790 to 4,930 psi).

- The development of the correlation between flexural and compressive strengths for the given materials will permit field quality control and assessment to be maintained by compressive strength testing of 100 x 200 mm (4 x 8 in) cylinders. Further, assessment of the quality of the actual pavement can be accomplished by testing cores.

- Current VDOT practice calls for testing beams by center-point loading if it is desired to open the pavement to traffic prior to an age of 14 days. Field verification for opening to traffic could readily be accomplished by compression testing of 100 x 200 mm cylinders using a minimum compressive strength of 22 MPa (3190 psi) for Class A3 paving concrete or equivalent.

- The strength characteristics and air-void parameters of the pavement in the I-66 paving project in Fairfax Co. represented by the cores indicate that the pavement slab meets or exceeds design expectations and should provide excellent service.

RECOMMENDATIONS

1. Implement the following:

    - Increase the minimum specified compressive strength for Class A3 (or equivalent) paving concretes from 20.7 to 25 MPa (3,000 to 3,625 psi).

    - Use a mean 28-day flexural strength by third-point loading of 4.0 MPa (580 psi) in pavement design calculations. Alternatively, determine the mean 28-day flexural strength of the proposed mixtures and use this value in pavement design calculations.

    - Specify a compressive strength of 22 MPa (3,200 psi) (flexural strength of 3.5 MPa [500 psi], third-point loading) as the minimum compressive strength for opening pavement to traffic prior to 14 days after placement.

2. As an alternate to 1, implement the following:

   - Where the design is based on a mean 28-day flexural strength of 4.5 MPa (650 psi), specify a minimum 28-day compressive strength of paving concrete of 30 MPa (4,350 psi).

   - Specify a minimum compressive strength of 26 MPa (3,800 psi) and a flexural strength of 3.9 MPa (570 psi, third-point loading) for opening pavement to traffic prior to 14 days after placement.

3. For projects for which a minimum flexural strength is specified, conduct trial batching of concrete materials proposed for use to develop the relationship between compressive and flexural strength by third-point loading. Select mixture proportions to ensure a range of 15 MPa (2,200 psi) in compressive strength. Specify that at least one mixture contain a W/C in excess of the maximum specified for the work. At a minimum, conduct tests at 3, 7, 28, and 56 days of age.

4. Fabricate and test compressive strength specimens to maintain quality control and assurance of paving projects using the relationship between compressive and flexural strength developed for the materials used. Test depth-check cores for compressive strength and air-void parameters to determine the quality of the in-place concrete. After measuring the length, maintain cores in a moist condition until tested for strength. At least 40 hours prior to testing, immerse them in lime-saturated water. Perform the testing as soon as feasible after 28 days of age.

5. Discontinue flexural testing of beams by center-point loading as it is inconsistent with the other recommendations.

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