ACCELERATED STRENGTH TESTS FOR QUALITY CONTROL OF CONCRETE PAVEMENTS

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Abstract

This paper presents the results of a laboratory based effort to evaluate potential methods of obtaining flexural strength for pavement quality control within 24 hr by accelerated test methods. Current Corps of Engineers pavement design procedures are based on and specify 28- and 90-day flexural strengths for roads and airfields, respectively. Quality control of pavement strengths use correlated 7- and 14-day flexural strengths to identify strength problems as early as possible, but compliance with specifications still depends on the 28- and 90-day strengths. These lengthy test times are not adequate to identify pavement strength problems, particularly with today's rapid construction techniques.

A literature review indicates that accelerated test methods employing elevated curing temperatures are available for evaluating compressive strength (ASTM C 684), but comparable procedures for the more sensitive flexural strength have not been published or accepted. Some success has been achieved in predicting long-term flexural strength by the use of the boiling method (ASTM C 684, Procedure B). More recent work indicates that a warm water curing method (ASTM C 684, Procedure A) is safer, may be more reliable, and causes less deleterious effects to the specimen, therefore it was pursued in this study.

To determine the most effective one day measure of concrete quality, accelerated (24 hr in an elevated temperature water bath) and 14-day flexural, splitting tensile, and compressive strengths were compared to 28- and 90-day flexural strengths. Three concrete mixtures were prepared by varying water cement ratios to provide a wide strength range. Ten batches of each mixture were cast into beams and cylinders for testing. A total of 1,061 specimens were fabricated and tested. Based upon the coefficient of determination (R^2) for regression equations, the warm water method provides reliability (R^2 = 0.894 to 0.945) equal to if not greater than the 14-day tests (R^2 = 0.785 to 0.920) in predicting 28- and 90-day flexural strength.

Introduction

Current Corps of Engineers pavement design procedures are based on and specify 28- and 90-day flexural strengths for roads and airfields, respectively. The basis is the most extensive controlled trafficking tests (1) recorded using full-scale loads at Lockburne AFB, Ohio, Sharonville, Ohio, and the Waterways Experiment Station (WES) from 1943 to 1973. Correlation between theory, small-scale model studies, and full-scale accelerated traffic tests has shown that maximum tensile stresses in the pavement occur when the vehicle wheels are tangent to a free or unsupported edge of the pavement. Based on theory and testing, a logarithmic relationship between flexural strength (modulus of rupture) and pavement life has been developed.(2) If the flexural strength falls slightly below the required strength it may result in a serious decrease in expected pavement life.

Quality control involves the early review of mix proportion, slump, air content, unit weight, and 7- or 14-day strength. The only penalty for performance which does not meet requirements is a revision in mix design. Quality assurance such as 28- or 90-day flexural strength involves a definition of the final product, and is generally the basis of payment. Frequently, a contractor is less concerned about quality control than he is about quality assurance, or how much money he will be paid. The emphasis should be on the quality of the concrete being placed at the time it is being placed. If concrete is properly proportioned, properly placed, and properly cured, it should achieve the desired strength.(3) Waiting even 7-days may be too long to correct deficiencies in concrete with today's rapid construction techniques. How do we evaluate flexural strength potential as early as possible?

Concrete strength relationships (4) between compressive, flexural, and splitting tensile have been previously investigated but do not always inspire a high degree of confidence. This lack of confidence in the relationships is attributed (5) to differences in aggregate properties and proportioning, water-cement ratio, degree of sample compaction, use of admixtures, etc.

There is strong interest in the use of compressive or splitting tensile strength testing for quality control of pavements since they employ an easy to handle 6 × 12 in. cylinder versus the larger 6 × 6 in. prismatic beam with a test span of 18 in. (typical length is 21 to 24 in.).

An accelerated strength testing procedure is available for compressive strength (ASTM C 684) but not for lower values representative of flexural strength. The boiling method (Procedure B of ASTM C 684) has previously been applied to flexural strength testing with some success.(6) Other work (7,8) using the boiling method has made correlations between compressive or splitting tensile strength and flexural strength. There has been some concern over the effects of boiling on the hydration products of cement. Results of a study evaluating all three methods in ASTM C 684 (9,10) indicate that Procedure A, the warm water method, yields specimens most reproducible and with least difference from these cured normally. Maturity, the integral of temperature with respect to time, for concrete is approximately the same for both the warm water and boiling method. Sacramento District, Corps of Engineers, has reported some success with warm water accelerated splitting tensile correlations to later age flexural strengths, but nothing is published yet. From the practical aspect, there is less danger of scalding associated with the warm water (95° ± 5° F) method. Therefore, the warm water method as described in ASTM C 684 is selected for evaluation of flexural strength testing. Since there is interest from field personnel in using an easier way to prepare and test cylindrical sample, splitting tensile and compressive strength tests were performed in this investigation.(11)

Scope of Investigation

Three concrete mixtures were proportioned by varying the water cement ratio, producing a range of flexural strengths from 545 to 925 psi. Ten 14-ft^3 batches per mixture (30 batches total) were produced, yielding fifteen beams and fifteen cylinders per batch (21 cylinders beginning with fourth batch). A total of 1,061 specimens were prepared and tested. Regression equations were developed to compare accelerated and 14-day flexural, splitting tensile, and compressive strengths to 28- and 90-day flexural strengths (accelerated and 90-day compressive strength specimens were prepared beginning with the fourth batch). Confidence in the regression equations was evaluated by the coefficient of determination (R^2).

Concrete Mixtures

Materials. Normal portland cement (ASTM Type I) was used for the concrete mixes. The physical properties and chemical analyses of the cement are given in Table 1.

The coarse aggregate was a No. 4 to 3/4 in. crushed limestone aggregate from Calera, AL. The fine aggregate was a locally available (Vicksburg, MS) natural sand. Both materials have a proven durability and soundness performance based on previous usage. There also have been no reported problems with alkali-aggregate reaction, deleterious substances, or flat and elongated particle shape in accordance with ASTM C 136. Specific gravity and absorption of coarse aggregate were determined in accordance with ASTM C 127. Specific gravity and absorption of the fine aggregate were determined in accordance with ASTM C 128. Since there was insufficient fine aggregate ordered to complete the low strength mix design, a new load from the same source was ordered and tested. Test results for all aggregates are listed in Table 2.

Table 1. Chemical and Physical Test Results of Cement.

Sample No.	
SiO_2, percent	21.50
Al_2O_3, percent	4.50
Fe_2O_3, percent	2.50
CaO, percent	63.20
MgO, percent	3.90
SO_3, percent	2.40
Loss on ignition, percent	0.60
Insoluble residue, percent	0.11
Na_2O, percent	0.05
K_2O, percent	0.79
Alkalies-total as Na_2O, percent	0.57
TiO_2	0.17
P_2O_5	0.02
C_3S, percent	52.00
C_3A, percent	8.00
C_2S, percent	22.00
$C_3A + C_3S$, percent	60.00
C_4AF, percent	7.00
$C_4AF + 2\ C_3A$, percent	24.00
Surface area, m^2/kg(AP) or sqm/kg(AP)	385.00
Air content, percent	9.00
Comp. strength, 3 D, psi	3,240.00
Comp. strength, 7 D, psi	4,340.00
Autoclave exp., percent	0.12
Initial set, min (Gillmore)	155.00
Final set, min (Gillmore)	310.00

Mix proportioning. Three concrete mixtures were proportioned with the intentions of covering a range of 75 percent of the 650 psi target flexural strength (i.e., 0.75 × 650 = 487.5, say 490; therefore range of 650 ± 245 psi). This was based on the recommendation of ACI 214.1R, "Use of Accelerated Strength Testing," which is normally applied to compressive strength testing. The water-cement ratio was used to adjust the strength of each mixture. The labeling of A, B, and C was applied to batch numbers (i.e., 1A,

Table 2. Test Results for Aggregates (a) Gradation (b) Physical Properties.

(a) Gradation

Coarse Aggregate		Fine Aggregate		
Sieve Size	Cumulative Percent Passing (Mixtures A, B, and C)	Sieve Size	Cumulative Percent Passing (Mixtures A and B)	Cumulative Percent Passing (Mixture C)
1-1/2	100	3/8	100	100
1	100	4	94	95
3/4	91	8	83	83
1/2	49	16	76	75
3/8	31	30	63	63
No. 4	10	50	9	23
No. 8	2	100	1	4

(b) Physical Properties

	Coarse	Fine (A and B)	Fine (C)
Specific gravity	2.74	2.62	2.60
Absorption, percent	0.33	0.80	1.10
Fineness modulus	--	2.74	2.57

2A, etc.) for high, mid, and low strength mixtures, respectively. Air entraining admixture (AEA) was used to maintain an air content of 6 ± 1 percent. Proportions were made to allow a design slump of not greater than 1-1/2 in. Mixture proportions are included in Table 3.

Properties of fresh concrete. As a part of quality control, the slump, air content, and unit weight of each batch was checked (ASTM C 143, ASTM C 231, and ASTM C 138, respectively) and found to satisfy specifications. The determined values are listed in Table 4.

Preparation and Testing of Specimens

Thirty batches of 14 cu ft each were mixed in accordance with ASTM C 192, "Making and Curing Test Specimens in the Laboratory." The revolving mixer was pre-wet prior to addition of dry materials. Coarse aggregate was added first followed by AEA, fine aggregate, cement, and water with the mixer running. After all ingredients were added, the concrete was mixed for at least 3 minute minimum followed by a 3 minute rest and then a final 2 minute mix. A representative sample was taken by tilting the revolving mixer into a forklift-supported pan. Fifteen beams and twenty-one cylinders (fifteen cylinders for first three high strength mixtures) were cast from each batch. Internal vibration was used for consolidation on all specimens and the beams were struck with a finishing trowel.

Disposable 6 × 12 in. plastic cylinders and lids were used for splitting tensile and compressive strength samples. Additional caution was taken by taping the lids to the cylinders at the interface. Steel 6 × 6 × 24 in. beam molds were used for flexural strength samples. The beam molds were lubricated to facilitate removal of cured specimens. Caulking was used to seal all permeable seams. Clear plexiglass covers were cut to fit the top of beam molds and were secured with dead weights.

Twelve beams and fifteen cylinders were subjected to standard moist curing at 73.4 ± 3° F. The other three beams and six cylinders were placed in a warm water bath for 23-1/2 hr ± 30 minute. The cylinders could be handled by one man, but the beams required two men placing a rope around each end. The warm water bath was kept at 95 ± 5° F using a heating element with a thermostat probe and circulating pump. Insulation board was placed over the water bath accelerated curing tank located in an insulated room. Temperature for both standard and accelerated cure rooms was checked daily.

Flexural strength testing was performed using ASTM C 78. Splitting tensile strength was performed using ASTM C 496. Compressive strength testing was performed using ASTM C 39.

Test Results and Their Analyses

Flexural, splitting tensile, and compressive strength test results are provided in Tables 5,

Table 3. Mixture Proportions (Cubic Yard).

Mixture	A	B	C
Cement (lb)	575.0	448.0	331.9
Fine aggregate (lb)	1,288.8	1,371.6	1,469.1
Coarse aggregate (lb)	1,861.3	1,901.5	1,877.7
Air entraining agent (oz.)	11.5	5.4	4.0
Water (lb)	130.0	224.0	232.3
Mixture Data			
Water/cement	0.40	0.50	0.70
Sand/aggregate (percent)	42.0	43.0	45.0

Table 4. Slump, Air Content, and Unit Weight for Each Batch.

Mix	Slump (inches)	Air Content (% by Volume)	Unit Weight (lb/ft^3)
1A	1.25	5.8	--
2A	1.00	6.0	146.0
3A	1.25	6.4	144.0
4A	1.00	6.2	146.4
5A	1.00	5.8	147.6
6A	1.00	5.6	148.8
7A	0.75	5.2	147.2
8A	0.75	5.0	148.0
9A	1.00	5.8	146.8
10A	1.00	5.8	148.8
1B	1.00	6.4	146.0
2B	1.00	6.4	146.0
3B	1.25	5.6	146.0
4B	1.00	5.5	146.0
5B	1.00	6.5	144.0
6B	1.25	5.4	147.2
7B	1.00	6.0	147.2
8B	1.00	5.8	148.0
9B	1.25	6.2	143.6
10B	0.75	5.8	146.4
1C	0.75	5.5	145.6
2C	1.00	5.6	146.0
3C	1.00	6.4	144.0
4C	0.75	6.5	144.0
5C	0.75	6.4	144.0
6C	0.75	5.8	145.6
7C	1.00	6.3	144.0
8C	1.00	6.1	144.8
9C	1.00	6.5	144.4
10C	1.00	6.8	143.6

6, and 7, respectively (1A represents the accelerated test while 1N, 14, 28, and 90 denote age in days of the standard cure test). Flexural and splitting tensile values are rounded to the nearest 5 psi and compressive strength values are rounded to the nearest 10 psi in accordance with ASTM procedures. Average accelerated strength overall coefficient of variation (COV) was 7.8, 5.8, and 8.6 percent for flexural, splitting tensile, and compressive strength, respectively. The average overall COV's for 28- and 90-day flexural strengths in this study were 4.1 and 3.9 percent, respectively. The "(n - 1)" denominator is used to calculate "TSTD DEV" (true standard deviation (TSTD DEV) and coefficient of variation (COV) instead of "n" to get a better estimate (i.e., small sample correction). Average within-test (batch) COV was also calculated. The variation in strength of concrete within a single test is found by computing the variation of a group of specimens fabricated from a sample of concrete taken from a single batch. Results are provided in Table 8. Based on ACI-214 standards (12) (applicable to compressive strength only) for overall standard deviation and within-test COV, the class of laboratory operation was good to excellent.

Figures 1 through 14 provide data plots, regression equations, and coefficients of determination (R^2) for the respective regressive equations. Linear regression equations were chosen for this analysis.

Discussion of Test Results

One of the first observations that was made in the test results was the similarity of the 1-day standard and accelerated cure flexural

Table 5. Flexural Strength Test Results (psi).

Mix	Flexural Strength Tests 1A	1N	14	28	90
1A	540	540	780	875	870
2A	525	525	790	815	835
3A	495	435	745	780	775
4A	475	450	800	770	835
5A	480	480	805	845	845
6A	570	505	795	820	885
7A	600	540	860	885	925
8A	475	460	695	860	855
9A	500	485	780	805	830
10A	545	530	815	820	830
1B	435	430	690	710	720
2B	375	360	680	695	725
3B	365	360	680	675	765
4B	395	395	710	680	740
5B	395	370	660	685	680
6B	415	405	725	730	735
7B	395	385	685	715	705
8B	415	380	710	715	710
9B	435	375	625	720	705
10B	450	435	730	760	780
1C	245	200	515	565	545
2C	245	195	525	595	575
3C	260	200	540	590	580
4C	280	195	525	590	560
5C	275	240	525	570	585
6C	245	245	540	605	590
7C	285	280	515	585	580
8C	275	250	545	590	600
9C	315	230	575	590	550
10C	250	220	530	525	570
MEAN A	520.5	495	786.5	827.5	845.5
COUNT	10	10	10	10	10
STD DEV A	40.77070	36.67424	41.23408	36.41771	37.61980
TSTD DEV A	42.97609	38.65804	43.46454	38.38764	39.65476
COVA	8.256693	7.809706	5.526324	4.638990	4.673513
MEAN B	407.5	389.5	689.5	708.5	726.5
COUNT	10	10	10	10	10
STD DEV B	26.00480	25.34265	29.95413	24.5	28.28869
TSTD DEV B	27.41147	26.71350	31.37442	25.82526	29.81889
COVB	6.726742	6.858408	4.579322	3.645062	4.104459
MEAN C	267.5	225.5	533.5	580.5	573.5
COUNT	10	10	10	10	10
STD DEV C	21.70829	27.15234	16.88934	21.5	16.59066
TSTD DEV C	22.88255	28.62108	17.80293	22.66298	17.48809
COVC	8.554224	12.69227	3.337007	3.904046	3.049362
AVC COV	7.845886	9.120130	4.480884	4.062699	3.942444

Table 6. Splitting Tensile Strength Test Results (psi).

	Splitting Tensile Strength Tests				
Mix	1A	1N	14	28	90
1A	320	290	475	515	415
2A	325	320	450	445	485
3A	795	285	460	430	420
4A	305	280	460	460	440
5A	310	270	480	405	485
6A	320	285	435	385	485
7A	355	330	425	455	475
8A	340	325	450	480	485
9A	315	265	440	425	500
10A	350	310	420	455	525
1B	260	240	400	445	415
2B	275	205	395	400	430
3B	265	245	350	450	445
4B	280	235	445	465	435
5B	250	230	380	420	520
6B	265	255	455	455	450
7B	265	240	425	375	460
8B	290	260	365	450	405
9B	265	255	415	355	375
10B	270	270	410	385	410
1C	155	130	305	370	375
2C	140	110	280	345	355
3C	145	120	285	335	315
4C	150	135	280	330	375
5C	145	120	340	345	395
6C	145	125	325	355	395
7C	175	135	295	365	380
8C	145	115	320	380	330
9C	160	150	320	375	370
10C	165	130	295	325	340
MEAN A	323.5	296	449.5	445.5	471.5
COUNT	10	10	10	10	10
STD DEV A	18.44586	22.22611	18.90105	35.17456	33.54474
TSTD DEV A	19.44365	23.42837	19.92346	37.07724	35.35926
COVA	6.010402	7.914992	4.432361	8.322614	7.499314
MEAN B	268.5	243.5	404	420	434.5
COUNT	10	10	10	10	10
STD DEV B	10.5	17.32772	31.60696	36.81032	37.04389
TSTD DEV B	11.06797	18.26502	33.31666	38.80148	39.04769
COVB	4.122149	7.501036	8.246698	9.238449	8.986810
MEAN C	152.5	127	304.5	352.5	363
COUNT	10	10	10	10	10
STD DEV C	10.54751	11	19.80530	18.47295	25.80697
TSTD DEV C	11.11805	11.59501	20.87662	19.47220	27.20294
COVC	7.290526	9.129935	6.856033	5.524029	7.493923
AVC COV	5.807692	8.181988	6.511697	7.695031	7.993349

Table 7. Compressive Strength Test Results (psi).

	Compressive Strength Tests			
Mix	1A	90	A1/2C	A2/3C
1A				
2A				
3A				
4A	3,180	5,700	56.39148	216.2476
5A	3,130	6,250	55.94640	213.9749
6A	3,200	6,090	56.56854	217.1534
7A	3,800	6,390	61.64414	243.5131
8A	3,200	6,430	56.56854	217.1534
9A	3,110	6,030	55.76737	213.0624
10A	3,770	6,350	61.40032	242.2297
1B	2,520	5,130	50.19960	185.1826
2B	2,370	5,130	48.68264	177.7592
3B	2,130	4,940	46.13192	165.5463
4B	2,230	5,610	47.22287	170.6880
5B	2,090	5,220	43.71651	163.4672
6B	2,200	5,580	46.90415	169.1538
7B	2,360	5,540	48.57983	177.2588
8B	2,510	5,630	50.09990	184.6924
9B	2,180	5,330	46.69047	168.1270
10B	2,780	5,660	52.72570	197.7105
1C	1,160	3,740	34.05877	110.4007
2C	1,190	3,700	34.49637	112.2960
3C	1,320	3,580	36.33180	120.3324
4C	1,300	3,760	36.05551	119.1138
5C	1,340	3,940	36.60601	121.5448
6C	1,190	3,870	34.49637	112.2960
7C	1,350	3,860	36.74234	122.1487
8C	1,280	3,730	35.77708	117.8890
9C	1,290	3,810	35.91656	118.5022
10C	1,060	3,480	32.55764	103.9610
MEAN A	3,341.428	6,177.142	57.75523	223.3335
COUNT	7	7	7	7
STD DEV A	282.4094	239.4466	2.399702	12.44393
TSTD DEV A	305.0370	258.6319	2.591975	13.44099
COVA	9.128942	4.186918	4.487860	6.018348
MEAN B	2,337	5,377	48.29736	175.9586
COUNT	10	10	10	10
STD DEV B	204.9414	246.1727	2.089196	10.19464
TSTD DEV B	216.0272	259.4888	2.202206	10.74609
COVB	9.243785	4.825903	4.559682	6.107172
MEAN C	1,248	3,747	35.30384	115.8485
COUNT	10	10	10	10
STD DEV C	89.08422	130.7707	1.279916	5.570861
TSTD DEV C	93.90302	137.8445	1.349150	5.872203
COVC	7.524280	3.678796	3.821539	3.068864
AVC COV	8.632336	4.230539	4.289694	5.731461

Table 8. Average Within Test (Batch) COV.

Strength Test	1A	1N	14	28	90
Flexural	5.194	7.206	4.897	3.961	3.520
Splitting tensile	6.541	8.536	9.138	9.026	8.875
Compressive	2.521	--	--	--	2.011

Figure 1. 1-Day accelerated versus 90-day flexural strength.

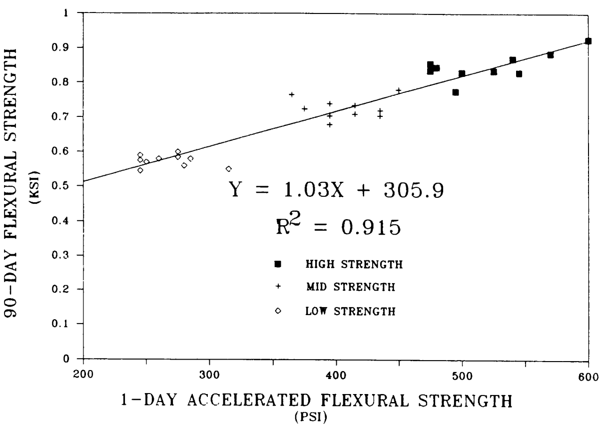


Figure 2. 1-Day accelerated splitting tensile strength versus 90-day flexural strength.

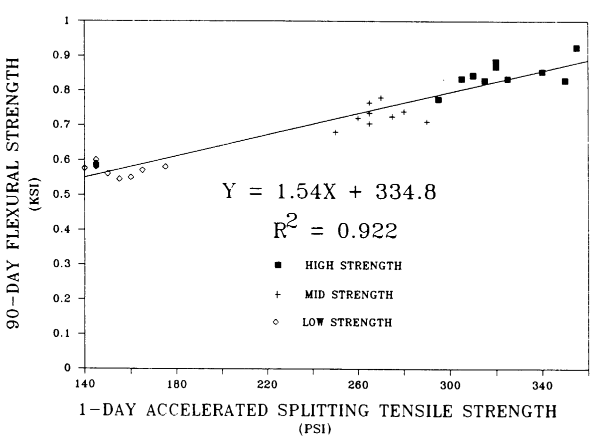


Figure 3. 1-Day accelerated compressive strength versus 90-day flexural strength.

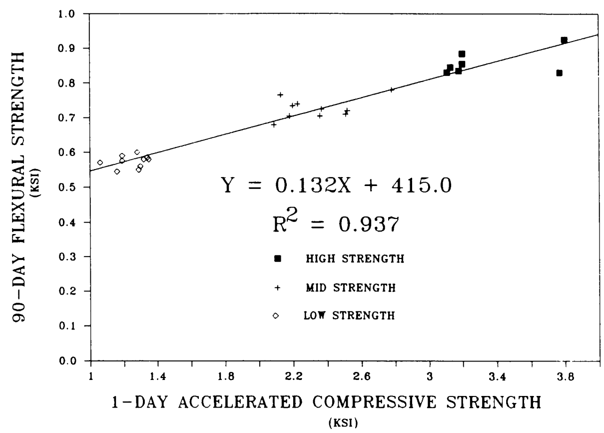


Figure 4. Square root of 1-day accelerated compressive strength versus 90-day flexural strength.

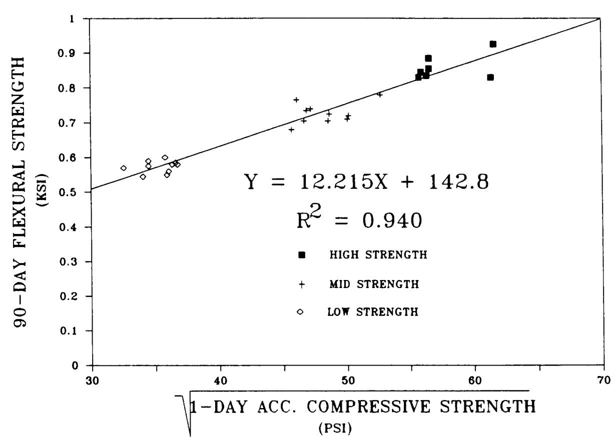


Figure 5. 2/3 Root of 1-day accelerated compressive strength versus 90-day flexural strength.

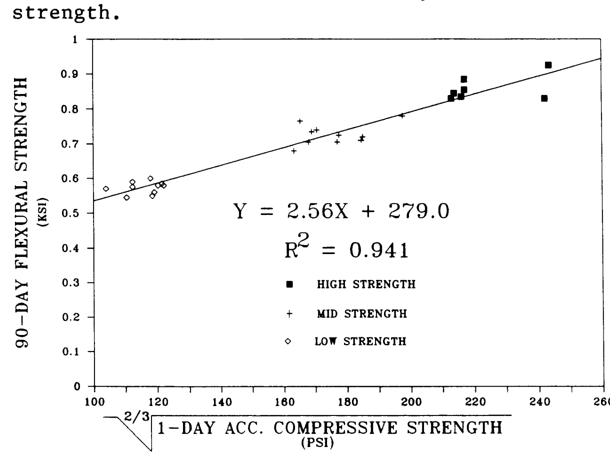


Figure 6. 1-Day accelerated versus 28-day flexural strength.

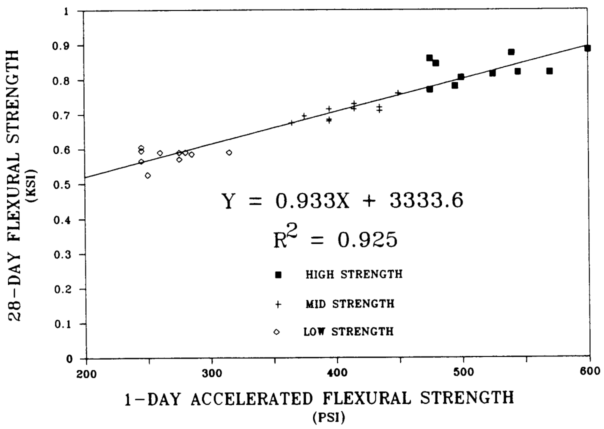


Figure 7. 1-Day accelerated splitting tensile strength versus 28-day flexural strength.

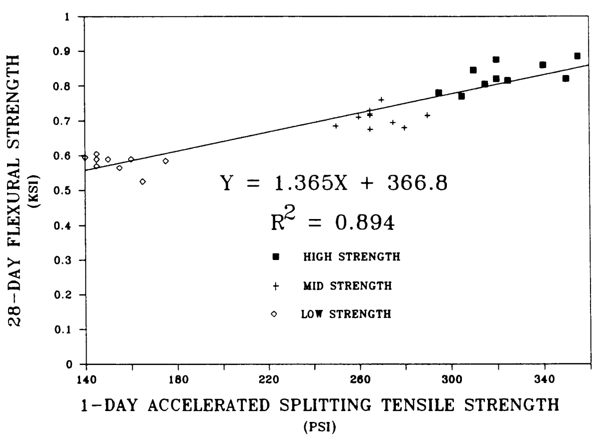


Figure 8. 1-Day accelerated compressive strength versus 28-day flexural strength.

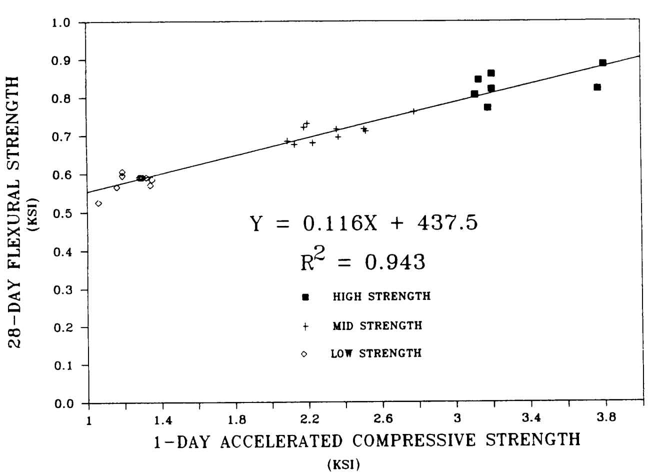


Figure 9. Square root of 1-day accelerated compressive strength versus 28-day flexural strength.

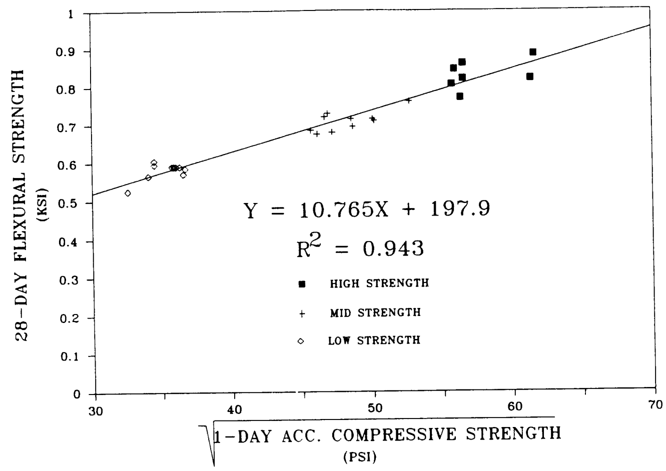


Figure 10. 2/3 Root of 1-day accelerated compressive strength versus 28-day flexural strength.

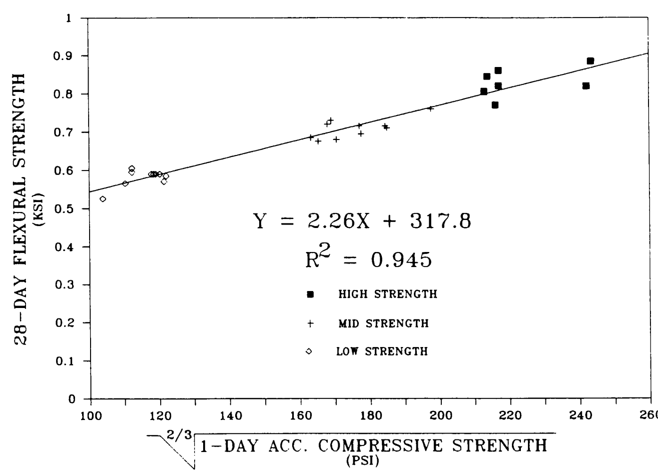


Figure 11. 14-Day flexural versus 90-day flexural strength.

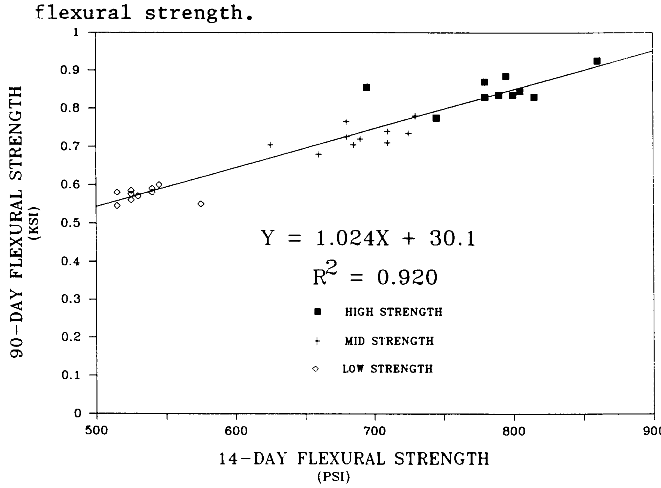


Figure 12. 14-Day flexural versus 28-day flexural strength.

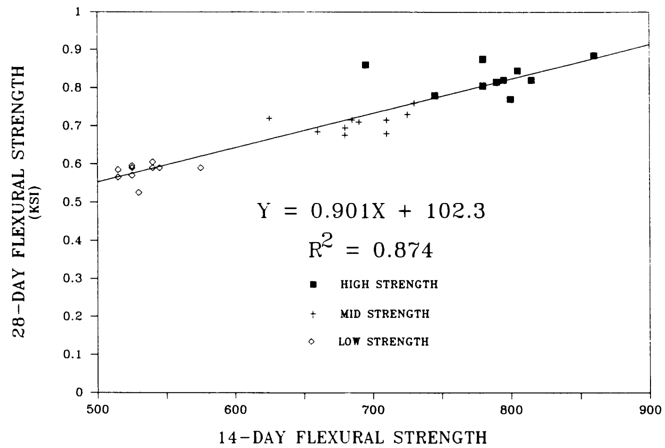


Figure 13. 14-Day splitting tensile versus 90-day flexural strength.

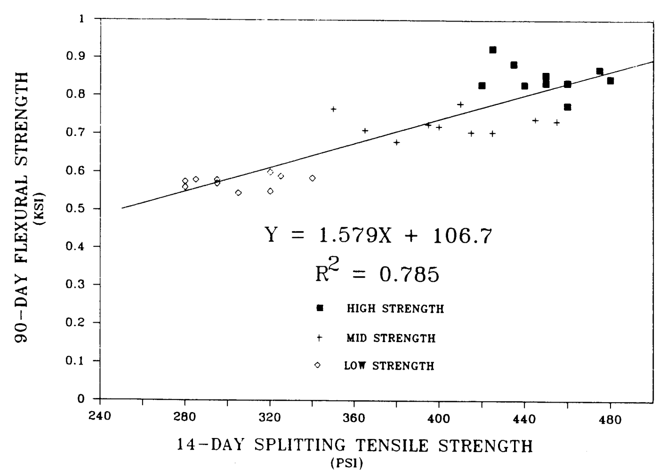
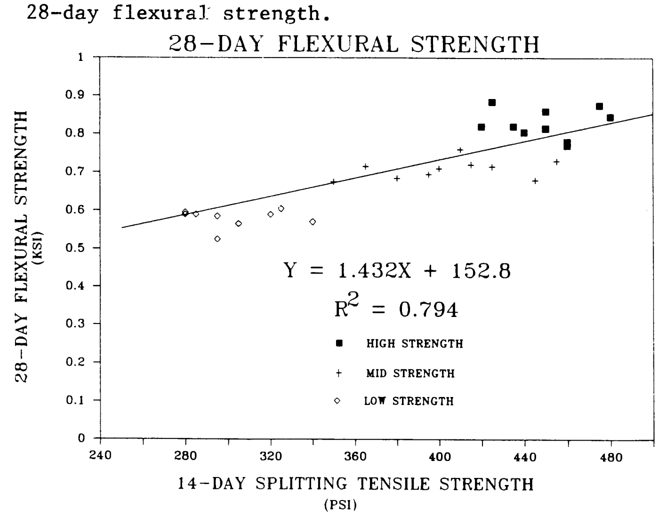


Figure 14. 14-Day splitting tensile versus 28-day flexural strength.



strength test results. The accelerated cure provides only a 5 percent strength increase for the high- and mid-strength mixtures (A and B), but yields a 19 percent increase for the low-strength mixture (C). The difference between 1-day standard and accelerated cure was greater for splitting tensile strength. The accelerated cure was approximately 10 percent greater for the high- and mid-strength mixture while the difference was 20 percent for the low strength mixture. No 1-day standard cure compressive strength samples were prepared for testing and comparison with the accelerated cure samples due to logistical restrictions. In all cases but one, the COV was less for the accelerated cure specimens than for the 1-day standard cure specimens.

The principle objective in simple linear regression is to establish a quantitative relationship between two variables that can be expressed in the form of an equation. Regression equations for all one-day accelerated and 14-day strengths to 28- and 90-day flexural strengths were determined and graphed. In addition, the compressive strength which is typically 6 to 10 times greater than flexural or splitting tensile strength was "squeezed" or compressed by taking the square root and 2/3 root of the accelerated results and performing analysis to the 28- and 90-day flexural strengths. As should be expected, the slopes of 90-day regression lines were greater than for the 28-day regression lines. As can be seen from Figures 1 through 14, all data plots closely follow the regression lines.

The coefficient of determination (R^2) expresses the proportion of the variation in the dependent variable (Y) related to the variation in the independent variable (X). If the R^2 value is 0.985, then you can be 98.5 percent certain that Y is related to X . If the actual and estimated values of Y are identical for every observation in the sample, there is an exact relationship between X and Y , and R^2 value equals 1.0. If R^2 value equal zero (R^2 = 0) then the two variables are unrelated. The coefficient of determination for all regression lines was very good (Table 9). The weakest relationships were found between 14-day splitting tensile and later age flexural strength. Based upon the coefficient of determination for regression equations, the warm water method provides reliability (R^2 = 0.894 to 0.945) equal to if not greater than the 14-day tests (R^2 = 0.785 to 0.920) in predicting 28- and 90-day flexural strength.

Table 9. Summary of Coefficient of Determination (R^2) values for 28- and 90-day Flexural Strength.

Strength Test	R^2 Values for Flexural Strength 28-day	90-day
Acc. flexural	0.925	0.915
Acc. splitting tensile	0.894	0.922
Acc. compressive	0.943	0.937
Sq. Root acc. compressive	0.943	0.940
2/3 Root acc. compressive	0.945	0.941
14 day flexural	0.874	0.920
14 day splitting tensile	0.794	0.785

In previous justifications for using accelerated strength test results for quality assurance, the argument was made that the COV for the accelerated test could be used for acceptance if the COV was equal to or less than the later age (28- and 90-day) COV. As shown by Tables 5-7, only the accelerated splitting tensile strengths had a lower COV than the 28- and 90-day splitting tensile strengths.

Conclusions and Recommendations

Based on standards set by ACI 214, the quality of laboratory operation was good to excellent. From an evaluation of the coefficient of determination (R^2) for regression equations generated in this study, the warm water method provides reliability (R^2 = 0.894 to 0.945) equal to if not greater than the 14-day tests (R^2 = 0.785 to 0.920) in predicting 28- and 90-day flexural strength. Interestingly, by "squeezing" the large values of the compressive strength data we can reduce the accelerated strength COV. This may indicate a peak "root" value can be found to optimize the relationship.

Based on the results of previous studies, differences in the relative effect of aggregate properties (shape, surface texture, modulus of elasticity) on concrete strength testing do not permit a satisfactory general equation to relate accelerated to later age strength results for all mixture designs. Therefore, it is suggested that a relationship based on three water-cement ratios be developed for every new mixture design before being used as an engineering tool.

It seems reasonable to expect strength relationships to show less correlation in the field due to additional variations in proportioning, transporting, specimen fabrications, and testing procedures.(7,13) Hammitt (4) reports that flexural strength COV is typically 15 to 20 percent in the field. COV's generated in this study do not substantiate acceptance of concrete based on accelerated strength results. Suggested use of accelerated strength testing would be as a quality control check in conjunction with slump, air content, and unit weight to determine potential performance of concrete at 1-day during rapid pavement construction instead of using correlated 7- to 14-day flexural strengths. It would seem reasonable that any of the three accelerated strength tests (flexural, splitting tensile, or compressive) could be used to indicate 28- or 90-day flexural strength if the relationship is supported by laboratory testing at a wide strength range based on three water cement ratios. Accelerated strength tests will indicate the potential of concrete flexural strength, but they cannot account for placement, vibration, and curing variations of in-place concrete.

Recommendations for further testing include a twin study which utilizes a slow strength gaining pozzolanic material such as fly ash. A collection of any previous pavement construction work using the warm water method (such as splitting tensile by Sacramento District, USACE) should be made and reported on. Deficiencies in field work should be determined and studies performed, with particular emphasis on the accelerated flexural strength test using ASTM C 684, Procedure A, as a guideline.

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