Publication No. FHWA-RD-91-080
February 1994

Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements

Volume II: Appendix

U.S. Department of Transportation
Federal Highway Administration

Research and Development
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FOREWORD

This report is one of a two-volume set documenting early age (4 to 24 hours) and early loading (1 to 28 days) tests to determine properties of highway concretes. Analyses are made for timing of sawcutting concrete pavement contraction joints and determining the earliest concrete pavement loadings. Correlations are developed for nondestructive tests versus concrete strength properties. Guidelines are developed for earliest "near" sawing time determinable from concrete strength properties and latest "far" sawing needed to avert uncontrolled pavement cracking. Guidelines are presented for earliest loading of new pavements with construction equipment.

Volume I consists of text and test results pertinent to developing correlations between early age concrete strength properties and nondestructive test results. Information, test data, and analysis leading to development of guidelines are provided. Volume II contains listings of test results not included within Volume I, and also includes a review of the state-of-the-art.

This report will be of interest to those involved in the design and construction of jointed concrete pavements. Sufficient copies are being distributed to provide two copies to each FHWA Region, and three copies to each FHWA Division and State highway agency. Direct distribution is being made to the FHWA Division Offices. Additional copies may be purchased from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.

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NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-9 l-080		

4. Title and Subtitle
Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements
Volume II - Appendix

5. Report Date
February 1994

6. Performing Organization Code

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8. Performing Organization Report No.

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)
2E2C1042

11. Contract or Grant No.
DTFH61-88-C-00062

12. Sponsoring Agency Name and Address
Office of Engineering and Highway Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296

13. Type of Report and Period Covered
Final Report
July 1988 -April 1991

14. Sponsoring Agency Code

15. Supplementary Notes
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16. Abstract
A study with the objectives of providing guidelines for timing of contraction joint sawcutting to avert uncontrolled pavement cracking and providing guidelines for early loading of pavements by construction traffic has been conducted. A laboratory study of early age (4 to 24 hours) and early pavement loading (1 to 28 days) concrete strength properties for a range of highway concrete mixes was made. Sawcutting tests were made to determine earliest contraction joint sawcutting. Earliest sawcut timing was correlated on basis of sawcut ratings to concrete strength properties and non-destructive test results that can be used for determining earliest sawcutting time. Concrete pavement placement and joint sawcutting were observed at three highway construction sites to verify test results. Latest sawcutting time was targeted on basis of buildup of restraint stresses attributable to slab cooling. Guidelines for sawcut timing are presented to facilitate construction site decision making based on non-destructive test methods.

Early loading by construction traffic was analyzed using ILLI-SLAB finite element models. Load tests were made at two pavement sites to verify that analytical model results are applicable to new pavements. Guidelines are presented to facilitate construction site decision making for early trafficking of new pavements based on nondestructive test methods.

This is the second of two volumes. The first volume is FHWA-RD-91-079, Guidelines for Timing Construction Joint Sawing and Earliest Loading for Concrete Pavements - Volume I - Final Report.

17. Key Words	18. Distribution Statement
Concrete, concrete strength properties, concrete pavements, contraction joints, sawcutting, restraint stresses, traffic loading, concrete pavement construction, sawcutting guidelines.	No restrictions. This document is available through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	224	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	26.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m*	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m*	candela/m*	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E360.

(Revised September 1993)

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Table 1. Early age (4 to 24 hours) concrete strength.

Test	Cement Content, lb/yd^3	Curing Temp.[1] °F	Crushed Limestone: Testing Age, hours 4	6	9	24	Crushed Quartzite: Testing Age, hours 4	6	9	24	Round River Gravel: Testing Age, hours 4	6	9	24
Compressive Strength, psi	500	50	10	30	80	690	10	10	30	500	10	10	30	700
		72	30	100	310	2400	30	150	470	1860	20	70	280	2180
		100	140	480	1490	2640	70	370	950	2180	70	450	1190	2370
ASTM C39	650	50	20	30	100	1340	10	20	50	806	10	30	90	1560
		72	60	280	970	3980	60	250	770	2560	20	130	500	2920
		100	270	1200	2110	3420	140	710	1590	2646	130	870	2030	2960
Split-Tensile Strength, psi	500	50	0	0	5	110	0	0	5	90	0	0	5	100
		72	5	20	70	290	5	20	75	220	0	5	35	230
		100	30	105	205	270	20	120	210	275	15	70	140	235
ASTM C496	650	50	0	5	15	190	0	0	10	130	0	5	10	165
		72	5	30	115	415	10	45	140	300	5	25	65	255
		100	30	145	235	335	25	140	240	325	10	70	155	235
Flexural Strength, psi	500	50	0	5	35	215	0	0	20	195	0	5	20	195
		72	15	40	125	475	5	50	125	465	0	35	75	315
		100	35	140	255	405	25	135	265	420	20	105	200	355
ASTM C78	650	50	0	15	70	390	0	5	45	310	0	10	45	330
		72	20	95	285	575	10	60	140	460	5	45	130	355
		100	70	240	340	525	55	190	325	485	30	125	205	395

[1] NOTE: At 50% relative humidity.

500 lb/yd^3 = 297 kg/m^3
650 lb/yd^3 = 386 kg/m^3
50°F=10°C, 72°F=22°C, 100°F=38°C

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Table 2. Early age (4 to 24 hours) concrete properties.

Test	Cement Content, lb/yd³	Curing Temp.,[1] °F	Crushed Limestone				Crushed Quartzite				Round River Gravel			
			Testing Age, hours				Testing Age, hours				Testing Age,hours			
			4	6	9	24	4	6	9	24	4	6	9	24
Concrete	500	50	127	177	249	600	124	172	239	581	112	158	226	577
Maturity,		72	192	297	469	1312	204	315	494	1341	179	277	436	1179
OF-hours		100	252	409	655	1743	257	419	661	1740	237	369	626	1666
Nurse-Saul														
(32 °Fdatum)	650	50	137	194	276	674	128	176	247	584	123	172	245	606
		72	209	331	533	1399	199	306	482	1321	161	265	460	1216
ASTM C1074		100	263	434	694	1603	262	434	685	1767	235	402	656	1727
Concrete	500	50	3.53	4.91	6.93	16.61	3.46	4.79	6.70	16.39	3.09	4.40	6.33	16.20
Maturity,'		72	5.84	9.21	15.02	43.27	6.42	10.09	16.32	44.62	5.29	6.30	13.41	36.49
equivalent age		100	9.27	16.46	26.29	73.69	9.67	17.29	28.70	73.35	6.33	15.03	25.91	67.31
hours at 68 °F														
	650	50	3.80	5.37	7.67	16.62	3.57	4.90	6.90	16.46	3.42	4.76	6.82	16.94
ASTM C1074		72	6.65	11.04	16.60	40.46	6.18	9.64	15.72	43.69	5.38	8.70	14.69	38.46
		100	101.09	18.75	32.16	79.62	10.11	18.85	31.17	76.14	6.26	16.50	29.46	73.42
Pulse	500	50	1,300	3.400	3,800	11,300	800	800	4,400	9,900	2,600	2,600	5,600	11,300
Velocity,		72	3,200	6,900	9,800	13,600	2,500	7,700	10,500	12.800	3,300	6,500	9,200	13,300
ft/s		100	7,600	10,500	13,100	13,700	5,600	9,700	12,000	13,100	6,600	10,100	11.800	13,100
ASTM C597	650	50	2,900	3,100	7,900	12,600	800	1,600	4,700	11,000	2,600	3,300	7,200	12,200
		72	6,400	9,800	12,200	14,700	4,300	8,100	11,100	13,400	4,100	7,700	10,400	13,600
		100	9,400	12,400	13,400	14,300	7,000	11,100	12,600	13,600	7,200	11,400	12,800	13,600

500 lb/yd³ = 297 kg/m³
650 lb/yd³ = 386 kg/m³
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C

NOTES: 1 Curing at 50% RH.

2 Activation energy divided by gas constant 5000 °K.

Table 3. Regression analysis of early age modulus of rupture on compressive strength.

Mix	Curing Temp. 1 °F	Testing Age, hours	Comp. Strength, psi	Modulus of Rupture, psi	General Equation* Predicted MR, psi	General Equation* Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	10	0	-15	-15	-18	-18	3
		6	30	5	5	0	3	-2	2
		9	80	35	36	1	35	0	1
500 lb/yd³ Cement		24	690	215	191	-24	196	-19	5
	72	4	30	15	5	-10	3	-12	2
		6	100	40	46	6	45	5	1
		9	310	125	114	-11	116	-9	2
		24	2400	475	395	-80	407	-68	12
	100	4	140	35	62	27	62	27	0
		6	480	140	152	12	156	16	3
		9	1490	255	302	47	311	56	9
		24	2640	405	416	11	429	24	13

500 lb/yd³ = 297 kg/m³
50°F=10°C, 72°F=22°C, 100°F=38°C
100 psi = 0.69 MPa

NOTES: [1] Cured at 50% RH.

[2] General prediction equation MR = 8.95*sqrt(f' c) - 43.6

[3] Mix specific prediction equation MR = 9.29*sqrt(f'c) - 47.8

Table 3. Regression analysis of early age modulus of rupture on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Modulus of Rupture, psi	General Equation' Predicted MR, psi	Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	20	0	-4	-4	-7	-7	4
		6	30	15	5	-10	2	-13	3
650 lb/yd^3 Cement		9	100	70	46	-24	46	-24	1
		24	1340	390	284	-106	305	-85	21
	72	4	60	20	26	6	25	5	1
		6	280	95	106	11	112	17	6
		9	970	265	235	-30	252	-13	17
		24	3980	575	521	-54	562	-13	41
	100	4	270	70	103	33	109	39	6
		6	1200	240	266	26	286	46	20
		9	2110	340	367	27	396	56	28
		24	3420	525	480	-45	518	-7	38

650 lb/yd^3= 386 kg/m^3
50 °F = 10 °C, 72°F = 22°C, 100 °F= 38 °C
100 psi = 0.69 MPa

NOTES: [1] Cured at 50% RH.

[2]General prediction equation MR = 8.95*sqrt(f'c) - 43.6

[3] Mix specific prediction equation MR = 9.72*sqrt(f'c) - 50.7

Table 3. Regression analysis of early age modulus of rupture on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quattzite	50	4	10	0	-15	-15	-33	-33	17
		6	10	0	-15	-15	-33	-33	17
		9	30	20	5	-15	-7	-27	12
500 lb/yd^3 Cement		24	500	195	156	-39	179	-16	23
	72	4	30	5	5	0	-7	-12	12
		6	150	50	66	16	68	18	2
		9	470	125	150	25	172	47	22
		24	1860	465	342	-123	409	-56	67
	100	4	70	25	31	6	25	0	6
		6	370	135	128	-7	145	10	3
		9	950	265	232	-33	273	8	25
		24	2180	420	374	-46	448	28	18

500 lb/yd^3= 297 kg/m^3
50°F=10°C,72°F=22°C,100°F=38°C
100 psi = 0.69 MPa

NOTES: [1] Cured at 50% RH.

[2] General prediction equation MR = 8.95*sqrt(f'c) - 43.6

[3] Mix specific prediction equation MR = 11.04*sqrt(f'c) - 67.5

Table 3. Regression analysis of early age modulus of rupture on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Modulus of Rupture, psi	General Equation' Predicted MR, psi	General Equation' Prediction Error, psi	Mix Specific' Predicted MR, psi	Mix Specific' Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	10	0	-15	-15	-22	-22	7
		6	20	5	-4	-9	-9	-14	6
		9	50	45	20	-25	16	-29	3
650 lb/yd^3 Cement		24	800	310	209	-101	225	-85	16
	72	4	60	10	26	16	23	13	3
		6	250	60	98	38	102	42	5
		9	770	140	205	65	220	80	15
		24	2560	460	409	-51	445	-15	36
	100	4	140	55	62	7	63	8	1
		6	710	190	195	5	209	19	14
		9	1590	325	313	-12	340	15	3
		24	2840	485	433	-52	472	-13	39

650 lb/yd^3= 386 kg/m^3
50°F=10°C,72°F=22°C,100°F=38°C
100 psi = 0.69 MPa

NOTES: 1Cured at 50% RH.

'General prediction equation MR = 8.95*sqrt(f'c) - 43.6

3 Mix specific prediction equation MR = 9.85*sqrt(f'c) - 53.3

Table 3. Regression analysis of early age modulus of rupture on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel	50	4	10	0	-15	-15	-8	-8	8
		6	10	5	-15	-20	-8	-13	8
		9	30	20	5	-15	10	-10	4
500 lb/yd³ Cement		24	700	195	193	-2	167	-28	26
	72	4	20	0	-4	-4	2	2	2
		6	70	35	31	-4	31	-4	0
		9	280	75	106	31	94	19	12
		24	2180	315	374	59	318	3	56
	100	4	70	20	31	11	31	11	0
		6	450	105	146	41	127	22	19
		9	1190	200	265	65	227	27	38
		24	2370	355	392	37	333	-22	15

500 lb/yd^3 = 297 kg/m^3
50°F=10°C, 72°F=22°C, 100 °F=38 °C
100 psi = 0.69 MPa

NOTES: [1] Cured at 50% RH.

[2] General prediction equation MR = 8.95*sqrt(f'c) - 43.6

[3] Mix specific prediction equation MR = 7.49*sqrt(f'c) - 31.4

Table 3. Regression analysis of early age modulus of rupture on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	General Equation[2] Prediction Error, psi	Mix Specific 3 Predicted MR psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel	50	4	10	0	-15	-15	-11	-11	4
		6	30	10	5	-5	5	-5	0
		9	90	45	41	-4	34	-11	7
650 lb/yd³ Cement		24	1560	330	310	-20	250	-80	60
	72	4	20	5	-4	-9	-2	-7	2
		6	130	45	58	13	48	3	11
		9	500	130	156	26	126	-4	23
		24	2920	355	440	85	354	-1	84
	100	4	130	30	58	28	48	18	11
		6	870	125	220	95	178	53	43
		9	2030	205	359	154	289	84	70
		24	2960	395	443	48	357	-38	10

650 lb/yd³= 386 kg/m³
50°F=10°C,72°F=22°C,100°F=38°C
100 psi = 0.69 MPa

NOTES: [1]Cured at 50% RH.

[2] General prediction equation MR = 8.95*sqrt(f'c) - 43.6

[3] Mix specific prediction equation MR = 7.18*sqrt(f'c) - 34.2

Table 4. Regression analysis of early age modulus of rupture on splitting tensile strength.

Mix	Curing Temp.,[1] °F	Testing Age, hours	Splitting Tensile Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	0	0	13	13	8	8	6
		6	0	5	13	8	8	3	6
500 lb/yd ^{3}		9	5	35	21	-14	15	-20	6
Cement		24	110	215	176	-39	171	-44	4
	72	4	5	15	21	6	15	0	6
		6	20	40	43	3	37	-3	0
		9	70	125	117	-8	112	-13	5
		24	290	475	442	-33	439	-36	2
	100	4	30	35	58	23	52	17	5
		6	105	140	168	28	164	24	4
		9	205	255	316	61	313	58	3
		24	270	405	412	7	410	5	3

500 lb/yd ^{3} = 297 kg/m ^{3}
50 °F = 10 °C, 72°F = 22 °C, 100°F = 38 °C
100 psi = 0.69 MPa

NOTES: [1] Cured at 50% RH.

[2] General prediction equation MR = 1.48*ST + 13.3

[3] Mix specific prediction equation MR = 1.49*ST + 7.7

Table 4. Regression analysis of early age modulus of rupture on splitting tensile strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Splitting Tensile Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted MR psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	0	0	13	13	38	38	25
		6	5	15	21	6	45	30	25
		9	15	70	35	-35	59	-11	24
650 lb/yd³ Cement		24	190	390	294	-96	306	-84	12
	72	4	5	20	21	1	45	25	25
		6	30	95	58	-37	81	-14	23
		9	115	265	183	-82	201	-64	17
		24	415	575	627	52	624	49	3
	100	4	30	70	58	-12	81	11	2
		6	145	240	228	-12	243	3	9
		9	235	340	361	21	370	30	9
		24	335	525	508	-17	511	-14	3

650 lb/yd³ = 386 kg/m³
50°F=10°C, 72°F=22°C, 100°F=38°C
100 psi = 0.69 MPa

NOTES: [1]Cured at 50% RH.

[2]General prediction equation MR = 1.48*ST + 13.3

[3] Mix specific prediction equation MR = 1.41*ST + 38.3

Table 4. Regression analysis of early age modulus of rupture on splitting tensile strength (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Splitting Tensile Strength, psi	Modulus of Rupture, psi	General Equation 2 Predicted MR, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted MR, psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	0	0	13	13	6	6	8
		6	0	0	13	13	6	6	8
		9	5	20	21	1	14	-6	6
500 lb/yd³ Cement		24	90	195	146	-49	148	-47	2
	72	4	5	5	21	16	14	9	7
		6	20	50	43	-7	37	-13	5
		9	75	125	124	-1	125	0	0
		24	220	465	338	-127	354	-111	16
	100	4	20	25	43	18	37	12	5
		6	120	135	191	56	196	61	5
		9	210	265	324	59	338	73	15
		24	275	420	420	0	441	21	21

500 lb/yd³ = 297 kg/m³
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C
100 psi = 0.69 MPa

NOTES: [1]Cured at 50% RH.

[2]General prediction equation MR = 1.48*ST + 13.3

[3]Mix specific prediction equation MR = 1.58*ST + 5.8

Table 4. Regression analysis of early age modulus of rupture on splitting tensile strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Splitting Tensile Strength, psi	Modulus of Rupture, psi	General Equation'[2] Predicted MR, psi	General Equation'[2] Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	0	0	13	13	9	9	5
		6	0	5	13	8	9	4	5
		9	10	45	28	-17	23	-22	5
650 lb/yd³ Cement		24	130	310	205	-105	197	-113	8
	72	4	10	10	28	18	23	13	5
		6	45	60	80	20	74	14	6
		9	140	140	220	80	212	72	8
		24	300	460	457	-3	444	-16	13
	100	4	25	55	50	-5	45	-10	5
		6	140	190	220	30	212	22	8
		9	240	325	368	43	357	32	11
		24	325	485	494	9	480	-5	4

650 lb/yd^3 = 386 kg/m^3
50°F=10°C, 72°F= 22°C,100°F=38°C
100 psi = 0.69 MPa

NOTES: [1]Cured at 50% RH.

[2]General prediction equation MR = 1.48*ST + 13.3

[3] Mix specific prediction equation MR = 1.45*ST + 8.8

Table 4. Regression analysis of early age modulus of rupture on splitting tensile strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Splitting Tensile Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel 500 lb/yd^3 Cement	50	4	0	0	13	13	12	12	1
		6	0	5	13	8	12	7	1
		9	5	20	21	1	19	-1	0
		24	100	195	161	-34	153	-42	8
	72	4	0	0	13	13	12	12	1
		6	5	35	21	-14	19	-16	2
		9	35	75	65	-10	61	-14	4
		24	230	315	353	38	337	22	16
	100	4	15	20	35	15	33	13	2
		6	70	105	117	12	111	6	6
		9	140	200	220	20	210	10	10
		24	235	355	361	6	345	-10	5

500 lb/yd^3 = 297 kg/m^3
50 °F = 10 °C, 72 °F = 22 °C 100 °F = 38 °C
100 psi = 0.69 MPa

NOTES: [1]Cured at 50% RH.

[2]General prediction equation MR = 1.48*ST + 13.3

[3]Mix specific prediction equation MR = 1.42*ST + 12.0

Table 4. Regression analysis of early age modulus of rupture on splitting tensile strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Splitting Tensile Strength, psi	Modulus of Rupture, psi	General Equation[2] Predicted MR, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted MR, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel	50	4	0	0	13	13	10	10	3
		6	5	10	21	11	18	8	3
		9	10	45	28	-17	25	-20	3
650 lb/yd^3 Cement		24	165	330	257	-73	261	-69	4
	72	4	5	5	21	16	18	13	3
		6	25	45	50	5	48	3	2
		9	85	130	139	9	140	10	1
		24	255	355	390	35	398	43	8
	100	4	10	30	28	-2	25	-5	3
		6	70	125	117	-8	117	-8	0
		9	155	205	242	37	246	41	4
		24	235	395	361	-34	368	-27	7

650 lb/yd^3 = 386 kg/m^3
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C
100 psi = 0.69 MPa

NOTES: [1] Cured at 50% RH.

[2] General prediction equation MR = 1.48*ST + 13.3

[3] Mix specific prediction equation MR = 1.52*ST + 10.1

Table 5. Regression analysis of early age splitting tensile on compressive strength.

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Splitting Tensile Strength, psi	General Equation [2] Predicted ST, psi	General Equation [2] Prediction Error, psi	Mix Specific[3] Predicted ST, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	10	0	-17	-17	-17	-17	0
		6	30	0	-4	-4	-3	-3	1
		9	80	5	17	12	19	14	2
500 lb/yd^3 Cement		24	690	110	120	10	126	16	6
	72	4	30	5	-4	-9	-3	-8	1
		6	100	20	23	3	25	5	2
		9	310	70	69	-1	73	3	1
		24	2400	290	255	-35	268	-22	13
	100	4	140	30	34	4	37	7	2
		6	480	105	94	-11	99	-6	5
		9	1490	205	193	-12	203	-2	10
		24	2640	270	269	-1	283	13	12

500 lb/yd^3= 297 kg/m^3
50°F=10°C,72°F=22°C,100°F=38°C
100 psi = 0.69 MPa

NOTES:

[1] Cured at 50% RH.

[2] General prediction equation ST = 5.94*sqrt(f'c) - 36.1

[3] Mix specific prediction equation ST = 6.22*sqrt(f'c) - 36.9

Table 5. Regression analysis of early age splitting tensile on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Splitting Tensile Strength, psi	General Equation[2] Predicted ST, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted ST, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone 650 lb/yd³ Cement	50	4	20	0	-9	-9	-29	-29	20
		6	30	5	-4	-9	-22	-27	19
		9	100	15	23	8	8	-7	2
		24	1340	190	181	-9	188	-2	6
	72	4	60	5	10	5	-7	-12	7
		6	280	30	63	33	54	24	10
		9	970	115	149	34	151	36	2
		24	3980	415	339	-76	366	-49	27
	100	4	270	30	62	32	52	22	10
		6	1200	145	170	25	174	29	5
		9	2110	235	237	2	251	16	14
		24	3420	335	311	-24	335	0	23

650 lb/yd³ = 386 kg/m³
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C
100 psi = 0.69 MPa

NOTES: [1]Cured at 50% RH.

[2]General prediction equation ST = 5.94*sqrt(f'c) - 36.1

[3] Mix specific prediction equation ST = 6.74*sqrt(f'c) - 59.2

Table 5. Regression analysis of early age splitting tensile on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Splitting Tensile Strength, psi	General Equation[2] Predicted ST, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted ST, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite 500 lb/yd³ Cement	50	4	10	0	-17	-17	-10	-10	7
		6	10	0	-17	-17	-10	-10	7
		9	30	5	-4	-9	4	-1	8
		24	500	90	97	7	111	21	14
	72	4	30	5	-4	-9	4	-1	8
		6	150	20	37	17	47	27	11
		9	470	75	93	18	107	32	14
		24	1860	220	220	0	242	22	22
	100	4	70	20	14	-6	23	3	4
		6	370	120	78	-42	91	-29	13
		9	950	210	147	-63	165	-45	18
		24	2180	275	241	-34	265	-10	24

500 lb/yd³ = 297 kg/m³
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C
100 psi = 0.69 MPa

NOTES:
1 Cured at 50% RH.

2 General prediction equation ST = 5.94*sqrt(f'c) - 36.1

3 Mix specific prediction equation ST = 6.32*sqrt(f' c) - 30.2

Table 5. Regression analysis of early age splitting tensile on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Splitting Tensile Strength, psi	General Equation[2] Predicted ST, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted ST, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	10	0	-17	-17	-19	-19	2
		6	20	0	-9	-9	-11	-11	1
650 lb/yd^3 Cement		9	50	10	6	-4	7	-3	1
		24	800	130	132	2	146	16	14
	72	4	60	10	10	0	11	1	1
		6	250	45	58	13	64	19	6
		9	770	140	129	-11	143	3	8
		24	2560	300	265	-35	293	-7	29
	100	4	140	25	34	9	38	13	4
		6	710	140	122	-18	135	-5	13
		9	1590	240	201	-39	223	-17	22
		24	2840	325	281	-44	311	-14	30

650 lb/yd^3 = 386 kg/m^3
50°F=10°C, 72°F=22°C, 100°F=38°C
100 psi = 0.69 MPa

NOTES:
[1] Cured at 50% RH.

[2] General prediction equation ST = 5.94*sqrt(f'c) - 36.1

[3] Mix specific prediction equation ST = 6.59*sqrt(f'c) - 40.1

Table 5. Regression analysis of early age splitting tensile on compressive strength (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Comp. Strength, psi	Splitting Tensile Strength, psi	General Equation[2] Predicted ST, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted ST, psi	Mix Specific[3] Prediction Error, psi	Difference of Absoulute Errors, psi
Rounded Gravel	50	4	10	0	**-17**	-17	-13	-13	4
		6	10	0	-17	-17	-13	-13	4
		9	30	5	-4	-9	-1	-6	3
500 lb/yd^3 Cement		24	700	100	121	21	109	9	12
	72	4	20	0	-9	-9	-6	-6	3
		6	70	5	14	9	14	9	1
		9	280	35	63	28	58	23	5
		24	2180	230	241	11	215	-15	4
	100	4	70	15	14	-1	14	-1	‘1
		6	450	70	90	20	81	11	9
		9	1190	140	169	29	151	11	18
		24	2370	235	253	18	225	-10	9

500 lb/yd^3 = 297 kg/m^3
50°F=10°C, 72°F=22°C, 100°F=38°C
100 psi = 0.69 MPa

NOTES:
1 Cured at 50% RH.

2 General prediction equation ST = 5.94*sqrt(f'c) - 36.1

3 Mix specific prediction equation ST = 5.24*sqrt(f'c) - 29.6

Table 5. Regression analysis of early age splitting tensile on compressive strength (continued).

Mix	Curing Temp.,1 °F	Testing Age, hours	Comp. Strength, psi	Splitting Tensile Strength, psi	General Equation 2 Predicted ST, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted ST, psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel	50	4	10	0	-17	-17	-14	-14	3
		6	30	5	-4	-9	-3	-8	0
		9	90	10	20	10	16	6	4
650 lb/yd3 Cement		24	1560	165	199	34	157	-8	26
	72	4	20	5	-9	-14	-8	-13	2
		6	130	25	32	7	25	0	7
		9	500	85	97	12	76	-9	3
		24	2920	255	285	30	225	-30	1
	100	4	130	10	32	22	25	15	7
		6	870	70	139	69	110	40	29
		9	2030	155	232	77	183	28	48
		24	2960	235	287	52	227	-8	44

650 lb/yd^3 = 386 kg/m^3
50°F=10°C, 72°F=22°C, 100°F=38°C
100 psi = 0.69 MPa

NOTES:
1 Cured at 50% RH.

2 General prediction equation ST = 5.94*sqrt(f'c) - 36.1

3 Mix specific prediction equation ST = 4.71 *sqrt(f'c) - 28.8

Table 6. Linear regression analysis summary of early age strengths (4 to 24 hours) for individual mixes.

Mix	Dependent Variable,' Y	Independent Variable, X	Slope Coefficient, m	y-intercept, b	Coeflicient of Determination, R - sq.	Minimum Prediction Error, [2] psi	Maximum Prediction Error, [2] psi	Average Prediction Error, [2] psi
Crushed Limestone 500 Ib/y^3 Cement	MR	sqrt(f' c)	9.29	-47.8	0.964	0	68	21
	MR	ST	1.49	7.7	0.972	0	58	19
	ST	sqlt(f'c)	6.22	-36.9	0.987	2	22	10
Crushed Limestone 650 lb/yd^3 Cement	MR	sqrt(f'c)	9.72	-50.7	0.966	5	85	27
	MR	ST	1.41	38.3	0.960	3	84	31
	ST	sqrt(f'c)	6.74	-59.2	0.965	0	49	21

NOTES: [1]MR = modulus of rupture in psi, ST = Split tensile strength in psi, and f'c = compressive strength in psi

General equation form Y = mX + b

[2] Statistic based on absolute values of the prediction error.

500 lb/yd^3= 297 kg/m^3
650 lb/yd^3 = 386 kg/m^3
100 psi = 0.69 MPa

Table 6. Linear regression analysis summary of early age strengths (4 to 24 hours) for individual mixes (continued).

Mix	Dependent Variable, [1] Y	Independent Variable, X	Slope Coefficient, m	y-intercept, b	Coefficient of Determination, R - sq.	Minimum Prediction Error, [2] psi	Maximum Prediction Error, [2] psi	Average Prediction Error, [2] psi
Crushed Quartzite 500 lb/yd^3 Cement	MR	sqrt(f'c)	11.04	-67.5	0.969	0	56	24
	MR	ST	1.58	5.8	0.901	0	111	30
	ST	sqft(f'c)	6.32	-30.2	0.945	1	45	18
Crushed Quartzite 550 lb/yd^3 Cement	MR	sqrt(f'c)	9.85	-53.3	0.948	8	85	27
	MR	ST	1.45	8.8	0.941	4	113	31
	ST	sqrt(f'c)	6.59	-40.1	0.985	1	19	21

NOTES: [1] MR = modulus of rupture in psi, ST = Split tensile strength in psi, and f'c = compressive strength in psi

General equation form Y = mX + b

[2] Statistic based on absolute values of the prediction error.

500 lb/yd^3 297 kg/m^3
650 lb/yd = 386 kg/m^3
100 psi = 0.69 MPa

Table 6. Linear regression analysis summary of early age strengths (4 to 24 hours) for individual mixes (continued).

Mix	Dependent Variable,[1] Y	Independent Variable, X	Slope Coefficient, m	y-intercept, b	Coefficient of Determination, R - sq.	Minimum Prediction Error,[2] psi	Maximum Prediction Error,[2] psi	Average Prediction Error,[2] psi
Rounded Gravel 500 lb/yd^3 Cement	MR	sqrt(f'c)	7.49	-31.4	0.980	2	28	14
	MR	ST	1.42	12.0	0.981	1	42	14
	ST	sqrt(f'c)	5.24	-29.6	0.981	1	23	11
Rounded Gravel 650 lb/yd^3 Cement	MR	sqrt(f'c)	7.18	-34.2	0.922	1	**84**	26
	MR	ST	1.52	10.1	0.958	3	69	21
	ST	sqrt(f'c)	4.71	-28.8	0.958	**0**	40	15

NOTES: [1]MR = modulus of rupture in psi, ST = Split tensile strength in psi, and f'c = compressive strength in psi

General equation form Y = mX + b

[2] Statistic based on absolute values of the prediction error.

500 lb/yd^3 = 297 kg/m^3
650 lb/yd = 386 kg/m^3
100 psi = 0.69 MPa

Table 7. Mix-specific linear regression summary of early age (4 to 24 hours) strength on Arrhenius maturity.

Mix	Dependent Variable [1]	Slope Coefficient, m [2]	y-intercept, b [2]	Coefficient of Determination, R - sq.
Crushed Limestone 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-11.059 -12.470 -9.937	3.454 2.715 2.792	0.943 0.974 0.968
Crushed Limestone 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-12.787 -12.251 -9.566	3.732 2.758 2.907	**0.984** **0.960** **0.958**
Crushed Quartzite 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-12.452 -13.151 -12.521	3.413 2.700 2.883	**0.973** **0.986** 0.941
Crushed Quartzite 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-11.707 -11.288 -10.538	3.568 2.735 2.887	**0.973** **0.970** **0.956**
Rounded Gravel 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-11.949 -13.297 -9.064	3.484 2.657 2.662	**0.968** **0.937** **0.956**
Rounded Gravel 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-11.806 -9.902 -9.278	3.664 2.549 2.755	**0.954** **0.932** **0.905**

NOTES: [1] MR = modulus of rupture in psi, ST = Split tensile strength in psi, and f'c = compressive strength in psi
Strength data at 4 hours cured at 50 ^{0}F not included in analysis.
1000 psi = 6.9 MPa
500 lb/yd^3= 297 kg/m^3, 650 lb/yd^3= 386 kg/m^3

[2] General equation form Strength = m / AR + b
where AR = Arrhenius maturity in equivalent hours at 68 ^{0}F

Table 8. Mix-specific linear regression summary of early age (4 to 24 hours) strength on Nurse-Saul maturity.

Mix	Dependent Variable 1	Slope Coefficient,2 m	y-intercept, 2 b	Coefficient of Determination, R - sq.
Crushed Limestone 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-402.13 -409.66 -360.63	**3.598** 2.780 2.920	0.954 0.896 0.975
Crushed Limestone 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-450.20 -437.71 -346.06	3.664 2.920 3.045	0.955 0.959 0.976
Crushed Quartzite 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-451.90 -428.77 -429.12	**3.589** 2.778 3.011	0.986 0.922 0.972
Crushed Quartzite 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-423.81 -380.17 -383.97	3.731 2.834 3.040	0.969 0.943 0.965
Rounded Gravel 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-434.71 -442.92 -336.08	3.627 2.727 2.787	0.971 0.882 0.986
Rounded Gravel 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	-430.02 -366.61 -334.97	3.817 2.695 2.896	0.965 0.975 0.955

NOTES: 1 MR = modulus of rupture in psi, ST = Split tensile strength in psi, and f'c = compressive strength in psi
Strength data at 4 hours cured at 50 ^{o}F not included in analysis.
1000 psi = 6.9 MPa
500 lb/yd^3= 297 kg/m,^{3}650 lb/yd^3= 386 kg/m^3

2 General equation form Strength = m / NS + b
where NS = Nurse-Saul maturity in ^{o}F - hours

Table 9. Mix-specific linear regression summary of early age (4 to 24 hours) strength on pulse velocity.

Mix	Dependent Variable [1]	Slope Coefficient,[2] m	y-intercept,[2] b	Coefficient of Determination, R - sq.
Crushed Limestone 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	0.176 0.171 0.147	0.890 0.132 0.602	0.972 0.993 **0.904**
Crushed Limestone 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	0.194 0.190 0.149	0.667 -0.223 0.565	**0.979** **0.946** **0.956**
Crushed Quartzite 500 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	0.183 0.175 0.174	0.840 0.153 0.402	**0.987** **0.947** **0.974**
Crushed Quartzite 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	0.181 0.167 0.157	0.916 0.258 0.556	0.994 **0.997** **0.938**
Rounded Gravel 500 lb/yd^3 Cement	log(F'c) log(ST) log(MR)	0.221 0.226 0.172	0.410 -0.561 0.284	0.990 **0.968** **0.984**
Rounded Gravel 650 lb/yd^3 Cement	log(f'c) log(ST) log(MR)	0.216 0.178 0.168	0.511 0.057 0.296	0.988 **0.959** 0.952

NOTES: 1 MR = modulus of rupture in psi, ST = Split tensile strength in psi, and f'c = compressive strength in psi
1000 psi = 6.9 MPa
500 lb/yd^3 = 297 kg/m^3, 650 lb/yd^3 = 386 kg/m^3

2 General equation form Strength = m * (PV/1000) + b
where PV = pulse velocity in ft/s
1000ft=305m

Table 10. Regression analysis of compressive strength on early age Arrhenius maturity.

Mix	Curing, Temp., °F	Testing Age, hours	Arrhenius Maturity, hours	Compres. Strength, psi	General Equation 2 Predicted f'c, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted f'c psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone 500 lb/yd^3 Cement	50	4	4	10	4	-6	2	-8	2
		6	5	30	26	-4	16	-14	10
		9	7	80	98	18	72	-8	11
		24	17	690	652	-38	625	-65	27
	72	4	6	30	54	24	36	6	18
		6	9	100	218	118	179	79	39
		9	15	310	557	247	522	212	35
		24	43	2400	1467	-933	1579	-821	112
	100	4	9	140	222	82	182	42	39
		6	16	480	634	154	606	126	29
		9	28	1490	1117	-373	1156	-334	39
		24	74	2640	1815	-825	2013	-627	198

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 3.390 - 9.681 / AR
where f'c = compressive strength and AR = Arrhenius maturity in equivalent hours at 68 °F.

3 Mix specific prediction equation Log(f'c) = 3.454 - 11.059 / AR
Compressive strength at 4 hours and 50 °F not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3, 100 psi = 0.69 MPa
50°F=10°C,72°F=22°C,100°F=38°C

Table 10. Regression analysis of compressive strength on -early age Arrhenius maturity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Arrhenius Maturity, hours	Compres. Strength, psi	General Equation 2 Predicted f'c, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted f'c, psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone 650 lb/yd³ Cement	50	4	4	20	7	-13	2	-18	5
		6	5	30	39	9	22	-8	1
		9	8	100	134	34	116	16	18
		24	19	1340	742	-598	1110	-230	368
	72	4	7	60	86	26	64	4	22
		6	11	280	326	46	375	95	49
		9	19	970	750	-220	1127	157	63
		24	48	3980	1551	-2429	2939	-1041	1388
	100	4	10	270	270	0	292	22	21
		6	19	1200	748	-452	1122	-78	374
		9	32	2110	1228	-882	2160	50	832
		24	80	3420	1857	-1563	3727	307	1256

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\mathrm{Log}(f'c) = 3.390 - 9.681 / AR$
where f'c = compressive strength and AR = Arrhenius maturity in equivalent hours at 68 °F.

3 Mix specific prediction equation $\mathrm{Log}(f'c) = 3.732 - 12.787 / AR$
Compressive strength at 4 hours and 50 °F not used in regression analysis

650 lb/yd³ = 386 kg/m³, 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 10. Regression analysis of compressive strength on early age Arrhenius maturity (continued).

Mix	Curing Temp., °F	Testing Age, hours	Arrhenius Maturity, hours	Compres. Strength, psi	General Equation 2 Predicted f'c, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted f'c psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite 500 lb/yd^3 Cement	50	4	3	10	4	-6	1	-9	3
		6	5	10	23	13	7	-3	10
		9	7	30	88	58	36	6	52
		24	16	500	630	130	450	-50	80
	72	4	6	30	76	46	30	0	46
		6	10	150	270	120	151	1	119
		9	16	470	627	157	447	-23	133
		24	45	1860	1494	-366	1365	-495	129
	100	4	10	70	245	175	133	63	112
		6	17	370	677	307	493	123	184
		9	29	950	1130	180	953	3	177
		24	73	2180	1813	-367	1751	-429	62

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 3.390 - 9.681 / AR
where f'c = compressive strength and AR = Arrhenius maturity in equivalent hours at 68 °F.

3 Mix specific prediction equation Log(f'c) = 3.413 - 12.452 / AR
Compressive strength at 4 hours and 50 °F not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3 , 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 10. Regression analysis of compressive strength on early age Arrhenius maturity (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Arrhenius Maturity, hours	Compres. Strength psi	General Equation[2] Predicted f'c, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted f'c, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	4	10	5	-5	2	-8	3
		6	5	20	26	6	15	-5	1
650 lb/yd^3		9	7	50	97	47	74	24	23
Cement		24	16	800	635	-165	720	-80	85
	72	4	6	60	67	7	47	-13	6
		6	10	250	243	-7	226	-24	17
		9	16	770	595	-175	666	-104	71
		24	44	2560	1475	-1085	1995	-565	521
	100	4	10	140	271	131	257	117	14
		6	19	710	753	43	885	175	132
		9	31	1590	1201	-389	1557	-33	356
		24	76	2840	1833	-1007	2596	-244	763

NOTES: [1] Cured at 50% RH.

[2] General prediction equation $\text{Log}(f'c) = 3.390 - 9.681 / AR$
where f'c = compressive strength and AR = Arrhenius maturity in equivalent hours at 68 °F.

[3] Mix specific prediction equation $\text{Log}(f'c) = 3.568 - 11.707 / AR$
Compressive strength at 4 hours and 50 °F not used in regression analysis.

650 lb/yd^3 = 386 kg/m^3, 100 psi = 0.69 MPa
50°F=10°C,72°F=22°C,100°F=38°C

Table 10. Regression analysis of compressive strength on early age Arrhenius maturity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Arrhenius Maturity, hours	Compres. Strength, psi	General Equation [2] Predicted Pc, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c, psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel 500 lb/yd^3 Cement	50	4	3	10	2	-8	0	-10	1
		6	4	10	15	5	6	-4	1
		9	6	30	73	43	39	9	33
		24	16	700	620	-80	558	-142	63
	72	4	5	20	36	16	17	-3	13
		6	8	70	167	97	111	41	57
		9	13	280	466	186	392	112	74
		24	36	2180	1333	-847	1434	-746	101
	100	4	8	70	169	99	112	42	57
		6	15	450	557	107	489	39	69
		9	26	1190	1039	-151	1054	-136	15
		24	67	2370	1764	-606	2025	-345	261

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\mathrm{Log}(f'c) = 3.390 - 9.681 / AR$
where fc = compressive strength and AR = Arrhenius maturity in equivalent hours at 68 °F.

3 Mix specific prediction equation $\mathrm{Log}(f'c) = 3.484 - 11.949 / AR$
Compressive strength at 4 hours and 50 °F not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3 , 100 psi = 0.69 MPa
50°F=10°C,72°F=22°C,100°F=38°C

Table 10. Regression analysis of compressive strength on early age Arrhenius maturity (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Arrhenius Maturity, hours	Compres. Strength, psi	General Equation[2] Predicted Pc, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted f'c psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel 650 lb/yd^3 Cement	50	4	3	10	4	-6	2	-8	2
		6	5	30	23	-7	16	-14	8
		9	7	90	93	3	86	-4	1
		24	17	1560	659	-901	927	-633	268
	72	4	5	20	39	-19	29	9	9
		6	9	130	189	59	203	73	13
		9	15	500	539	39	725	225	186
		24	38	2920	1376	-1544	2275	-645	899
	100	4	8	130	166	36	173	43	7
		6	17	670	636	-234	688	18	216
		9	29	2030	1153	-877	1633	-197	661
		24	73	2960	1613	-1147	3186	226	921

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\mathrm{Log}(\hat{f'c}) = 3.390 - 9.661 / AR$
where fc = compressive strength and AR = Arrhenius maturity in equivalent hours at 68 °F.

3 Mix specific prediction equation $\mathrm{Log}(f'c) = 3.664 - 11.806 / AR$
Compressive strength at 4 hours and 50 °F not used in regression analysis.

650 lb/yd^3 = 386 kg/m^3, 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 11. Regression analysis of early age compressive strength on Nurse-Saul maturity.

Mix	Curing Temp., 1 ^{0}F	Testing Age, hours	Nurse-Saul Maturity, deg.F-h	Compres. Strength, psi	General Equation 2 Predicted f'c, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted f'c, psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	127	10	5	-5	3	-7	2
		6	177	30	32	2	21	-9	7
		9	249	80	123	43	96	16	27
500 lb/yd^3 Cement		24	600	690	878	166	847	157	31
	72	4	192	30	46	16	32	2	14
		6	297	100	212	112	175	75	37
		9	469	310	595	285	550	240	45
		24	1312	2400	1869	-531	1957	-443	86
	100	4	252	140	126	-12	101	-39	28
		6	409	480	456	-22	412	-68	46
		9	655	1490	987	-503	964	-526	23
		24	1743	2640	2187	-453	2330	-310	143

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 3.548 - 362.760 / NS
where fc = compressive strength and NS = Nurse-Saul maturity in ^{0}F - hours

3 Mix specific prediction equation Log(f'c) = 3.598 - 402.13 / NS
Compressive strength at 4 hours and 50 ^{0}F not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3, 100 psi = 0.69 MPa
50°F=10^{o}C,72^{o}F=22^{o}C,100^{0}F=38^{0}C

Table 11. Regression analysis of early age compressive strength on Nurse-Saul maturity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Nurse-Saul Maturity deg.F-h	Compres. Strength, psi	General Equation [2] Predicted f'c, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone	50	4	137	20	8	-12	4	-16	4
		6	194	30	48	18	37	7	11
		9	278	100	175	75	184	84	9
650 lb/yd3		24	674	1340	1023	-317	1645	305	13
Cement									
	72	4	209	60	65	5	54	-6	1
		6	331	280	283	3	334	54	51
		9	533	970	737	-233	1095	125	108
		24	1399	3980	1944	-2036	3649	-331	1705
	100	4	263	270	147	-123	149	-121	1
		6	434	1200	515	-685	703	-497	187
		9	694	2110	1060	-1050	1719	-391	659
		24	1803	3420	2222	-1198	4308	888	309

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\text{Log}(f'c) = 3.548 - 362.760 / NS$
where f'c = compressive strength and NS = Nurse-Saul maturity in °F - hours

3 Mix specific prediction equation $\text{Log}(f'c) = 3.884 - 450.20 / NS$
Compressive strength at 4 hours and 50 °F not used in regression analysis.

650 lb/yd^3 = 386 kg/m^3, 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 11. Regression analysis of early age compressive strength on Nurse-Saul maturity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Nurse-Sat Maturity, deg.F-h	Compres. Strength, psi	General Equation [2] Predicted f'c psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	124	**10**	4	-6	1	-9	3
		6	172	**10**	27	17	9	-1	17
		9	239	30	107	77	50	20	57
500 lb/yd ^{3} Cement		24	581	500	839	339	647	147	191
	72	4	204	30	59	29	24	-6	23
		6	315	150	249	99	143	-7	92
		9	494	470	651	181	472	2	179
		24	1341	1860	1894	34	1787	-73	39
	100	4	257	70	137	67	68	-2	65
		6	419	370	481	111	324	-46	65
		9	661	950	998	48	804	-146	98
		24	1740	2180	2185	5	2134	-46	40

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\text{Log}(f'c) = 3.548 - 362.760 / NS$
where fc = compressive strength and NS = Nurse-Saul maturity in °F-hours

3 Mix specific prediction equation $\text{Log}(f'c) = 3.589 - 451.90 / NS$
Compressive strength at 4 hours and 50 °F not used in regression analysis.

500 lb/yd ^{3} = 297 kg/m ^{3}, 100 psi = 0.69 MPa
50°F=10°C,72°F=22°C,100°F=38°C

Table 11. Regression analysis of early age compressive strength on Nurse-Saul maturity (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Nurse-Saul Maturity, deg.F-h	Compres. Strength, psi	General Equation[2] Predicted f'c, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted f'c psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	128	10	5	-5	3	-7	3
		6	176	20	31	11	21	1	10
650 lb/yd^3		9	247	50	120	70	104	54	16
Cement		24	584	800	845	45	1012	212	167
	72	4	199	60	53	-7	40	-20	13
		6	306	250	230	-20	222	-28	9
		9	482	770	624	-146	711	-59	86
		24	1321	2560	1877	-683	2571	11	672
	100	4	262	140	146	6	130	-10	4
		6	434	710	515	-195	568	-142	53
		9	685	1590	1043	-547	1295	-295	252
		24	1767	2840	2201	-639	3099	259	380

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f' c) = 3.548 - 362.760 / NS
where f'c = compressive strength and NS = Nurse-Saul maturity in °F-hours

3 Mix specific prediction equation Log(f 'c) = 3.731 - 423.81 / NS
Compressive strength at 4 hours and 50°F not used in regression analysis.

650 lb/yd^3 = 386 kg/m^3 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 11. Regression analysis of early age compressive strength on Nurse-Saul maturity (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Nurse-Saul Maturity, deg.F-h	Compres Strength, psi	General Equation[2] Predicted f'c, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted f'c, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel 500 lb/yd^3 Cement	50	4	112	10	2	-8	1	-9	1
		6	158	10	18	8	8	-2	5
		9	226	30	88	58	51	21	37
		24	577	700	830	130	747	47	83
	72	4	179	20	33	13	16	-4	9
		6	277	70	173	103	114	44	59
		9	436	280	520	240	427	147	93
		24	1179	2180	1739	-441	1813	-367	73
	100	4	237	70	104	34	62	-8	26
		6	389	450	413	-37	323	-127	89
		9	626	1190	930	-260	856	-334	74
		24	1666	2370	2139	-231	2323	-47	184

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\text{Log}(f'c) = 3.548 - 362.760 / NS$
where f'c = compressive strength and NS = Nurse-Saul maturity in °F - hours

3 Mix specific prediction equation $\text{Log}(f'c) = 3.6271 - 434.71 / NS$
Compressive strength at 4 hours and 50 °F not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3, 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 11. Regression analysis of early age compressive strength on Nurse-Saul maturity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Nurse-Saul Maturity, deg.F-h	Compres Strength, psi	General Equation [2] Predicted f'c, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel	50	4	123	10	4	-6	2	-8	2
		6	172	30	27	-3	21	-9	7
		9	245	90	117	27	115	25	1
650 lb/yd ^{3} Cement		24	606	1560	890	-670	1281	-279	391
	72	4	181	20	35	15	28	8	7
		6	285	130	188	58	203	73	15
		9	460	500	575	75	762	262	188
		24	1216	2920	1777	-1143	2906	-14	1130
	100	4	235	130	101	-29	97	-33	4
		6	402	870	442	-428	559	-311	117
		9	658	2030	992	-1038	1457	-573	465
		24	1727	2960	2177	-783	3698	738	44

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 3.548 - 362.760 / NS
where f'c = compressive strength and NS = Nurse-Saul maturity in °F - hours

3 Mix specific prediction equation Log(f'c) = 3.817 - 430.02 / NS
Compressive strength at 4 hours and 50 °F not used in regression analysis.

650 lb/yd ^{3} = 386 kg/m ^{3}, 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 12. Regression analysis of compressive strength on early age pulse velocity.

Mix	Curing Temp.,[1] °F	Testing Age, hours	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation[2] Predicted f'c, psi	General Equation[2] Prediction Error, psi	Mix Specific[3] Predicted f'c, psi	Mix Specific[3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed	50	4	1,300	10	10	0	13	3	3
Limestone		6	3,400	30	24	-6	31	1	5
500 lb/yd^3		9	3,800	80	29	-51	36	-44	7
Cement		24	11,300	690	797	107	756	66	41
	72	4	3,200	30	22	‘8	28	-2	6
		6	6,900	100	114	14	127	27	13
		9	9,800	310	411	101	412	102	1
		24	13,600	2400	2204	-196	1921	-479	283
	100	4	7,600	140	155	15	169	29	14
		6	10,500	480	560	80	547	67	13
		9	13,100	1490	1767	277	1569	79	198
		24	13,700	2640	2304	-336	2001	-639	303

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\mathrm{Log}(f'c) = 0.732 + 0.192 * (PV/1000)$
where PV = Pulse velocity in ft/sec

3 Mix specific prediction equation $\mathrm{Log}(f'c) = 0.890 + 0.176 * (PV/1000)$

500 lb,yd = 297 kg/m^3, 100 psi = 0.69 MPa
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C

Table 12. Regression analysis of compressive strength on early age pulse velocity (continued).

Mix	Curing Temp.,[1] °F	Testing Age, hours	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation [2] Predicted f'c, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Limestone 650 lb/yd^3 Cement	50	4	2,900	20	19	-1	17	-3	2
		6	3,100	30	21	-9	19	-11	3
		9	7,900	100	177	77	158	58	19
		24	12,600	1340	1416	76	1292	-48	29
	72	4	6,400	60	91	31	81	21	10
		6	9,800	280	411	131	370	90	41
		9	12,200	970	1187	217	1081	111	106
		24	14,700	3980	3584	-396	3302	-678	282
	100	4	9,400	270	344	74	309	39	35
		6	12,400	1200	1297	97	1182	-18	79
		9	13,400	2110	2017	-93	1848	-262	170
		24	14,300	3420	3003	-417	2762	-658	241

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 0.732 + 0.192 * (PV/1OOO)
where PV = Pulse velocity in ft/sec

3 Mix specific prediction equation Log(f'c) = 0.667 + 0.194 (PV /1 000)

650 lb/yd^3 = 386 kg/m^3, 100 psi = 0.69 MPa
50°F=10°C,72°F=22°C,100°F=38°C

Table 12. Regression analysisof compressive strength on early age pulse velocity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation [2] Predicted f'c, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c, psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite	50	4	800	10	8	-2	10	0	2
		6	800	10	8	-2	10	0	2
500 lb/yd^3		9	4,400	30	38	8	44	14	6
. Cement		24	9,900	500	429	-71	448	-52	19
	72	4	2,500	30	16	-14	20	**-10**	4
		6	7,700	150	162	12	**177**	27	15
		9	10,500	470	560	90	577	107	18
		24	12,800	1860	1547	-313	1522	-338	25
	100	4	5,600	70	64	-6	73	3	3
		6	9,700	370	393	23	412	42	19
		9	12,000	950	1086	136	1086	136	0
		24	13,100	2180	1767	-413	1727	-453	40

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 0.732 + 0.192 * (PV/1000)
where PV = Pulse velocity in ft/sec

3 Mix specific prediction equation Log(f'c) = 0.840 + 0.183 * (PV /1000)

500 lb/yd^3 = 297 kg/m^3 ,100 psi = 0.69 MPa
50°F=10°C,72°F=22°C,100°F=38°C

Table 12. Regression analysis of compressive strength on early age pulse velocity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation [2] Predicted f'c, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c, psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Crushed Quartzite 650 lb/yd^3 Cement	50	4	800	10	8	-2	12	2	1
		6	1,600	20	11	-9	16	-4	5
		9	4,700	50	43	-7	58	8	2
		24	11,000	800	698	-102	807	7	95
	72	4	4,300	60	36	-24	49	-11	13
		6	8,100	250	194	-56	241	-9	47
		9	11,100	770	730	-40	842	72	31
		24	13,400	2560	2017	-543	2195	-365	177
	100	4	7,000	140	119	-21	152	12	8
		6	11,100	710	730	20	842	132	112
		9	12,800	1590	1547	-43	1709	119	77
		24	13,600	2840	2204	-636	2386	-454	182

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 0.732 + 0.192 * (PV/1000)
where PV = Pulse velocity in ft/sec

3 Mix specific prediction equation Log(f'c) = 0.916 + 0.181 * (PV /1OOO)

650 lb/yd^3 = 386 kg/m^3 100 psi = 0.69 MPa
50°F = 10°C, 72°F = 22°C, 100°F = 38°C

Table 12. Regression analysis of compressive strength on early age pulse velocity (continued).

Mix	Curing Temp., 1 °F	Testing Age, hours	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation 2 Predicted f'c, psi	General Equation 2 Prediction Error, psi	Mix Specific 3 Predicted f'c, psi	Mix Specific 3 Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel 500 lb/yd^3 Cement	50	4	2,600	10	17	7	10	0	7
		6	2,600	10	17	7	10	0	7
		9	5,800	30	70	40	49	19	21
		24	11,300	700	797	97	808	108	11
	72	4	3,300	20	23	3	14	-6	3
		6	6,500	70	95	25	70	0	25
		9	9,200	280	315	35	277	-3	33
		24	13,300	2180	1930	-250	2235	55	195
	100	4	6,800	70	109	39	82	12	27
		6	10,100	450	469	19	439	-11	8
		9	11,800	1190	994	-196	1042	-148	47
		24	13,100	2370	1767	-603	2019	-351	252

NOTES: 1 Cured at 50% RH.

2 General prediction equation $\text{Log}(f'c) = 0.732 + 0.192 * (PV/1000)$
where PV = Pulse velocity in ft/sec

3 Mix specific prediction equation $\text{Log}(f'c) = 0.410 + 0.221 * (PV/1000)$

500 lb/yd^3 = 297 kg/m^3, 100 psi = 0.69 MPa
50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C

Table 12. Regression analysis of compressive strength on early age pulse velocity (continued).

Mix	Curing Temp., [1] °F	Testing Age, hours	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation [2] Predicted f'c, psi	General Equation [2] Prediction Error, psi	Mix Specific [3] Predicted f'c, psi	Mix Specific [3] Prediction Error, psi	Difference of Absolute Errors, psi
Rounded Gravel	50	4	2,600	10	17	7	12	2	5
		6	3,300	30	23	-7	17	-13	6
650 [3] Cement		9	7,200	90	130	40	116	26	14
		24	12,200	1560	1187	-373	1400	-160	213
	72	4	4,100	20	33	13	25	5	8
		6	7,700	130	162	32	149	19	13
		9	10,400	500	536	36	572	72	36
		24	13,600	2920	2204	-716	2809	-111	605
	100	4	7,200	130	130	0	116	-14	13
		6	11,400	870	833	-37	941	71	34
		9	12,800	2030	1547	-483	1887	-143	340
		24	13,600	2960	2204	-756	2809	-151	605

NOTES: 1 Cured at 50% RH.

2 General prediction equation Log(f'c) = 0.732 + 0.192 * (PV/1 000)
where PV = Pulse velocity in ft/sec

3 Mix specific prediction equation Log(f'c) = 0.511 + 0.216 * (PV /1000)

650 lb/yd ^{3} = 386 kg/m^3 , 100 psi = 0.69 MPa
50°F=10°C, 72°F=22°C, 100°F=38°C

Table 13. Early age (4 to 24 hours) modulus of elasticity.

Cement Content, lb/yd^3	Age, hours	Compressive Strength, psi	Modulus of Elasticity, psi	Predicted Modulus,' psi	Prediction Error, psi
500	4	30	50,000	330,000	560
		40	50,000	390,000	680
	6	130	600,000	700,000	17
		140	****	720,000	****
	9	440	1,450,000	1,280,000	-12
		450	1,450,000	1,300,000	-10
	24	1790	2,700,000	2,580,000	-4
		1860	2,600,000	2,630,000	1
650	4	50	50,000	430,000	760
		50	50,000	430,000	760
	6	160	900,000	770,000	-14
		160	450,000	770,000	71
	9	480	1,550,000	1,340,000	-14
		440	1,400,000	1,280,000	-9
	24	2000	2,550,000	2,730,000	7
		1970	2,800,000	2,710,000	-3

NOTE: [1]Ec = 61,078*sqrt(f'c)
where Ec = modulus of elasticity, psi
and f'c = compressive strength, psi

500 lb/yd^3 = 297 kg/m^3
650 lb/yd^3 = 386 kg/m^3
1 million psi = 6,900 MPa

Table 14. Early age (4 to 24 hours) modulus of elasticity and compressive strength prediction models.

Dependent Variable,[1] Y	Independent Variable,[2] X	Coefficient, m	t-statistic	Constant, b	t-statistic	Coef. of Determination, R-squared
E_c	In (f'c)	683,438	19.6	-2,614,299	-12.9	0.967
E_c	sqrt (f'c)	68,497	18.3	-231,600	-2.4	0.963
E_c	sqrt (fc)	61,078	24.4	****	****	0.946

NOTES: [1] E_c = modulus of elasticity in psi
[2] f'c = compressive strength in psi
1000 psi = 6.9 MPa

General equation form Y = mX + b

Table 15. Concrete strength at 1 to 28 days.

Test	Cement Content, lbs/yd ^{3}	Curing Temp., ^oF	Relative Humidity, percent	Crushed Limestone					Crushed Quartzite				
				Testing Age, days					Testing Age, days				
				1	3	7	14	28	1	3	7	14	28
Compressive Strength, psi	500	50	50	860	2720	3880	4560	5060	740	2310	3420	3800	4250
		72	50	2470	3780	4350	4820	4990	2230	3200	3830	4530	5140
		100	50	3050	3890	4390	4800	5110	2450	3110	3660	4220	4560
		72	100	2440	3260	3790	4250	4650	2180	3370	4000	4220	4820
ASTM C39	650	50	50	1330	3860	4850	5620	6300	1320	3520	4310	4810	5250
		72	50	3700	4390	4900	5550	6090	3470	4280	4970	5330	6010
		100	50	3970	4750	5190	5460	5700	3360	3950	4630	4920	5140
		72	100	3090	4390	4410	5280	5800	3430	4170	4670	5280	5560
Flexural Strength, psi	500	50	50	355	525	550	605	645	270	390	510	550	585
		72	50	435	505	585	630	705	460	440	510	525	580
		100	50	435	455	440	555	605	420	555	500	555	550
		72	100	465	580	700	715	715	420	590	695	750	835
ASTM C78	650	50	50	475	575	540	710	605	225	530	570	605	620
		72	50	625	600	620	610	845	525	565	595	580	655
		100	50	585	540	565	620	585	560	545	575	575	610
		72	100	570	760	860	885	895	530	700	830	930	905

500 lb/yd ^{3} = 297 kg/m3 , 650 lb/yd ^{3} = 386 kg/m ^{3}
1000 psi = 6.9 MPa

50 ^oF = 10 ^oC, 72 $^\circ F$ = 22 ^oC, 100 ^oF = 38 ^oC

Table 15. Concrete strength at 1 to 28 days (continued).

Test	Cement Content, lbs/yd ^{3}	Curing Temp., ^oF	Relative Humidity, percent	Crushed Limestone: Testing Age, days 1	3	7	14	28	Crushed Quartzite: Testing Age, days 1	3	7	14	28
Modulus of Elasticity, million psi	500	50	50	1.80	3.55	3.75	4.10	4.35	1.55	2.95	3.70	3.90	4.20
		72	50	3.05	4.00	4.15	4.20	4.35	2.95	3.80	3.95	4.25	4.40
		100	50	3.60	3.90	4.30	4.30	4.45	2.70	3.65	3.45	4.15	4.15
		72	100	3.30	3.80	4.05	4.20	4.50	2.85	3.85	4.10	4.30	4.55
ASTM C496	650	50	50	2.15	3.65	4.25	4.50	4.65	2.20	3.55	4.05	4.20	4.30
		72	50	3.75	4.25	4.15	4.40	4.55	3.60	4.25	4.35	4.60	4.70
		100	50	4.00	4.40	4.50	4.75	4.75	3.60	3.95	4.30	4.35	4.35
		72	100	3.40	4.15	4.05	4.45	4.75	3.55	4.00	4.35	4.40	4.65

500 lb/yd ^{3} = 297 kg/m^3 ,650 lb/yd^3 = 386 kg/m^3
1 ,000,000 psi = 6900 MPa

50°F=10^{o}C, 72^{o}F=22^{o}C, 100^{o}F=38^{o}C

Table 16. Concrete properties at 1 to 28 days.

Test	Cement Content, lbs/yd^3	Curing Temp., ^oF	Relative Humidity, percent	Crushed Limestone					Crushed Quartzite				
				Testing Age, days					Testing Age, days				
				1	3	7	14	28	1	3	7	14	28
Concrete Maturity, ^oF-days Nurse-Saul (32^oF datum) ASTM C1074	500	50	50	25	61	134	261	516	24	58	127	249	491
		72	50	48	132	298	590	1174	52	138	310	611	1213
		100	50	70	203	471	939	1876	69	202	467	931	1859
		72	100	55	141	313	614	1216	46	127	289	571	1137
	650	50	50	26	61	130	252	496	25	60	131	254	500
		72	50	53	140	315	621	1233	53	139	311	612	1214
		100	50	72	206	474	943	1881	71	207	478	951	1899
		72	100	51	137	310	611	1215	53	139	311	612	1214
Concrete Maturity [1] Equivalent age days at 63 ^oF ASTM C1074	500	50	50	0.69	1.79	4.00	7.86	15.57	0.67	1.73	3.87	7.61	15.09
		72	50	1.48	3.38	8.68	17.08	33.88	1.65	4.15	9.16	17.91	35.42
		100	50	2.82	7.96	18.25	36.25	72.25	2.81	7.86	17.97	35.66	71.04
		72	100	1.82	4.33	9.33	18.08	35.59	1.40	3.70	8.31	16.37	32.49
	650	50	50	0.72	1.79	3.93	7.66	15.19	0.70	1.78	3.93	7.71	15.27
		72	50	1.72	4.28	9.39	18.34	36.24	1.75	4.25	9.25	18.00	35.51
		100	50	3.04	8.20	18.52	36.57	72.67	3.00	8.26	18.79	37.21	74.05
		72	100	1.63	4.13	9.15	17.93	35.49	1.75	4.26	9.26	18.01	35.52

1 NOTE: Activation energy divided by gas constant 5000 ^oK.

500 lb/yd^3 = 297 kg/m^3, 650 lb/yd^3 = 386 kg/m^3
^oC = 5/9(^oF-32), 1000 f/s = 305 m/s

Table 18. Concrete properties at 1 to 28 days (continued).

Test	Cement Content, lbs/yd^3	Curing Temp., ^oF	Relative Humidity, percent	Crushed Limestone Testing Age, days 1	3	7	14	28	Crushed Quartzite Testing Age, days 1	3	7	14	28
Pulse Velocity, ft/s	500	50	50	11,700	13,800	14,400	14,600	14,800	10,900	13,000	13,700	14,300	14,100
ASTMC597		72	50	13,700	14,500	14,700	15,000	15,100	13,100	13,800	14,200	14,400	14,600
		100	50	14,300	14,500	15,100	14,900	15,100	13,500	13,700	13,900	14,400	14,600
		72	100	14,100	14,800	14,800	15,100	15,300	13,300	14,100	14,400	14,500	14,700
	650	50	50	12,500	14,500	14,500	15,200	14,800	11,900	13,800	14,100	14,300	14,500
		72	50	13,300	14,700	15,000	15,200	15,300	13,700	14,200	14,500	14,800	15,000
		100	50	14,700	14,900	15,100	15,200	15,100	14,000	14,200	14,200	14,600	14,400
		72	100	14,200	13,800	15,300	15,300	15,600	13,700	14,200	14,500	14,600	14,600

500 lb/yd^3 =297kg/m^3 , 650lb/yd^3=386kg/m^3
1000f/s=305m/s

Table 17. Curing-specific regression analysis of early load strengths (1 to 28 days) for individual mixes.

Mix	Curing Condition[1]	Dependent Variable,[2] Y	Independent Variable, X	Slope Coefficient, m	y-intercept, b	Coefficient of Determination, R - sq.	Maximum Prediction Error,[3] percent	Average Prediction Error,[3] percent
Crushed Limestone 500 lb/yd^3 Cement	T=50, RH=50	MR	sqrt(f'c)	6.57	164.8	0.978	4	2
	T=72, RH=50	MR	sqrt(f'c)	19.72	-712.3	0.936	4	2
	T=100, RH=50	MR	sqrt(f'c)	10.43	-160.9	0.896	8	4
	T=72, RH=100	MR	sqrt(f'c)	14.45	-236.1	0.925	7	3
Crushed Limestone 650 lb/yd^3 Cement	T=50, RH=50	MR	sqrt(f'c)	3.90	329.3	0.580	12	6
	T=72, RH=50	MR	sqrt(f'c)	3.04	399.2	0.657	7	2
	T=100, RH=50	MR	sqrt(f'c)	9.26	-95.0	0.599	5	3
	T=72, RH=100	MR	sqrt(f'c)	16.18	-296.5	0.869	10	5

NOTES:

[1] T = curing temperature in deg. F, RH = relative humidity in percentage
[2] MR = modulus of rupture in psi, f'c = compressive strength in psi
General equation form Y = mX + b
Outlier data not used for cement=500 lb/yd^3 : 1 day at 72 and 7 day at 100 °F at 50% RH.
Outlier data not used for cement=650 lb/yd^3 : 1 day at 100 °F at 50% RH.
[3] Statistics based on absolute values of the prediction percent error.

500 lb/yd^3 = 297 kg/m^3
650 lb/yd^3 = 386 kg/m^3
100 psi = 0.69 MPa
50 °F = 10 °C
72 °F = 22°C
100 °F = 38 °C

Table 17. Curing-specific regression analysis of early load strengths (1 to 28 days) for individual mixes (continued).

Mix	Curing Condition[1]	Dependent Variable,[2] Y	Independent Variable, X	Slope Coefficient, m	y-intercept, b	Coefficient of Determination, R - sq.	Maximum Prediction Error,[3] percent	Average Prediction Error,[3] percent
Crushed Quartzite 500 lb/yd ^{3} Cement	T=50, RH=50	MR	sqrt(f'c)	11.49	-161.9	0.999	1	0
	T=72, RH=50	MR	sqrt(f'c)	8.53	-35.3	0.944	3	2
	T=100, RH=50	MR	sqrt(f'c)	7.75	36.7	0.970	3	1
	T=72, RH=100	MR	sqrt(f'c)	21.79	-675.0	0.995	1	1
Crushed Quartzite 650 lb/yd ^{3} Cement	T=50, RH=50	MR	sqrt(f'c)	7.07	109.9	0.991	1	0
	T=72, RH=50	MR	sqrt(f'c)	6.17	157.7	0.869	5	2
	T=100, RH=50	MR	sqrt(f'c)	6.34	144.1	0.846	9	3
	T=72, RH=100	MR	sqrt(f'c)	25.21	-928.6	0.959	35	3

NOTES:

[1] T = curing temperature in °F, RH = relative humidity in percentage
[2] MR = modulus of rupture in psi, f'c = compressive strength in psi
General equation form Y = mX + b
Outlier data not used for cement=500 lb/yd ^{3} : 1 day at 50 and 72 °F at 50% RH, 3 days at 100 °F at 50% RH, and 1 day at 72 °F at 100 % RH.
Outlier data not used for cement=650 lb/yd ^{3} : 1 day at 50 °F at 50% RH.
[3] Statistics based on absolute values of the prediction percent error.

500 lb/yd ^{3} = 297 kg/m ^{3}
650 lb/yd ^{3} = 386 kg/m ^{3}
100 psi = 0.69 MPa
50 °F = 10 °C
72 °F = 22°C
100 °F = 38 °C

Table 18. Regression analysis of early load (1-to 28 day) modulus of rupture on compressive strength.

Mix	Curing Condition	Testing Age, days	Comp. Strength psi	Modulus of Rupture, psi	General Equation Pred. MR, psi	General Equation Pred. Error, percent	Agg.-Specific Pred. MR, psi	Agg.-Specific Pred. Error, percent	Mix-Specific Pred. MR, psi	Mix-Specific Pred. Error, percent	Curing-Specific Pred. MR psi	Curing-Specific Pred. Error, percent
Crushed Limestone	50 ^{0}F	1	860	355	258	-27	312	-12	197	-45	358	1
500 lb/yd^3 Cement	50% RH	3	2720	525	451	-14	474	-10	429	-18	508	-3
		7	3880	550	537	-2	545	-1	532	-3	574	4
		14	4560	605	581	-4	582	-4	585	-3	609	1
		28	5060	645	611	-5	608	-6	621	-4	632	-2
	72 ^{0}F	1	2470	435	430	-1	456	5	404	-7	268	-38
	50% RH	3	3780	505	530	5	540	7	523	4	500	-1
		7	4350	585	568	-3	571	-2	569	-3	588	1
		14	4820	630	597	-5	596	-5	604	-4	657	4
		28	4990	705	607	-14	604	-14	616	-13	680	-3
	100 ^{0}F	1	3050	435	477	10	495	14	460	6	415	-5
	50% RH	3	3890	455	537	18	546	20	532	17	469	8
		7	4390	440	570	30	573	30	572	30	530	20
		14	4800	555	596	7	595	7	603	9	561	1
		28	5110	605	614	2	610	1	625	3	584	-3
	72 ^{0}F	1	2440	465	593	28	612	32	524	13	478	3
	100% RH	3	3260	580	658	13	667	15	603	4	589	2
		7	3790	700	696	-1	698	0	648	-7	653	-7
		14	4250	715	727	2	724	1	685	-4	706	-1
		28	4650	715	752	5	745	4	715	0	749	5

500 lb/yd^3 = 297 kg/m^3 ,650 lb/yd^3 = 386 kg/m^3 1000 psi = 6.9 MPa 50 ^{0}F = 10 ^{0}C, 72 ^{0}F = 22 ^{0}C, 100 ^{0}F = 38 ^{0}C

Table 18. Regression analysis of early load (1-to 28-day modulus of rupture on compressive strength (continued).

Mix	Curing Condition	Testing Age, days	Comp. Strength, psi	Modulus of Rupture, psi	General Equation Pred. MR, psi	General Equation Pred. Error, psi	Agg.-Specific Pred. MR, psi	Agg.-Specific Pred. Error, psi	Mix-Specific Pred. MR, psi	Mix-Specific Pred. Error, psi	Curing-Specific Pred. MR, psi	Curing-Specific Pred. Error, psi
Crushed Limestone 650 lb/yd^3 Cement	50 ^{0}F 50% RH	1	1330	475	318	-33	363	-24	354	-25	472	-1
		3	3860	575	535	-7	544	-5	540	-6	572	-1
		7	4850	540	599	11	597	11	594	10	601	11
		14	5620	710	644	-9	635	-11	633	-11	622	-12
		28	6300	605	681	13	666	10	665	10	639	6
	72 ^{0}F 50% RH	1	3700	625	524	-16	535	-14	531	-15	584	-7
		3	4390	600	570	-5	573	-4	570	-5	601	0
		7	4900	620	602	-3	600	-3	597	-4	612	-1
		14	5550	610	640	5	631	4	630	3	626	3
		28	6090	645	670	4	656	2	655	2	637	-1
	100 ^{0}F 50% RH	1	3970	585	543	-7	550	-6	546	-7	489	-16
		3	4750	540	593	10	592	10	589	9	544	1
		7	5190	565	619	10	614	9	612	8	572	1
		14	5460	620	635	2	627	1	625	1	590	-5
		28	5700	585	648	11	639	9	637	9	604	3
	72 ^{0}F 100% RH	1	3090	570	645	13	656	15	708	24	603	6
		3	4390	760	736	-3	731	-4	786	3	775	2
		7	4410	860	737	-14	733	-15	787	-9	778	-10
		14	5280	885	790	-11	777	-12	832	-6	879	-1
		28	5800	895	820	-8	801	-10	857	-4	935	5

500 lb/yd^3 = 297 kg/m^3 ,650 lb/yd^3 = 386 kg/m^3 1000 psi = 6.9 MPa 50 *F = 10 ^{0}C, 72 ^{0}F = 22 ^{0}C, 100 ^{0}F = 38 ^{0}C

Table 18. Regression analysis of early load (1 to 28 day) modulus of rupture on compressive strength (continued).

Mix	Curing Condition	Testing Age, days	Comp. strength psi	Modulus of Rupture, psi	General Equation Pred. MR, psi	General Equation Pred. Error, psi	Agg.-Specific Pred. MR, psi	Agg.-Specific Pred. Error, psi	Mix-Specific Pred. MR, psi	Mix-Specific Pred. Error, psi	Curing-Specific Pred. MR, psi	Curing-Specific Pred. Error, psi
Crushed Quartzite	50 °F 50% RH	1	740	270	240	-11	190	-30	185	-31	151	-44
500 lb/yd^3 Cement		3	2310	390	416	7	394	1	393	1	391	0
		7	3420	510	504	-1	496	-3	497	-3	510	0
		14	3800	550	531	-3	527	-4	528	-4	547	-1
		28	4250	585	561	-4	561	-4	564	-4	587	0
	72 °F 50% RH	1	2230	460	409	-11	386	-16	385	-16	368	-20
		3	3200	440	488	11	477	8	478	9	447	2
		7	3830	510	533	5	529	4	531	4	493	-3
		14	4530	525	579	10	582	11	585	11	539	3
		28	5140	560	616	6	625	8	628	8	576	-1
	100 °F 50% RH	1	2450	420	428	2	408	-3	407	-3	420	0
		3	3110	555	481	-13	469	-15	470	-15	469	-16
		7	3660	500	521	4	515	3	517	3	505	1
		14	4220	555	559	1	559	1	561	1	540	-3
		28	4560	550	581	6	584	6	587	7	560	2
	72 °F 100% RH	1	2180	420	570	36	548	31	521	24	342	-19
		3	3370	590	666	13	659	12	634	7	590	0
		7	4000	695	710	2	710	2	686	-1	703	1
		14	4220	750	725	-3	727	-3	703	-6	740	-1
		28	4820	835	763	-9	770	-8	747	-11	837	0

500 lb/yd^3 = 297 kg/m^3 , 650 lb/yd^3 = 386 kg/m^3 1000 psi = 6.9 MPa   50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C

Table 18. Regression analysis of early load (1 to 28-day) modulus of rupture on compressive strength (continued).

Mix	Curing Condition	Testing Age, days	Comp. Strength, psi	Modulus of Rupture, psi	General Equation Pred. MR, psi	General Equation Pred. Error, psi	Agg.-Specific Pred. MR, psi	Agg.-Specific Pred. Error, psi	Mix-Specific Pred. MR, psi	Mix-Specific Pred. Error, psi	Curing-Specific Pred. MR, psi	Curing-Specific Pred. Error, psi
Crushed Quartzite 650 lb/yd^3 Cement	50 °F 50% RH	1	1320	225	317	41	279	24	248	10	367	63
		3	3520	530	512	-3	504	-5	494	-7	529	0
		7	4310	570	565	-1	566	-1	561	-2	574	1
		14	4810	605	596	-1	602	0	601	-1	600	-1
		28	5250	620	623	0	632	2	634	2	622	0
	72 °F 50% RH	1	3470	525	508	-3	500	-5	489	-7	521	-1
		3	4280	565	563	0	564	0	559	-1	561	-1
		7	4970	595	606	2	613	3	613	3	593	0
		14	5330	580	627	8	638	10	640	10	608	5
		28	6010	655	666	2	682	4	688	5	636	-3
	100 °F 50%RH	1	3360	560	500	-11	491	-12	479	-14	511	-9
		3	3950	545	541	-1	538	-1	531	-3	542	0
		7	4630	575	585	2	589	2	587	2	575	0
		14	4920	575	603	5	610	6	609	6	589	2
		28	5140	610	616	1	625	2	626	3	599	-2
	72 °F 100% RH	1	3430	530	671	27	664	25	681	29	548	3
		3	4170	700	722	3	723	3	745	6	699	0
		7	4670	630	753	-9	760	-8	785	-5	794	-4
		14	5280	930	790	-15	802	-14	832	-11	903	-3
		28	5560	905	806	-11	821	-9	852	-6	951	5

500 lb/yd^3 = 297 kg/m^3 ,650 lb/yd^3 = 386 kg/m^3 1000 psi = 6.9 MPa 50 °F = 10 °C, 72 °F = 22 °C, 100 °F = 38 °C

Table 19. Concrete maturity activation energy and datum temperature.

Aggregate	Cement Content, lb/yd^3	Curing Temp.,[1] ^{0}F	Limiting Comp. Strength,[2] psi	Trial 1[3] Rate Constant, kt (1 /days)	Trial 1[3] Activation Energy, kJ/mol	Trial 1[3] Datum Temp., ^{0}F	Trial 2[4] Rate Constant, kt (1 /days)	Trial 2[4] Activation Energy, kJ/mol	Trial 2[4] Datum Temp., ^{0}F	Average Activation Energy, kJ/mol	Average Datum Temp., oF
Crushed Limestone	500	50	5610	0.3396	35.5	30.2	0.2039	48.3	32.3	41.9	31.3
		72	5290	0.9062			1.0935				
		100	5380	1.3293*			1.3293				
	650	50	6920	0.4563	38.2	26.7	0.3067	44.1	34.0	41.2	30.4
		72	6570	1.785*			1.7850				
		100	5860	2.0023*			2.0023				
Crushed Quartzite	500	50	4530	0.3757	27.2	28.5	0.2050	48.3	34.6	37.8	31.6
		72	5740	0.4488			0.6937				
		100	4970	1.0421*			1.0421				
	650	50	5610	0.6103	27.0	27.5	0.3067	42.1	34.7	34.6	31 .l
		72	6270	0.7680			1.2064				
		100	5310	1.6811*			1.6811				

NOTES:

1 At 50% RH.

‘Extrapolated using hyperbolic function with 7, 14, and 28-day compressive strengths.

3 Using early age (4 to 24 hour) and 1,3-day early load compressive strength data.
Rate constant data marked with (*) excludes 3day strength data.

4 Using early age (4 to 24 hour) and l-day early load compressive strength data.

500 lb/yd^3 = 297 kg/m^3
650 lb/yd^3 = 386 kg/m^3
1000 psi = 6.9 MPa
^{0}C = 5/9 (“F-32)

Table **20. Regression analysis of compressive strength on early load (1- to 28day) Arrhenius maturity.**

Mix	Curing Temp., °F	Curing RH, percent	Testing Age, days	Arrhenius Maturity, days	Comp. Strength, psi	General Equation [1] Predicted f'c, psi	General Equation [1] Prediction Error, percent	Mix Specific [2] Predicted f'c, psi	Mix Specific [2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Limestone 500 lb/yd^3 Cement	50	50	1	0.69	860	1615	88	1486	73	15
			3	1.79	2720	2698	-1	2617	-4	3
			7	4.00	3880	3513	-9	3555	-8	1
			14	7.86	4560	3994	-12	4145	-9	3
			28	15.57	5060	4295	-15	4532	-10	5
	72	50	1	1.48	2470	2479	0	2380	-4	3
			3	3.88	3780	3487	-8	3523	-7	1
			7	8.68	4350	4048	-7	4214	-3	4
			14	17.08	4820	4325	-10	4570	-5	5
			28	33.88	4990	4482	-10	4777	-4	6
	100	50	1	2.82	3050	3187	4	3170	4	1
			3	7.96	3890	4001	3	4154	7	4
			7	18.25	4390	4344	-1	4596	5	4
			14	36.25	4800	4492	-6	4791	0	6
			28	72.25	5110	4571	-11	4897	-4	6
	72	100	1	1.82	2440	2716	11	2638	8	3
			3	4.33	3260	3580	10	3635	12	2
			7	9.33	3790	4085	8	4261	12	5
			14	18.08	4250	4342	2	4592	8	6
			28	35.59	4650	4490	-3	4788	3	0

NOTE:

1 General prediction equation: **1000/f'c =** 0.4149 **+ 0.2789 / AR - 0.0004** * **CEMENT**
where f'c = compressive strength in psi, AR = Arrhenius maturiiy in equivalent days at 68 °F
CEMENT = cement content in lb/yd^3
Data point of **T** = 50 °F and t = 1 day not used in regression analysis.
2 Mix specific prediction equation: 1 000/f'c = 0.1997 + 0.3264 * (1/AR)
Data point of **T=** 50 °F and t = 1 day not used in regression analysis.

500 lb/yd^3 = 297 kg/m3
°C = 5/9 (°F-32)
1000 psi = 6.9 MPa

Table 20. Regression analysis of compressive strength on early load (1- to 28day) Arrhenlus maturity (continued).

Mix	Curing Temp., ^{0}F	Curing RH, percent	Testing Age, days	Arrhenius Maturity, days	Comp. Strength, psi	General Equation [1] Predicted Pc, psi	General Equation [1] Prediction Error, percent	Mix Specific [2] Predicted fc, psi	Mix Specific [2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Limestone 650 lb/yd^3 Cement	50	50	1	0.72	1330	1844	39	2182	64	25
			3	1.79	3860	3218	-17	3465	-10	6
			7	3.93	4850	4427	-9	4417	-9	0
			14	7.68	5620	5230	-7	4975	-11	5
			28	15.19	6300	5772	-8	5323	-16	7
	72	50	1	1.72	3700	3154	-15	3410	-8	7
			3	4.28	4390	4544	4	4501	3	1
			7	9.39	4900	5417	11	5098	4	7
			14	18.34	5550	5879	6	5390	-3	3
			28	36.24	6090	6150	1	5554	-9	8
	100	50	1	3.04	3970	4054	2	4138	4	2
			3	8.20	4750	5293	11	5017	6	6
			7	18.52	5190	5884	13	5393	4	9
			14	38.57	5460	6153	13	5556	2	11
			28	72.67	5700	6300	11	5643	-1	10
	72	100	1	1.63	3090	3067	-1	3336	8	7
			3	4.13	4390	4496	2	4466	2	1
			7	9.15	4410	5394	22	5083	15	7
			14	17.93	5280	5867	11	5382	2	9
			28	35.49	5800	6144	6	5551	-4	2

NOTE:

650 lb/yd^3 = 386 kg/m^3
^{0}C = 5/9 ("F-32)
1000 psi = 6.9 MPa

1 General prediction equation: 1000/f'c = 0.4149 + 0.2789 / AR - 0.0004 * CEMENT
where f'c = compressive strength in psi, AR = Arrhenius maturity in equivalent days at 68 ^{0}F.
CEMENT = cement content in lb/yd^3
Data point of T = 50 ^{0}F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: 1000/f'c = 0.1744 + 0.2044 * (l/AR)
Data point of T= 50 ^{0}F and 1= 1 day not used in regression analysis.
Also data points with compressive strength of 6300, 3700, and 4390 (moist cure) psi not used in regression analysis.

Table 20. Regression analysis of compressive strength on early load (1-to 28-day) Arrhenius maturity (continued).

Mix	Curing Temp., °F	Curing RH, percent	Testing Age, days	Arrhenius Maturity, days	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Quartzite 500 lb/yd^3 Cement	50	50	1	0.67	740	1584	114	1291	74	40
			3	1.73	2310	2659	15	2306	0	15
			7	3.87	3420	3485	2	3181	-7	5
			14	7.61	3800	3975	5	3745	-1	3
			28	15.09	4250	4285	1	4120	-3	2
	72	50	1	1.65	2230	2605	17	2252	1	16
			3	4.15	3200	3545	11	3248	2	9
			7	9.16	3830	4076	6	3865	1	6
			14	17.91	4530	4339	-4	4187	-8	3
			28	35.42	5140	4489	-13	4376	-15	2
	100	50	1	2.81	2450	3183	30	2851	16	14
			3	7.86	3110	3994	28	3767	21	7
			7	17.97	3660	4340	19	4188	14	4
			14	35.66	4220	4490	6	4377	4	3
			28	71.04	4560	4570	0	4479	-2	2
	72	100	1	1.40	2180	2415	11	2064	-5	5
			3	3.70	3370	3445	2	3137	-7	5
			7	8.31	4000	4025	1	3804	-5	4
			14	16.37	4220	4312	2	4153	-2	1
			28	32.49	4820	4475	-7	4358	-10	2

NOTE:

$500\ lb/yd^3 = 297\ kg/m^3$
$^0C = 5/9\ (^0F-32)$
1000 psi = 6.9 MPa

1 General prediction equation: 1000/f'c = 0.4149 + 0.2789 / AR - 0.0004 * CEMENT
where f'c = compressive strength in psi, AR = Arrhenius maturiiy in equivalent days at 68 ^0F.
CEMENT = cement content in lb/yd^3
Data point of T = 50 ^0F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: 1000/f'c = 0.2180 + 0.3730 * (1/AR)
Data point of T= 50 ^0F and t = 1 day not used in regression analysis.

Table 20. Regression analysis of compressive strength on early load (1 to 28-day) Arrhenius maturity (continued).

Mix	Curing Temp.,	Curing RH, percent	Testing Age, days	Arrhenius Maturity, days	Comp. Strength, psi	General Equation [1] Predicted f'c, psi	General Equation [1] Prediction Error, percent	Mix Specific [2] Predicted f 'c, psi	Mix Specific [2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Quartzite 650 lb/yd[3] Cement	50	50	1	0.70	1320	1807	37	2165	64	27
			3	1.78	3520	3209	-9	3375	-4	5
			7	3.93	4310	4427	3	4209	-2	0
			14	7.71	4810	5234	9	4678	-3	6
			28	15.27	5250	5775	10	4963	-5	5
	72	50	1	1.75	3470	3182	-8	3354	-3	5
			3	4.25	4280	4535	6	4275	0	6
			7	9.25	4970	5404	9	4770	-4	5
			14	18.00	5330	5869	10	5010	-6	4
			28	35.51	6010	6144	2	5145	-14	12
	100	50	1	3.00	3360	4034	20	3958	18	2
			3	8.26	3950	5300	34	4714	19	15
			7	18.79	4630	5891	27	5021	8	19
			14	37.21	4920	6158	25	5151	5	20
			28	74.05	5140	6303	23	5220	2	21
	72	100	1	1.75	3430	3182	-7	3354	-2	5
			3	4.26	4170	4538	9	4277	3	6
			7	9.26	4670	5405	16	4770	2	14
			14	18.01	5280	5869	11	5010	-5	6
			28	35.52	5560	6144	11	5145	-7	3

NOTE:

1 General prediction equation: $1000/f'c = 0.4149 + 0.2789 / AR - 0.0004 * CEMENT$
where fc = compressive strength in psi, AR = Arrhenius maturity in equivalent days at 68 °F.
CEMENT = cement content in lb/yd^3
Data point of T = 50 ^{0}F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: $1000/f'c = 0.1890 + 0.1910 * (1/AR)$
Data point of T= 50 ^{0}F and t = 1 day not used in regression analysis.

$650\ lb/yd^3 = 386\ kg/m^3$
°C = 5/9 (°F-32)
1000 psi = 6.9 MPa

Table 21. Regression analysis of compressive strength on early load (1- to 28-day) Nurse-Saul maturity.

Mix	Curing Temp., ^0F	Curing RH. percent	Testing Age, days	Nurse - Saul Maturity, "F-days	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Limestone 500 lb/yd^3 Cement	50	50	1	25	860	1751	104	1634	90	14
			3	61	2720	2756	1	2716	0	1
			7	134	3880	3520	-9	3623	-7	3
			14	261	4560	3968	-13	4192	-8	5
			28	516	5060	4250	-16	4566	-10	6
	72	50	1	48	2470	2487	1	2415	-2	2
			3	132	3780	3508	-7	3607	-5	3
			7	298	4350	4035	-7	4280	-2	6
			14	590	4820	4289	-11	4619	-4	7
			28	1,174	4990	4430	-11	4812	-4	8
	100	50	1	70	3050	2905	-5	2886	-5	1
			3	203	3890	3821	-2	4002	3	1
			7	471	4390	4220	-4	4527	3	1
			14	939	4800	4394	-8	4762	-1	8
			28	1,876	5110	4486	-12	4890	-4	8
	72	100	1	55	2440	2641	8	2586	6	2
			3	141	3260	3561	9	3674	13	3
			7	313	3790	4058	7	4311	14	7
			14	614	4250	4300	1	4634	9	8
			28	1,216	4650	4435	-5	4820	4	1

NOTE:

1 General prediction equation: $1000/f'c = 0.4182 + 8.8263 / NS - 0.0004 * CEMENT$
where f'c = compressive strength in psi, NS = Nurse-Saul maturiiy in ^0F - days
CEMENT = cement content in lb/yd^3
Data point of T = 50 ^0F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: $1000/f'c = 0.1990 + 10.3229 * (1/NS)$
Data point of T= 50 ^0F and t = 1 day not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3
^0C = 5/9 ("F-32)
1000 psi = 6.9 MPa

Table 21. Regression analysis of compressive strength on early load (l-to 28day) Nurse-Saul maturity (continued).

Mix	Curing Temp., ^oF	Curing RH. percent	Testing Age, days	Nurse - Saul Maturity, "F-days	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Limestone 3 650 lb/yd Cement	50	50	1	26	1330	2009	51	2374	79	27
			3	61	3860	3301	-14	3584	-7	7
			7	130	4850	4423	-9	4485	-8	1
			14	252	5620	5175	-8	5028	-11	3
			28	496	6300	5682	-10	5365	-15	5
	72	50	1	53	3700	3079	-17	3390	-8	8
			3	140	4390	4520	3	4558	4	1
			7	315	4900	5370	10	5159	5	4
			14	621	5550	5800	5	5441	-2	3
			28	1,233	6090	6047	-1	5598	-8	7
	100	50	1	72	3970	3561	-10	3804	-4	6
			3	206	4750	4974	5	4886	3	2
			7	474	5190	5655	9	5348	3	6
			14	943	5460	5968	9	5548	2	8
			28	1,881	5700	6139	8	5655	-1	7
	72	100	1	51	3090	3019	-2	3336	8	6
			3	137	4390	4492	2	4537	3	1
			7	310	4410	5357	21	5150	17	5
			14	611	5280	5792	10	5436	3	7
			28	1,215	5800	6044	4	5596	-4	1

NOTE:

650 lb/yd ^{3} = 386 kg/m ^{3}
^0C = 5/9 (^oF-32)
1000 psi = 6.9 MPa

1 General prediction equation: 1000/f'c = 0.4182 + 8.8263 / NS - 0.0004 * CEMENT
where f'c = compressive strength in psi, NS = Nurse-Saul maturity in ^0F - days
CEMENT = cement content in lb/yd ^{3}
Data point of T = 50 ^0F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: 1000/f'c = 0.1734 + 6.4423 * (1/NS)
Data point of T= 50 ^0F and t = 1 day not used in regression analysis.
Also data points with compressive strength of 6300, 3700, and 4390 (moist cure) psi not used in regression analysis.

Table 21. Regression analysis of compressive strength on early load (1 to 28-day) Nurse-Saul maturity (continued).

Mix	Curing Temp., oF	Curing RH, percent	Testing Age, days	Nurse - Saul Maturity, “F-days	Comp. Strength, psi	General Equation [1] Predicted f'c, psi	General Equation [1] Prediction Error, percent	Mix Specific [2] Predicted f'c, psi	Mix Specific [2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Quartzite 500 lb/yd^3 Cement	50	50	1	24	740	1707	131	1388	88	43
			3	58	2310	2700	17	2357	2	15
			7	127	3420	3476	2	3220	-6	4
			14	249	3800	3942	4	3792	0	4
			28	491	4250	4234	0	4172	-2	1
	72	50	1	52	2230	2578	16	2230	0	16
			3	138	3209	3544	11	3301	3	8
			7	310	3830	4054	6	3935	3	3
			14	611	4530	4298	-5	4258	-6	1
			28	1,213	5140	4435	-14	4444	-14	0
	100	50	1	69	2450	2889	18	2558	4	14
			3	202	3110	3818	23	3635	17	6
			7	467	3660	4218	15	4150	13	2
			14	931	4220	4392	4	4385	4	0
			28	1,859	4560	4485	-2	4514	-1	1
	72	100	1	46	2180	2439	12	2088	-4	8
			3	127	3370	3476	3	3220	-4	1
			7	289	4000	4020	1	3891	-3	2
			14	571	4220	4280	1	4233	0	1
			28	1,137	4820	4426	-8	4431	-8	0

NOTE:

1 General prediction equation: $1000/f'c = 0.4182 + 8.8263 / NS - 0.0004 * CEMENT$
where f'c = compressive strength in psi, NS = Nurse-Saul maturity in ^{0}F - days
CEMENT = cement content in lb/yd^3
Data point of T = 50 ^{0}F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: $1000/f'c = 0.2150 + 12.1370 * (1 / NS)$
Data point of T= 50 ^{0}F and t = 1 day not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3
oC = 5/9 (“F-32)
1000 psi = 6.9 MPa

Table 21. Regression analysis of compressive strength on early load (1-to 28-day) Nurse-Saul maturity (continued).

Mix	Curing Temp., °F	Curing RH, percent	Testing Age, days	Nurse - Saul Maturity, °F-days	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Quartzite	50	50	1	25	1320	1956	48	2323	76	28
			3	60	3520	3275	-7	3460	-2	5
650 lb/yd ^{3}			7	131	4310	4433	3	4268	-1	2
Cement			14	254	4810	5183	8	4720	-2	6
			28	500	5250	5687	8	4997	-5	3
	72	50	1	53	3470	3079	-11	3307	-5	7
			3	139	4280	4511	5	4318	1	5
			7	311	4970	5360	8	4819	-3	5
			14	612	5330	5793	9	5053	-5	3
			28	1,214	6010	6043	1	5182	-14	13
	100	50	1	71	3360	3540	5	3658	9	4
			3	207	3950	4979	26	4602	17	10
			7	478	4630	5660	22	4983	8	15
			14	951	4920	5971	21	5145	5	17
			28	1,899	5140	6141	19	5230	2	18
	72	100	1	53	3430	3079	-10	3307	-4	7
			3	139	4170	4511	8	4318	4	5
			7	311	4670	5360	15	4819	3	12
			14	612	5280	5793	10	5053	-4	5
			28	1,214	5560	6043	9	5182	-7	2

NOTE:

[1] General prediction equation: 1000/f'c = 0.4182 + 8.8263 / NS - 0.0004 * CEMENT
where f'c = compressive strength in psi, NS = Nurse-Saul maturity in °F - days
CEMENT = cement content in lb/yd ^{3}
Data point of T = 50 °F and t = 1 day not used in regression analysis.

[2] Mix specific prediction equation: 1000/f'c = 0.1880 + 6.0620 * (1/NS)
Data point of T= 50 °F and t = 1 day not used in regression analysis.

650 lb/yd ^{3} = 386 kg/m ^{3}
°C = 5/9 (°F-32)
1000 psi = 6.9 MPa

Table 22. Regression analysis of compressive strength on early load (1 to 28-day) pulse velocity.

Mix	Curing Temp., oF	Curing RH, percent	Testing Age, days	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Limestone	50	50	1	11,700	860	2072	141	1795	109	32
			3	13,800	2720	3226	19	3017	11	8
500 lb/yd ^{3}			7	14,400	3880	3922	1	3761	-3	2
Cement			14	14,600	4560	4414	-3	4280	-6	3
			28	14,800	5060	4967	-2	4870	-4	2
	72	50	1	13,700	2470	2759	12	2554	3	8
			3	14,500	3780	3566	-6	3413	-10	4
			7	14,700	4350	4094	-6	3966	-9	3
			14	15,000	4820	4674	-3	4593	-5	2
			28	15,100	4990	5186	4	5135	3	1
	100	50	1	14,300	3050	3006	-1	2839	-7	5
			3	14,500	3890	3566	-8	3413	-12	4
			7	15,100	4390	4335	-1	4256	-3	2
			14	14,900	4800	4607	-4	4513	-6	2
			28	15,100	5110	5186	1	5135	0	1
	72	100	1	14,100	2440	2922	20	2741	12	7
			3	14,800	3260	3722	14	3599	10	4
			7	14,800	3790	4153	10	4036	7	3
			14	15,100	4250	4741	12	4675	10	2
			28	15,300	4650	5336	15	5319	14	0

NOTE:

1 General prediction equation: Log(f'c) = 2.2886 + 0.0622 * (PV/1000) + 0.0006 * CEMENT + 0.1292 log(AGE)
where f'c = compressive strength in psi, PV = Pulse velocity in ft/s,
CEMENT = cement content in lb/yd ^{3}, AGE = curing period in days
Data point of T = 50 deg. F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: Log (f'c) = 2.3578 + 0.0766 * (PV /1000) + 0.1355 * Log(AGE)
Data point of T= 50 ^{0}F and t = 1 day not used in regression analysis.

500 lb/yd ^{3} = 297 kg/m ^{3}
^{0}C = 5/9 (^{0}F-32)
1000 psi = 6.9 MPa
1000 ft/s = 305 m/s

Table 22. Regression analysis of compressive strength on early load (1 to 28-day) pulse velocity (continued).

Mix	Curing Temp., oF	Curing RH, percent	Testing Age, days	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed	50	50	1	12,500	1330	2858	115	2848	114	1
Limestone			3	14,500	3860	4387	14	4120	7	7
			7	14,500	4850	4894	1	4564	-6	5
650 lb/yd^3			14	15,200	5620	5917	5	5392	-4	1
Cement			28	14,800	6300	6111	-3	5592	-11	8
	72	50	1	13,300	3700	3205	-13	3131	-15	2
			3	14,700	4390	4514	3	4219	-4	1
			7	15,000	4900	5258	7	4843	-1	6
			14	15,200	5550	5917	7	5392	-3	4
			28	15,300	6090	6565	8	5932	-3	5
	100	50	1	14,700	3970	3917	-1	3695	-7	6
			3	14,900	4750	4645	-2	4320	-9	7
			7	15,100	5190	5333	3	4900	-6	3
			14	15,200	5460	5917	8	5392	-1	7
			28	15,100	5700	6380	12	5794	2	10
	72	100	1	14,200	3090	3646	18	3482	13	5
			3	13,800	4390	3968	-10	3793	-14	4
			7	15,300	4410	5488	24	5018	14	11
			14	15,300	5280	6003	14	5456	3	10
			28	15,600	5800	6853	18	6147	6	12

NOTE:

[1] General prediction equation: Log(fc) = 2.2886 + 0.0622 . (PV/1000) + 0.0006 * CEMENT + 0.1292 * log(AGE)
where fc = compressive strength in psi, PV = Pulse velocity in ft/s,
CEMENT = cement content in lb/yd^3, AGE = curing period in days
Data point of T = 50 deg. F and t = 1 day not used in regression analysis.

[2] Mix specific prediction equation: Log(f'c) = 2.812 + 0.0514 . (PV /1000 + 0.1208 . Log(AGE)
Data point of T= 50 oF and t = 1 day not used in regression analysis.
Also data points with compressive strength of 6300, 3700, and 4390 (moist cure) psi not used in regression analysis.

650 lb/yd^3 = 386 kg/m^3
oC = 5/9 (°F-32)
1000 psi = 6.9 MPa
1000 ft/s = 305 m/s

Table 22. Regression analysis of compressive strength on early load (l-to28-day) pulse velocity (continued).

Mix	Curing Temp., oF	Curing RH, percent	Testing Age, days	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted f'c, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Quartzite 500 lb/yd^3 Cement	50	50	1	10,900	740	1847	150	1166	58	92
			3	13,000	2310	2876	25	2416	5	20
			7	13,700	3420	3548	4	3238	-5	2
			14	14,300	3800	4228	11	4149	9	2
			28	14,100	4250	4494	6	4208	-1	5
	72	50	1	13,100	2230	2532	14	2217	-1	13
			3	13,800	3200	3226	1	3051	-5	4
			7	14,200	3830	3811	0	3748	-2	2
			14	14,400	4530	4289	-5	4272	-6	0
			28	14,600	5140	4827	-6	4870	-5	1
	100	50	1	13,500	2450	2681	9	2492	2	8
			3	13,700	3110	3180	2	2964	-5	2
			7	13,900	3660	3651	0	3433	-6	6
			14	14,400	4220	4289	2	4272	1	0
			28	14,600	4560	4827	6	4870	7	1
	72	100	1	13,300	2180	2605	20	2350	8	12
			3	14,100	3370	3367	0	3331	-1	1
			7	14,400	4000	3922	-2	3973	-1	1
			14	14,500	4220	4351	3	4398	4	1
			28	14,700	4820	4897	2	5014	4	2

NOTE:

1 General prediction equation: Log(f'c) = 2.2886 + 0.0622 * (PV/1000) + 0.0006 * CEMENT + 0.1292 * log(AGE)
where f'c = compressive strength in psi, PV = Pulse velocity in ft/s,
CEMENT = cement content in lb/yd^3, AGE = curing period in days
Data point of T = 50 deg. F and t = 1 day not used in regression analysis.
2 Mix specific prediction equation: Log(f'c) = 1.6847 + 0.1268 * (PV /1000) + 0.1047 * Log(AGE)
Data point of T= 50 ^{0}F and t = 1 day not used in regression analysis.

500 lb/yd^3 = 297 kg/m^3
^{0}C = 5/9 (°F-32)
1000 psi = 6.9 MPa
1000 ft/s = 305 m/s

Table 22. Regression analysis of compressive strength on early load (1 to 28-day) pulse velocity (continued).

Mix	Curing Temp., ^{0}F	Curing RH, percent	Testing Age, days	Pulse Velocity, ft/s	Comp. Strength, psi	General Equation[1] Predicted f'c, psi	General Equation[1] Prediction Error, percent	Mix Specific[2] Predicted fc, psi	Mix Specific[2] Prediction Error, percent	Difference of Absolute Errors, percent
Crushed Quartzite	50	50	1	11,900	1320	2623	99	2184	65	33
			3	13,800	3520	3968	13	3749	6	6
			7	14,100	4310	4622	7	4321	0	7
650 lb/yd ^{3}			14	14,300	4810	5202	8	4802	0	8
Cement			28	14,500	5250	5854	12	5336	2	10
	72	50	1	13,700	3470	3394	-2	3337	-4	2
			3	14,200	4280	4202	-2	4119	-4	2
			7	14,500	4970	4894	-2	4748	-4	3
			14	14,800	5330	5588	5	5402	1	3
			28	15,000	6010	6289	5	6003	0	5
	100	50	1	14,000	3360	3543	5	3582	7	1
			3	14,200	3950	4202	6	4119	4	2
			7	14,200	4630	4688	1	4424	-4	3
			14	14,600	4920	5430	10	5153	5	6
			28	14,400	5140	5771	12	5212	1	11
	72	100	1	13,700	3430	3394	-1	3337	-3	2
			3	14,200	4170	4202	1	4119	-1	0
			7	14,500	4670	4894	5	4748	2	3
			14	14,600	5280	5430	3	5153	-2	0
			28	14,600	5560	5939	7	5464	-2	5

NOTE:

1 General prediction equation: Log(fc) = 2.2886 + 0.0622 * (PV/1000) + 0.0006 * CEMENT + 0.1292 * log(AGE)
where fc = compressive strength in psi, PV= Pulse velocity in ft/s,
CEMENT = cement content in lb/yd^3 , AGE = curing period in days
Data point of T = 50 deg. F and t = 1 day not used in regression analysis.

2 Mix specific prediction equation: Log(fc) = 2.3578 + 0.0766 * (PV /1000 + 0.1355 * Log(AGE)
Data point of T= 50 ^{0}F and t = 1 day not used in regression analysis.

650 lb/yd 3 = 386 kg/m3
^{0}C = 5/9 (OF-32)
1000 psi = 6.9 MPa
1000 ft/s = 305 m/s

Table 23. Summary of slab A sawcut test data (crushed limestone, cement content 660 lb/yd^3).

Saw-cut No.	Age, hours	Cylinder					Slab			
		f'c, psi	NS [1] Maturity, °F-h	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi	NS [1] Maturity, °F	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi
1	2.2	350	115	52	10,500	506	123	67	8,500	207
2	3.0	490	190	258	12,800	1,413	199	290	11,700	865
3	3.5	900	228	392	13,000	1,545	240	432	12,000	989
4	3.9	1,210	267	529	13,200	1,690	281	574	12,100	1,034

NOTES: 1 Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

2 Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

3 Estimated compressive strength from early age laboratory developed mix - specific pulse velocity equation.

650 lb/yd 3 = 386 kg/m^3 , 1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s, 32 °F = 0 °C

Table 24. Summary of slab B sawcut test data (crushed limestone, cement content 500 lb/yd 3).

Saw-cut No.	Age, hours	Cylinder					Slab			
		f'c, psi	NS [1] Maturity, °F-h	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi	NS [1] Maturity, °F	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi
1	3.2	70	137	101	4,600	50	142	111	****	****
2	4.1	140	185	242	9,000	298	192	267	2,600	22
3	4.7	310	211	331	10,500	547	219	361	8,700	264
4	5.2	425	239	429	1 1 ,800	926	248	461	9,800	412
5	6.1	680	299	635	13,000	1,507	310	673	11,100	698
6	7.1	910	361	633	13,500	1,845	379	885	11,900	965
7	8.1	1,130	421	1,003	13,300	1,701	448	1,071	12,200	1,089

NOTES: 1 Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

2 Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

3 Estimated compressive strength from early age laboratory developed mix - specific pulse velocity equation.

500 lb/yd 3 = 297 kg/m 3,1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s, 32 °F = 0 °C

Table 25. Summary of slab C sawcut test data (crushed quartzite, cement content 650 lb/yd 3(.

Saw-cut No.	Age, hours	Cylinder					Slab			
		f'c, psi	NS 1 Maturity, °F-h	Est. f'c 2 psi	Pulse Velocity, ft/s	Est. f'c 3 psi	NS 1 Maturity, °F	Est. f'c 2 psi	Pulse Velocity, ft/s	Est. f'c 3 psi
1	3.6	170	160	162	8,100	241	159	159	6,800	140
2	4.6	430	215	345	10,300	603	211	332	8,900	336
3	5.3	525	275	555	11,100	842	270	537	10,000	532
4	6.3	900	342	776	11,900	1,175	335	752	11,000	807
5	7.3	1,350	413	982	12,500	1 ,508	403	954	11,700	1 ,081
6	8.5	1,825	485	1,161	12,900	1 ,782	472	1,131	12,200	1,331

NOTES: 1 Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

2 Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

3 Estimated compressive strength from early age laboratory developed mix - specific pulse velocity equation.

650 lb/yd ^{3} = 386 kg/m ^{3}, 1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s, 32 °F = 0 °C

Table 26. Summary of slab D sawcut test data (crushed quartrite, cement content 500 lb/yd ^{3}).

Saw - cut No.	Age, hours	Cylinder f'c, psi	Cylinder NS [1] Maturity, °F-h	Cylinder Est. f'c [2] psi	Cylinder Pulse Velocity, ft/s	Cylinder Est. f'c [3] psi	Slab NS[1] Maturity, °F	Slab Est. f'c [2] psi	Slab Pulse Velocity, ft/s	Slab Est. Pc [3] psi
1	5.1	250	246	453	10,300	531	238	426	8,100	210
2	6.3	500	336	758	11,500	880	324	720	9,500	379
3	7.1	680	370	858	12,000	1,086	355	814	10,100	488
4	a.2	930	440	1,050	12,500	1,341	418	993	10,700	628
5	9.2	1,140	512	1,222	12,600	1,399	481	1,152	11,200	776
6	10.3	1,280	620	1,432	12,700	1,459	577	1,353	11,500	880
7	12.1	1,430	718	1,587	13,000	1,656	669	1,514	11,700	957
a	25.1	1,840	1,103	1,993	13,100	1,727	1,321	2,138	12,400	1,286

NOTES: [1] Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

[2] Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

[3] Estimated compressive strength from early age laboratory developed mix - specific pulse velocity equation.

500 lb/yd ^{3} = 297 kg/m ^{3}, 1000 psi = 6.9 MPa, 1OOOft/s=3O5 m/s,32°F = O°C

Table 27. Summary of slab E sawcut test data (rounded gravel, cement content 500 lb/yd^3).

Saw-cut No.	Age, hours	Cylinder					Slab			
		f'c, psi	NS[1] Maturity, °F-h	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi	NS [1] Maturity, °F	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi
I	3.6	110	171	198	7,300	106	203	304	7,600	123
2	4.9	200	242	439	8,900	238	305	656	9,800	377
3	6.3	370	316	693	10,200	462	412	978	10,800	626
4	7.3	600	371	863	11,400	850	462	1,154	11,100	730
5	8.3	870	428	1,019	12,000	1,153	551	1,303	11,500	a94

NOTES: 1 Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

2 Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

3 Estimated compressive strength from early age laboratory developed mix - specific pulse velocity equation.

500 lb/yd^3 = 297 kg/m^3 1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s, 32 °F = 0

Table 28. Summary of slab F sawcut test data (rounded gravel, cement content 650 lb/yd ^{3}).

Saw-cut No.	Age, hours	Cylinder f'c psi	Cylinder NS[1] Maturity, °F-h	Cylinder Est. f'c[2] psi	Cylinder Pulse Velocity, ft/s	Cylinder Est. f'c[3] psi	Slab NS[1] Maturity, °F	Slab Est. f'c[2] psi	Slab Pulse Velocity, ft/s	Slab Est. f'c[3] psi
1	2.8	280	156	151	8,800	258	166	182	7,500	135
2	3.4	400	188	253	10,200	518	199	289	8,400	212
3	3.9	540	222	371	11,600	1,039	234	413	9,600	384
4	4.4	680	259	498	12,000	1,268	273	548	10,400	572
5	4.9	900	296	628	12,400	1,547	313	684	11,000	771
6	6.4	1,920	412	978	12,600	1,708	437	1,043	11,600	1,039

NOTES: 1 Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

2 Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

3 Estimated compressive strength from early age laboratory developed mix- specific pulse velocity equation.

650 lb/yd ^{3} = 386 kg/m ^{3}, 1000 psi = 6.9MPa, 1000 ft/s = 305 m/s, 32 °F = 0 °C

Table 29. Summary of slab G sawcut test data (crushed limestone, cement content 650 lb/yd ^{3}).

Saw-cut No.	Age, hours	Cylinder					Slab			
		f'c, psi	NS[1] Maturity, °F-h	Est. f'c [2] psi	Pulse Velocity, ft/s	Est. f'c [3] psi	NS [1] Maturity, °F	Est. f'c [2], psi	Pulse Velocity, ft/s	Est. f'c [3] psi
1	3.0	260	159	161	10,000	405	164	174	6,900	101
2	3.5	300	195	276	11,100	661	197	283	8,200	181
3	3.9	410	234	411	12,200	1,081	234	410	9,300	296
4	4.4	520	274	552	12,900	1,478	273	547	10,800	578
5	4.9	1,180	315	688	13,200	1,690	313	682	11,500	791

NOTES: 1 Nurse-Saul maturity in °F - hours (datum temperature 32 °F).

2 Estimated compressive strength from sawing slab regression analysis of cylinder strength on maturity.

3 Estimated compressive strength from early age laboratory developed mix - specific pulse velocity equation.

650 lb/yd ^{3} = 386 kg/m ^{3}, 1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s, 32 °F = 0 °C

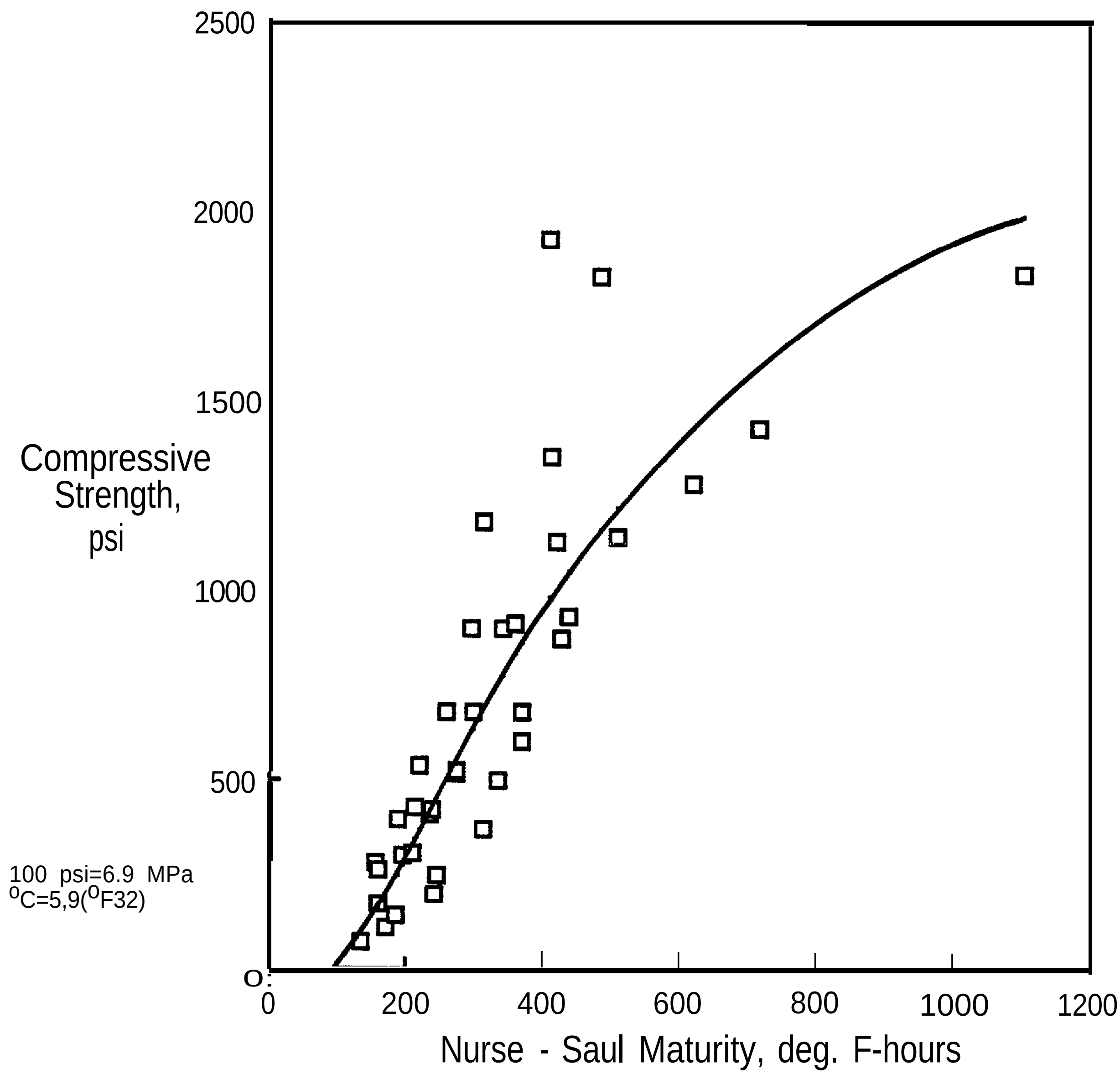


Figure 1. Sawing slab concrete Nurse-Saul maturity versus compressive strength.

Table 30. Estimation of early age compressive strength from Clegg hammer impact reading.

Slab No.	Age, hours	Cylinder f'c, [1] psi	Slab Clegg Reading	Est. f'c [2] psi	50 °F, Block Clegg Reading	Est. f'c [2] psi	72 °F, Block Clegg Reading	Est. f'c, [2] psi	100 °F, Block Clegg Reading	Est. f'c, [2] psi
A	1.5	****	28	128	34	150	48	206	60	262
	2.3	350	76	346	80	369	181	1,193	188	1,267
Crushed	3.1	490	172	1,100	****	****	****	****	****	****
Limestone	3.6	900	146	854	52	224	184	1,225	190	1,289
	3.8	1,120	142	819	****	****	****	****	****	****
650 lb/yd ^{3}	4.3	1,540	****	****	183	1,214	188	1,267	191	1,300
Cement	4.5	1,680	185	1,235	****	****	****	****	****	****
	5.6	2,350	189	1,278	****	****	****	****	****	****
	7.1	2,680	191	1,300	192	1,311	181	1,193	189	1,278
B	1.9	****	4	59	****	****	****	****	****	****
	2.9	****	10	74	****	****	****	****	****	****
Crushed	3.2	****	15	87	****	****	****	****	****	****
Limestone	3.4	70	****	****	16	90	27	125	33	146
		140	35	153	32	142	54	233	62	272
500 lb/yd ^{3}	4.6	220	55	238	****	****	****	****	****	****
Cement	4.8	310	****	****	46	198	91	436	103	515
	5.1	410	76	346	****	****	****	****	****	****
	5.9	640	104	522	79	363	153	917	165	1,031
	6.9	900	146	854	****	****	****	****	****	****
	7.3	980	****	****	132	735	167	1,051	189	1,278
	8.0	1,130	163	1,012	160	983	189	1,278	189	1,278

NOTES: 1 Estimated compressive strength from cylinder strength vs.time curve.

2 Estimated compressive strength from sawing slab linear regression analysis.

1000 psi = 6.9 MPa, 50 °F = 10 °C, 70 °F = 21 °C, 100 °F = 38 °C

500 lb/yd ^{3} = 297 kg/m ^{3} ,650 lb/yd ^{3} = 386 kg/m ^{3}

Table 30. Estimation of early age compressive strength from Clegg hammer impact reading (continued).

Slab No.	Age, hours	Cylinder f'c, [1] psi	Slab Clegg Reading	Est. f'c, [2] psi	50 ^oF, Block Clegg Reading	Est. f'c, [2] psi	72 ^oF, Block Clegg Reading	Est. f'c, [2] psi	100 ^oF, Block Clegg Reading	Est. f'c, [2] psi
C	2.9	****	16	90	8	69	16	90	20	102
	3.3	****	24	115	14	85	22	108	29	132
Crushed	4.3	300	60	262	29	132	59	257	91	436
Quartzite	5.3	525	101	502	60	262	120	639	172	1,100
	6.3	900	138	785	88	417	184	1,225	188	1,267
650 lb/yd ^{3}	7.3	1,350	144	837	****	****	****	****	****	****
Cement	7.7	1.480	****	****	160	963	185	1,235	185	1,235
	8.7	1,810	167	1,051	176	1,141	186	1,246	186	1,246
D	3.5	***	10	74	****	****	****	****	****	****
	4.0	80	17	93	****	****	****	****	****	****
Crushed	4.7	182	34	150	11	76	17	93	23	112
Quartzite	6.0	400	55	238	30	135	43	185	65	287
	7.1	680	74	335	37	161	72	324	103	515
500 lb/yd ^{3}	8.1	910	102	509	62	272	109	558	150	890
Cement	9.1	1,110	117	616	****	****	****	****	****	****
	9.6	1,210	****	*****	99	488	143	828	151	899
	10.1	1,230	132	735	****	****	****	****	****	****
	24.0	1,830	127	694	143	828	187	1,257	183	1,214

NOTES: 1 Estimated compressive strength from cylinder strength vs time curve.

2 Estimated compressive strength from sawing slab linear regression analysis.

1000psi=6.9MPa, 50 ^oF=10 ^oC, 70 ^oF=21 ^oC, 100°F=38 ^oC

500 lb/yd ^{3} ,297 kg/m ^{3} ,650 lb/yd ^{3} = 386 kg/m ^{3}

Table 30. Estimation of early age compressive strength from Clegg hammer impact reading (continued).

Slab No.	Age, hours	Cylinder f'c,[1] psi	Slab Clegg Reading	Est. f'c[2] psi	50 °F, Block Clegg Reading	Est. f'c,[2] psi	72 °F, Block Clegg Reading	Est. f'c,[2] psi	100 °F, Block Clegg Reading	Est. f'c,[2] psi
E	2.8	****	24	115	19	99	29	132	40	173
	4.8	190	55	238	136	768	152	908	77	352
Rounded	5.8	270	93	449	****	****	****	****	****	****
Gravel	5.9	290	****	****	146	854	177	1,151	155	936
	6.5	420	128	702	155	936	187	1,257	187	1,257
500 lb/yd³	7.3	600	165	1,031	****	****	****	****	****	****
Cement	7.5	640	****	****	185	1,235	182	1,203	190	1,289
	8.2	820	184	1,225	****	****	****	****	****	****
F	2.4	****	27	125	19	99	26	121	31	139
	2.8	****	44	189	****	****	****	****	****	****
Rounded	3.1	290	***	***	38	165	86	292	65	287
Gravel	3.3	340	69	308	65	287	118	624	148	872
	3.9	510	96	468	****	****	****	****	****	****
650 lb/yd³	4.4	650	132	735	****	****	****	****	*****	****
Cement	4.8	800	****	****	147	863	194	1,333	187	1,257
	4.9	860	182	1,203	****	****	****	****	****	****
	6.2	1,720	185	1,235	****	****	****	****	****	****

NOTES: 1 Estimated compressive strength from cylinder strength vs time curve.

2 Estimated compressive strength from sawing slab linear regression analysis.

1000psi=6.9MPa, 50°F=10°C, 70°F=21 °C, 100°F=38°C

500 lb/yd ^{3} = 297 kg/m^3 , 650 lb/yd ^{3} = 386 kg/m ^{3}

Table 30. Estimation of early age compressive strength from Clegg hammer impact reading (continued).

Slab No.	Age, hours	Cylinder f'c,[1] psi	Slab Clegg Reading	Est. f'c [2] psi	50 °F Block Clegg Reading	Est. f'c[2] psi	72 °F Block Clegg Reading	Est. f'c,[2] psi	100 °F, Block Clegg Reading	Est. f'c [2] psi
G	1.9	****	12	79	****	****	****	****	****	****
	2.4	****	19	****	****	****	****	****	****	****
Crushed	2.9	****	43	185	****	****	****	****	****	****
Limestone	3.4	300	61	287	****	****	****	****	****	****
	3.8	390	74	335	****	****	****	****	****	****
650 lb/yd^3	4.1	450	93	449	****	****	****	****	****	****
Cement	4.6	730	129	710	****	****	****	****	****	****
	5.1	1,260	142	819	****	****	****	****	****	****
	6.2	1,860	171	1,090	****	*****	****	****	****	****
	7.2	2,190	182	1,203	****	****	****	****	****	****
	7.9	2,390	188	1,267	****	****	****	****	****	****

NOTES: [1] Estimated compressive strength from cylinder strength vs time curve.

[2] Estimated compressive strength from sawing slab linear regression analysis.

1000 psi = 6.9 MPa, 50 °F = 10 °C, 70 °F = 21 °C. 100 °F = 38 °C

500 lb/yd^3 = 297 kg/m^3, 650 lb/yd^3 = 386 kg/m^3

Table 31. Sawcut rating versus time to initial and final set of mortar.

Sawing Slab	Cement Content, lb/yd 3	Time to Initial Set, hours	Time to Final Set, hours	Time of First Sawcut, hours	Rating of First Sawcut
A	650	1.4	2.0	2.2	1.8
B	500	2.7	3.8	3.2	1.0
C	650	2.5	3.3	3.6	1.0
D	500	3.1	4.0	5.1	1.0
E	500	2.2	3.0	3.6	1.0
F	650	1.7	2.4	2.8	1.0
G[1]	650	1.5	2.5	3.0	1.7
G[2]	650	1.5	2.5	3.0	1.2

NOTES: [1]Diamond blade cut.

[2]Abrasive blade cut.

500 lb/yd ^{3} = 297 kg/m ^{3}
650 lb/yd ^{3} = 386 kg/m ^{3}

Table 32. Mortar cube compressive strength for sawcut slabs.

Slab B		Slab C		Slab D		Slab E		Slab F		Slab G	
Age, hours	f'c[1] psi	Age, hours	f'c,[1] psi	Age, hours	f'c,[1] psi	Age, hours	f'c,[1] psi	Age, hours	f'c,[1] psi	Age, hours	f'c,[1] psi
3.3	60	3.4	120	4.1	180	3.3	80	3.7	100	3.0	340
5.1	330	4.7	490	5.4	390	4.8	270	4.3	740	4.2	1180
5.6	490	6.5	2000	7.1	840	6.3	510	6.6	1270	4.9	1630
6.8	1030	7.7	2320	8.1	1270	7.3	790	****	****	5.5	1980
7.8	1470	8.6	2590	8.9	1580	8.3	1180	****	****	6.2	2300

NOTES: [1]fc = cube compressive strength, psi

No data for slab A.

100 psi = 0.69 MPa

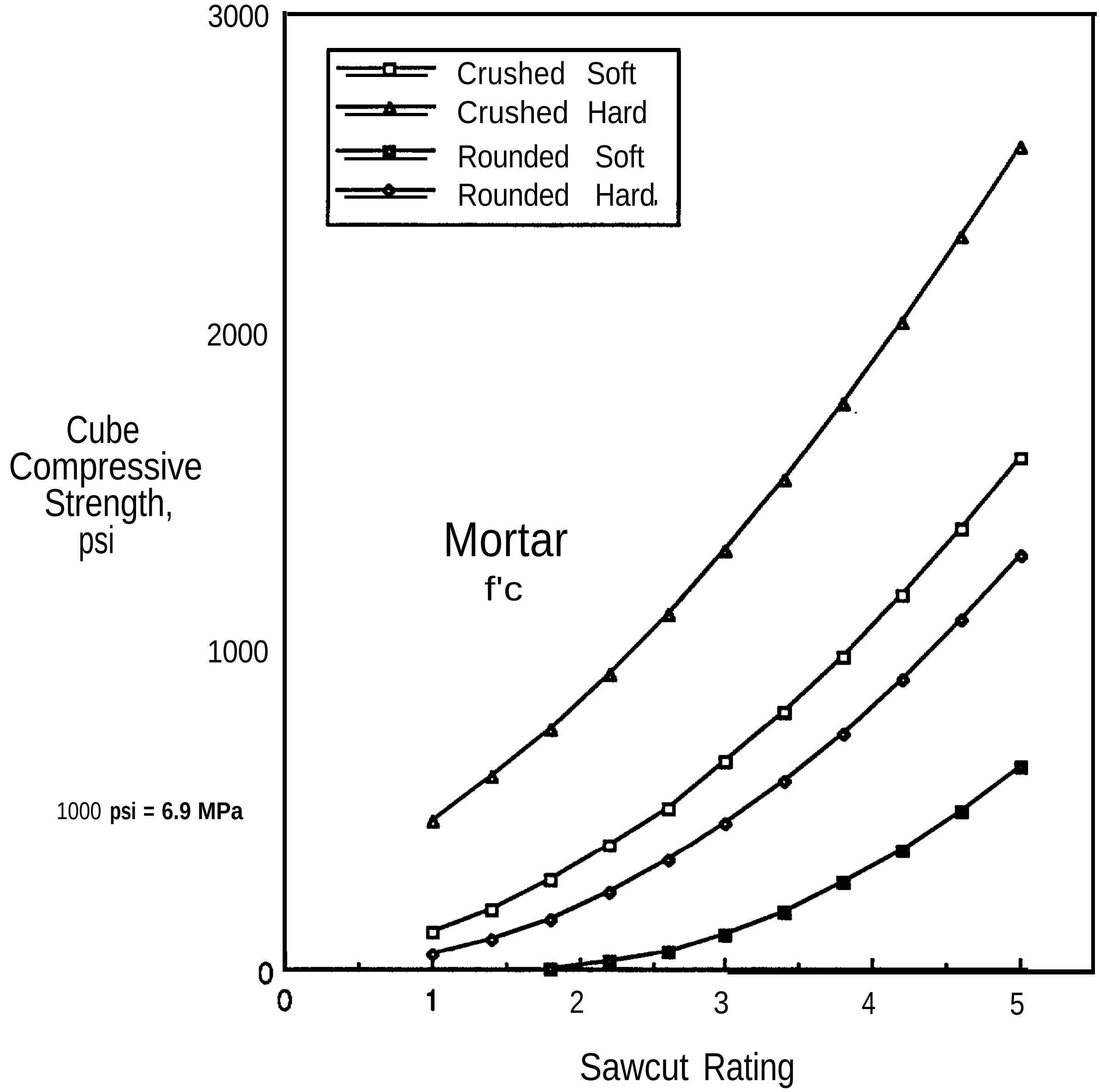


Figure 2. Sawcut rating versus mortar compressive strength.

PETROGRAPHIC EXAMINATION

Core D7. Length = 10.7 in (27.2 cm), Diameter = 3.7 in (9.4 cm)

Examination of a lapped core slice intersecting the sawcut reveals a relatively smooth, straight, sawcut with very little loss of mortar. Cracks or spalls are not observed in concrete adjacent to the sawcut. Analysis of the sawcut indicates slight relief due to minor erosion of the paste and aggregate particles. The relief extends up to 0.5 mm and occurs primarily in the paste fraction of the concrete. A few aggregate particles have been dislodged from paste in the sawed areas. Some aggregate particles are shattered or fractured as a result of stresses caused by sawing. Most of the aggregate particles are intact, except occasionally along particle peripheries. Damage thus described is extremely minor and not perceived without the aid of a stereomicroscope.

Core E3. Length = 10.7 in (27.2 cm), Diameter = 3.7 in (9.4 cm)

As in core D7, the sawcut is relatively smooth with very little mortar loss. However, detailed examination reveals that mortar loss of slightly more prevalent and relief by paste erosion occurs to 0.6 to 0.8 in (1.5 to 2.0 cm) depth from the sawcut. The river gravel exhibits very little fracturing and shattering along the sawcut when compared to the hard little quartzite of core D7. One isolated microcrack occurs at the base of the sawcut in this core. It is not certain if the crack was a result of drying shrinkage or stress due to early sawing.

Core G3E. Length = 10.7 in (27.2 cm), Diameter = 3.7 in (9.4 cm)

The sawcut of this core appears straight but microscopically is somewhat wavy in comparison to cores D7 and E3. Fractures are not observed in paste adjacent to the sawcut, however, microfractures do occur in some of the dolomite aggregate particles. Microcracks in the aggregate particles occur normal to the sawcut and terminate at the juncture of cement paste embedding the aggregate particle in the concrete. Thus, the microcracks appear to be due to stresses caused by sawing.

Relief due to erosion of paste extends to 0.8 mm from the sawcut. Some aggregate particles have been dislodged from cement paste. Ravelling and aggregate fractures arc more prominent in this core than in other cores examined.

APPENDIX D: FIELD JOINT SAWCUTTING DATA

Table 33. Fort Dodge, Iowa mix design.

	Weight, lb/yd^3	Specific Gravity	Unit Volume
Coarse Aggregate	1687	2.67	0.375
Fine Aggregate	1375	2.65	0.308
Cement	487	3.14	**0.092**
Flyash (Class C)	82	2.55	0.019
Water	246	1 .00	0.146
Air Content, percent	****	****	0.060
Unit Weight, lb/ft ^{3}	143.6	****	****

100 lb/ft ^{3} =1602kg/m^3 1000 lb/yd ^{3} = 593 kg/m ^{3}

Table 34. Utah field study specified concrete properties.

Item	Quantity
Minimum Compressive Strength at 28 days, psi	5210
Minimum Flexural Strength at 7 days, psi	490
Maximum Water to Cement Ratio, percent	0.44
Maximum Water to Cementitious Material Ratio, percent	0.46
Minimum Cement Content, lb/yd^3	611
Entrained Air Content, percent by volume	6.0+1.5
Slump Range, in	0.5 to 3.5

1000 lb/yd^3 = 593 kg/m^3
1000 psi = 6.9 MPa
1 in = 25 mm

Table 35. Wisconsin field study concrete mix design.

Item	Quantity
Virgin Coarse Aggregate, lb/yd^3 (OD)	**1002**
Recycled Coarse Aggregate, lb/yd^3 (OD)	820
Virgin Fine Aggregate, lb/yd^3 (OD)	**962**
Recycled Fine Aggregate, lb/yd^3 (OD)	412
Cement, lb/yd^3	530
Flyash, lb/yd^3	**0**
Water, lb/yd^3 (SSD)	258

*NOTES: Dry aggregate weight.

Air entraining agent and
water reducer admixtures used.

1000 lb/yd^3 = 593 kg/m^3

Table 36. Regression analysis of laboratory compressive strength on NDT data for Iowa field test.

Cylinder No.	Age, Days	Cylinder f'c psi	Nurse-Saul Maturity, °F-h	f'c from Maturity [1] psi	Prediction Error, psi	Pulse Velocity, ft/s	f'cfrom PV [2] psi	Prediction Error, psi
1	0.21	105	222	104	-2	9,500	87	-18
2	0.21	100	222	104	3	9,600	93	-7
3	0.25	189	271	223	34	10,900	231	41
4	0.25	191	271	223	32	10,600	187	-4
5	0.30	355	320	386	32	11,500	350	-5
6	0.30	448	320	386	-62	12,100	532	84
7	1 .00	3,748	1,056	3,100	-648	14,800	3,486	-262
8	1.00	3,613	1,056	3,100	-512	14,700	3,252	-361
9	1.17	3,768	1,218	3,497	-271	14,700	3,252	-516
10	1.17	3,883	1,218	3,497	-386	15,000	4,007	124
11	0.79	3,585	858	2,515	-1,070	14,600	3,033	-552
12	0.79	3,692	858	2,515	-1,177	14,900	3,738	45
13	2.00	4,289	2,018	4,776	486	15,400	5,294	1,005
14	2.00	4,230	2,018	4,776	546	14,900	3,738	-492
15	2.17	4,345	2,178	4,945	600	15,200	4,606	261
16	2.17	4,401	2,178	4,945	544	15,200	4,606	205
17	1.79	4,576	1,818	4,533	-43	15,200	4,606	30
18	1.79	4,257	1,818	4,533	275	15,200	4,606	349
19	3.00	4,926	2,978	5,564	639	14,900	3,738	-1,188
20	3.00	4,830	2,978	5,564	734	14,800	3,486	-1,344
21	2.79	5,157	2,778	5,437	280	15,300	4,938	-218
22	2.79	5,252	2,778	5,437	185	15,100	4,296	-956
23	6.18	5,515	6,028	6,547	1,032	15,400	5,294	-220

Table 36. Regression analysis of laboratory compressive strength on NDT data for Iowa field test (continued).

Cylinder No.	Age, Days	Cylinder f'c psi	Nurse-Saul Maturity, °F-h	f'c from Maturity[1] psi	Prediction Error, psi	Pulse Velocity, ft/s	f'c from PV[2] psi	Prediction Error, psi
24	6.18	5,745	6,028	6,547	801	15,400	5,294	-451
25	14.22	6,959	13,748	7,158	198	15,700	6,524	-435
26	14.22	7,066	13,748	7,158	91	15,700	6,524	-542
27	17.22	7,584	16,628	7,244	-339	15,900	7,499	-85
28	17.22	7,011	16,628	7,244	234	15,300	4,938	-2,073
29	31.30	8,133	30,148	7,434	-699	16,100	8,619	487
30	31.30	8,252	30,148	7,434	-818	16,000	8,040	-212
31	1.50	1,680	****	****	****	13,800	1,738	58
32	2.00	1,820	****	****	****	14,400	2,639	819
33	2.50	1,600	****	****	****	14,200	2,296	696
34	5.00	2,260	****	****	****	14,800	3,486	1,226
35	5.50	3,180	****	****	****	15,200	4,606	1,426

NOTES: 1 Prediction equation: log(f'c) = 3.885 - 415.706 / MAT
where MAT = Nurse-Saul maturity in °F-hours, fc = compressive strength in psi.

2 Prediction equation: log(f'c) = -0.933 + 0.302 * (PV/1000)
where PV = pulse velocity in ft/s, fc = compressive strength in psi.

°C = 5/9 (°F - 32), 1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s

Table 37. Regression analysis of laboratory compressive strength on NDT data for Utah field test.

Cylinder No.	Age, Days	Cylinder f'c psi	Nurse-Saul Maturity, "F-h	f'cfrom Maturity 1 psi	Prediction Error, psi	Pulse Velocity, ft/s	f'cfrom PV 2 psi	Prediction Error, psi
1	0.34	88	406	25	-63	4,800	8	-80
2	0.47	287	593	332	45	10,400	326	39
3	0.47	364	593	332	-32	10,800	427	63
4	0.53	539	647	530	-9	11,000	488	-51
5	0.53	532	647	530	-2	10,800	427	-105
6	1.03	1,469	1,222	1,420	-49	12,400	1,247	-221
7	1.05	1,476	1,264	1,494	19	12,700	1,525	49
8	1.21	1,888	1,445	1,801	-87	13,300	2,280	392
9	1.39	2,377	1,707	2,201	-177	13,500	2,607	230
10	2.13	3,216	2,542	3,163	-53	13,800	3,188	-28
11	2.38	3,146	2,797	3,384	238	13,900	3,409	262
12	2.96	3,810	3,357	3,787	-23	13,900	3,409	-402
13	3.38	3,531	3,737	4,010	479	13,800	3,188	-343
14	4.04	4,300	4,345	4,303	3	14,300	4,457	157
15	4.36	4,055	4,649	4,427	372	14,500	5,096	1,041
16	4.97	4,457	5,200	4,621	164	14,300	4,457	0
17	5.51	4,474	5,694	4,769	294	14,300	4,457	-17
18	6.08	4,474	6,207	4,901	427	14,500	5,096	622
19	7.02	5,103	7,062	5,085	-19	14,500	5,096	-7
20	7.03	4,824	7,062	5,085	261	14,400	4,766	-58

Table 37. Regression analysis of laboratory compressive strength on NDT data for Utah field test (continued).

Cylinder No.	Age, Days	Cylinder f'c psi	Nurse-Saul Maturity, °F-h	f'c from Maturity 1 psi	Prediction Error, psi	Pulse Velocity, ft/s	f'c from PV 2 psi	Prediction Error, psi
21	41.13	6,641	63,107	6,445	-196	14,600	5,450	-1,192
22	41.13	6,903	63,107	6,445	-458	14,800	6,231	-672
23	41.13	7,043	63,107	6,445	-598	14,900	6,663	-380
24	41.13	6,851	63,107	6,445	-406	14,900	6,663	-188
25	0.50	1,311	765	1,171	-141	12,800	1,631	319
26	0.50	1,154	765	1,171	17	12,700	1,525	371
27	0.45	665	711	842	177	12,200	1,091	426
28	0.39	682	655	564	-118	12,100	1,020	338

NOTES: 1 Prediction equation: log(f'c) = 4.955 - 1442.926 / MAT for age < 1 day
log(f'c) = 3.822 - 818.747 / MAT for age > 1 day
where MAT = Nurse-Saul maturity in °F-hours, f'c = compressive strength in psi.

2 Prediction equation: log(f'c) = -0.514 + 0.291 * (PV/1000)
where PV = pulse velocity in ft/s, f'c = compressive strength in psi.

°C = 5/9 (°F - 32), 1000 psi = 6.9 MPa, 1000 ft/s = 305 m/s

Table 38. Regression analysis of laboratory compressive strength on NDT data for Wisconsin field test.

Cylinder No.	Age, days	Cylinder f'c psi	Nurse-Saul Maturity, ^{0}F-hr	f'c from Maturity [1] psi	Prediction Error, psi	Pulse Velocity, ft/s	f'c from PV [2] psi	Prediction Error, psi
1	3.12	2,970	2,835	3,338	368	14,000	2,742	-228
2	28.08	3,580	26,795	4,327	747	14,900	4,995	1,415
3	0.23	90	228	121	31	6,800	23	-67
4	14.08	4,190	13,355	4,195	5	****	****	****
5	0.32	290	338	391	101	10,800	325	35
6	0.45	910	502	867	-43	12,600	1,079	169
7	0.46	910	511	892	-18	12,100	773	-137
8	0.90	1,820	804	1,604	-216	13,300	1,720	-100
9	1.02	800	860	1,714	914	12,200	826	26
10	1.02	1,980	860	1,714	-266	13,700	2,245	265
11	1.02	490	860	1,714	1,224	11,400	485	-5
12	1.14	2,200	965	1,902	-298	13,300	1,720	-480
13	1.15	2,030	975	1,919	-111	13,600	2,101	71
14	1.16	2,240	979	1,926	-314	13,600	2,101	-139
15	1.25	2,200	1,080	2,083	-117	13,400	1,838	-362
16	1.41	2,240	1,261	2,324	84	13,500	1,965	-275
17	28.08	4,520	26,795	4,327	-193	14,800	4,673	153
18	3.12	3,500	2,835	3,338	-162	14,200	3,133	-367
19	14.08	4,400	13,355	4,195	-205	****	****	****
20	28.08	3,330	26,795	4,327	997	14,900	4,995	1,665
21	7.08	4,090	6,635	3,941	-149	14,500	3,826	-264
22	7.08	3,600	6,635	3,941	341	14,300	3,349	-251
23	28.08	4,240	26,795	4,327	87	14,400	3,580	-660

Table 38. Regression analysis of laboratory compressive strength on NDT data for Wisconsin field test (continued).

Cylinder No.	Age, days	Cylinder f'c psi	Nurse-Saul Maturity, ^{0}F-hr	f'c from Maturity [1] psi	Prediction Error, psi	Pulse Velocity, ft/s	f'c from PV [2] psi	Prediction Error, psi
24	2.22	2,530	1,974	2,941	411	13,900	2,565	35
25	2.22	2,520	1,974	2,941	421	14,000	2,742	222
26	0.45	1,430	502	867	-563	13,000	1,408	-22
27	2.22	2,800	1,974	2,941	141	14,000	2,742	-58
28	0.26	180	270	212	32	10,100	204	24
29	0.32	520	338	391	-129	11,300	454	-66
30	0.46	1,330	516	906	-424	13,100	1,505	175
31	0.51	800	567	1,046	246	12,200	826	26
32	0.52	730	571	1,056	326	12,300	883	153
33	0.60	1,820	644	1,244	-576	13,400	1,838	18
34	0.60	1,190	647	1,251	61	13,200	1,609	419
35	1.29	3,080	1,121	2,142	-938	14,100	2,931	-149
36	1.25	2,200	1,080	2,083	-117	13,200	1,609	-591
37	2.90	2,970	2,619	3,259	289	14,100	2,931	-39
38	2.06	2,200	1,824	2,842	642	13,600	2,101	-99
39	3.76	3,430	3,449	3,515	85	14,100	2,931	-499

NOTES: 1 Prediction equation: log(f'c) = 3.650 - 357.239 / MAT
where MAT = Nurse-Saul maturity in deg. F-hours; f'c = compressive strength in psi

2 Prediction equation: log(f'c) = -0.614 + 0.289 * (PV/1OOO)
where PV = pulse velocity in ft/s; f'c = compressive strength in psi

^{0}C = 5/9 (^{0}F - 32), 1000 psi = 6.9 MPa, 1000 ft/s= 305 m/s

Table 39. Crack width and joint depth measurements on Iowa slabs.

Joint No.	Station	Crack Width, in [1]	Transverse Joint Depth, in [2]	Longitudinal Joint Depth, in [3]
1	375+87	0.002	3.500	3.750
2	375+70	0.003	4.000	3.750
3	375+50	0.002	4.000	3.750
4	375+30	0.007	4.000	3.625
5	375+10	0.002	3.750	3.500
6	374+90	0.060	3.750	3.500
7	374+70	0.002	3.500	3.750
8	374+50	0.003	3.000	3.625
9	374+30	0.003	3,125	3.500
10	374+10	0.002	3.500	3.500
11	373+90	0.002	3.375	3.500
12	373+70	0.050	3.500	3.375
13	373+50	0.002	3.250	3.250
14	373+30	0.002	3.500	3.750
15	373+10	0.002	3.375	3.750
16	372+90	0.005	4.000	3.625
17	372+70	0.002	3.250	4.000
18	372+50	0.002	4.000	4.000
19	372-1-30	0.040	3.250	4.000
20	372+10	0.016	3.750	4.000
21	371+90	0.003	3.750	3.875
22	371+70	0.002	3.500	4.000
23	371+00	0.050	****	****

NOTES: 1 Measured on 08/16/90.

2 Measured on 08/14/90.

3 Measured on 08/14/90;
Measured at station intersections.

1 in = 25.4 mm

Table 40. Crack width measurements on Wisconsin slabs.

Joint No.	Station	Cast Time [1]	Age at Sawcut, Hours	Crack Width, in[2]
****	****	****	****	****
1	149+50	6:54	11.6	
****	****	****	****	****
****	****	****	****	****
****	****	****	****	****
2	150+00	7:06	11.4	****
****	****	****	****	****
****	150+30	****	****	0.000
****	150+49	****	****	0.125
3	150+60	7:20	11.0	0.000
****	150+79	****	****	0.000
****	150+92	****	****	0.020
****	151+11	****	****	0.125
4	151+30	7:37	11:3	0.000
****	151+41	****	****	0.025
****	151+54	****	****	****
****	****	****	****	****
5	151+90	7:52	11.1	
****	****	****	****	****
****	****	****	****	****
****	****	****	****	****
6	152+50	8:06	11.6	0.000
****	152+62	****	****	0.125
****	152+75	****	****	0.000
****	152+94	****	****	0.000
7	153+10	8:21	11.7	0.060
****	153+22	****	****	0.000
****	153+35	****	****	0.000
****	153+54	****	****	0.000
8	153+70	8:35	11.5	0.125
****	153+82	****	****	0.000
****	153+95	****	****	0.060

Table 40. Crack width measurements on Wisconsin slabs (continued).

Joint No.	Station	Cast Time [1]	Age at Sawcut, Hours	Crack Width, in^2
****	154+14	****	****	0.000
9	154+30	8:47	11.4	0.000
****	154+42	****	****	0.125
****	154+55	****	****	0.000
****	154+74	****	****	0.000
10	154+90	9:04	11.2	0.025
****	155+02	****	****	0.125
****	155+15	****	****	0.000
****	155+34	****	****	0.000
11	155+60	9:30	10.9	0.000
****	155+72	****	****	0.060
****	155+85	****	****	0.020
****	156+04	****	****	0.000
12	156+20	9:43	10.8	0.040
****	156+32	****	****	0.030
****	156+45	****	****	0.000
****	156+64	****	****	0.000
13	156+80	9:56	10.7	0.125
****	156+92	****	****	0.000
****	157+05	****	****	0.050
****	157+32	****	****	0.000
14	157+50	10:11	11.1	0.000
****	157+62	****	****	0.125
****	157+75	****	****	0.000
****	157+94	****	****	0.000
15	158+10	10:24	10.9	0.000
****	158+22	****	****	0.000
****	158+25	****	****	0.125
****	158+44	****	****	0.000
16	158+70	10:36	10.8	0.000
****	158+82	****	****	0.125
****	158+95	****	****	0.000

Table 40. Crack width measurements on Wisconsin slabs (continued).

Joint No.	Station	Cast Time [1]	Age at Sawcut, Hours	Crack Width, in[2]
****	159+14	****	****	0.000
17	159+30	10:49	10.7	0.040
****	159+42	****	****	0.000
****	159+55	****	****	0.125
****	159+74	****	****	0.000
18	160+00	11:04	10.5	0.000
****	160+12	****	****	0.000
****	160+25	****	****	0.063
****	160+44	****	****	0.000
19	160+60	11:17	10.4	0.000
****	160+72	****	****	0.000
****	160+85	****	****	0.188
****	161+04	****	****	0.000
20	161+20	11:30	10.3	0.050
****	161+32	****	****	0.000
****	161+45	****	****	0.000
****	161+64	****	****	0.125
21	161+80	11:44	10.1	0.010
****	161+92	****	****	0.000
****	162+05	****	****	0.125
****	162+24	****	****	0.000
22	162+50	12:01	9.9	0.000
****	162+62	****	****	0.060
****	162+75	****	****	0.125
****	162+94	****	****	0.000
23	163+10	12:16	9.8	0.188
****	163+22	****	****	0.000
****	163+35	****	****	0.060

NOTES: [1]Constructed on 10/02/90.

[2] Measured on 10/09/90.

1 in = 25.4 mm

Table 41. Estimated compressive strength at sawing for Iowa test.

Joint No.	Station	Cast Time	Age at Sawcut, hours	Ravelled Area, sq(mm)/ft	Sawcut Rating[1]	f'c from Rating,[2] psi	f'c from Clegg,[3] psi	f'c from PV,[4] psi	f'c from NS,[5] psi
1	375+87	10:20	7.6	0.0	5.0	1060	620	970	****
2	375+70	10:25	7.4	0.0	5.0	1060	1040	700	****
3	375+50	10:30	7.3	6.2	3.7	660	650	650	960
4	375+30	10:35	7.3	6.2	3.7	660	620	740	****
5	375+10	10:41	7.2	12.4	3.3	570	760	440	****
6	374+90	10:46	7.2	31.0	2.8	450	690	500	****
7	374+70	10:52	7.1	24.8	2.9	480	750	350	****
8	374+50	10:57	7.1	24.8	2.9	480	690	310	****
9	374+30	11:03	7.1	24.8	2.9	480	670	390	****
10	374+10	11:08	7.0	24.8	2.9	480	850	310	****
11	373+90	11:14	7.0	31.0	2.8	450	650	420	****
12	373+70	11:19	6.9	37.2	2.7	430	850	610	****
13	373+50	11:26	6.8	0.0	5.0	1060	720	760	****
14	373+30	11:40	6.6	0.0	5.0	1060	700	800	****
15	373+10	11:45	6.6	6.2	3.7	660	700	640	****

Table 41. Estimated compressive strength at sawing for Iowa test (continued).

Joint No.	Station	Cast Time	Age at Sawcut, hours	Ravelled Area, sq (mm) / ft	Sawcut Rating [1]	f'c for Rating, [2] psi	f'c from Clegg,[3] psi	f'c from PV,[4] psi	f'c from NS,[5] psi
16	372+90	11:50	6.5	37.2	2.7	430	540	300	****
17	372+70	12:00	6.4	24.8	2.9	480	520	270	690
18	372+50	12:04	6.3	37.2	2.7	430	540	390	****
19	372+30	12:09	6.3	24.8	2.9	480	680	570	****
20	372+10	12:13	6.2	31 .0	2.8	450	420	340	****
21	371+90	12:18	6.2	37.2	2.7	430	440	300	****
22	371+70	12:22	6.2	31 .0	2.8	450	420	210	****
23	371 +00	12:27	6.1	31 .0	2.8	450	530	390	****

NOTES: 1From equation developed in sawing slab study (chapter 4, equation 12).

2 From equation developed in sawing slab study (chapter 4, equation 16).

3 From equation developed in sawing slab study (chapter 4, equation 14).

4 PV = pulse velocity in ft/s;
From equation developed using Iowa field test data.

5 NS = Nurse - Saul maturity in °F- hours:
From equation developed using Iowa field test data.

1 ft=30.5cm
100 psi = 0.69 MPa

Table 42. Estimated compressive strength at sawing for Utah test.

Joint No.	Station	Cast Time [1]	Age at Sawcut, hours	Ravelled Area, sq (mm)/ft	Sawcut Rating[2]	Minimum f'c, [3] psi	f'c from Clegg, [4] psi	f'c from PV,[5] psi	f'cfrom NS,[6] psi
1	2470+88	11:00	7.7	0.0	5.0	1,440	840	1,530	****
2	2471+03	11:09	7.0	17.0	3.2	810	950	1,020	****
3	2471+14	11:17	6.9	17.0	3.2	810	1,060	890	****
4	2471+24	11:26	6.7	0.0	5.0	1,440	920	1,250	****
5	2471+38	11:34	6.6	0.0	5.0	1,440	640	890	****
6	2471+53	11:43	6.5	0.0	5.0	1,440	800	1,090	****
7	2471+64	11:51	6.4	0.0	5.0	1,440	550	680	****
8	2471+74	12:00	6.3	0.0	5.0	1,440	520	490	****
9	2471+88	12:08	6.2	17.0	3.2	810	510	730	****
10	2473+74	12:42	6.0	25.5	2.9	740	520	560	****
11	2473+85	12:50	5.9	0.0	5.0	1,440	680	830	****
12	2474+00	13:00	5.7	8.5	3.5	920	480	460	****
13	2533+86	22:00	8.0	76.4	2.3	570	1,280	1,630	****
14	2534+00	22:03	9.0	0.0	5.0	1,440	960	1,090	****
15	2534+15	22:07	8.9	0.0	5.0	1,440	890	1,170	****
16	2534+26	22:10	8.9	0.0	5.0	1,440	820	****	****
17	2534+36	22:14	8.8	0.0	5.0	1,440	550	780	****
18	2534+50	22:17	8.8	0.0	5.0	1,440	550.	560	****
19	2534+65	22:21	8.8	12.7	3.3	850	540	780	****
20	2534+76	22:24	8.7	0.0	5.0	1,440	720	680	****
21	2534+86	22:28	8.7	0.0	5.0	1,440	600	460	****
22	2535+00	22:31	8.7	0.0	5.0	1,440	660	460	****
23	2535+15	22:35	8.6	0.0	5.0	1,440	1,050	1,430	****
24	2535+26	22:38	8.6	0.0	5.0	1,440	1,020	1,330	****
25	2535+36	22:42	8.5	0.0	5.0	1,440	930	1,250	****
26	2535+50	22:45	8.5	0.0	5.0	1,440	960	1,250	****
27	2535+65	22:49	8.5	17.0	3.2	810	770	1,090	****

Table 42. Estimated compressive strength at sawing for Utah test (continued).

Joint No.	Station	Cast Time[1]	Age at Sawcut, hours	Ravelled Area, sq(mm)/ft	Sawcut Rating [2]	Minimum f'c,[3] psi	f'c from Clegg,[4] psi	f'c from PV,[5] psi	f'c from NS,[6] psi
28	2535+76	22:52	8.4	0.0	5.0	1,440	530	1,090	****
29	2535+86	22:56	8.4	0.0	5.0	1,440	810	****	****
30	2536+00	23:00	8.4	0.0	5.0	1,440	910	1,090	****
31	2536+15	23:03	8.3	8.5	3.5	920	550	1,090	****
32	2536+26	23:07	8.3	0.0	5.0	1,440	730	1,530	****
33	2536+36	23:10	8.3	17.0	3.2	810	640	830	****
34	2536+50	23:14	8.2	46.7	2.6	650	710	830	****
35	2536+65	23:17	8.2	17.0	3.2	810	580	830	****
36	2536+76	23:21	8.2	34.0	2.8	700	620	520	****
37	2537+00	23:24	8.1	8.5	3.5	920	830	490	****
36	2537+26	23:28	8.1	0.0	5.0	1,440	910	400	****
39	2537+50	23:31	8.0	12.7	3.3	850	660	250	****
40	2537+76	23:35	8.0	0.0	5.0	1,440	1,040	1,250	****
41	2538+00	23:38	8.0	0.0	5.0	1,440	1,230	600	****
42	2538+26	23:42	7.9	19.1	3.1	790	1,080	830	****
43	2538+50	23:45	7.9	0.0	5.0	1,440	980	640	****
44	2538+76	23:49	7.9	0.0	5.0	1,440	1,010	830	****
45	2539+00	23:52	7.8	12.7	3.3	850	850	400	****
46	2539+26	23:56	7.8	140.1	1.9	490	690	520	****
47	2539+50	****	****	50.9	2.5	630	900	1,090	****
48	2539+76	****	****	8.5	3.5	920	620	780	****
49	2540+00	****	****	8.5	3.5	920	620	350	****
50	2540+26	****	****	34.0	2.8	700	570	370	****
51	2540+50	****	****	4.2	3.9	1,040	780	350	****
52	2540+76	****	****	0.0	5.0	1,440	540	520	****
53	2541+00	****	****	8.5	3.5	920	690	1,170	****
54	2541+26	****	****	25.5	2.9	740	550	1,020	****

Table 42. Estimated compressive strength at sawing for Utah test (continued).

Joint No.	Station	Cast Time [1]	Age at sawcut, hours	Ravelled Area, sq (mm) / ft	Sawcut Rating [2]	Minimum Pc, [3] psi	f'c from Clegg, [4] psi	f'c from PV, [5] psi	f'c from NS, [6] psi
55	2541+50	****	****	0.0	5.0	1,440	790	1,250	****
56	2541+76	****	****	0.0	5.0	1,440	770	1,530	****
57	2542+00	****	****	4.2	3.9	1,040	780	1,430	****
58	2542+26	****	****	21.2	3.0	770	920	1,740	****
59	2542+50	****	****	127.3	2.0	500	1,150	1,430	****
60	2542+76	****	****	135.8	2.0	490	640	1,020	****
61	2543+00	****	****	67.9	2.4	590	900	1,170	****
62	2543+26	****	****	4.2	3.9	1,040	1,070	1,090	****
63	2543+50	****	****	0.0	5.0	1,440	670	890	****
64	2532+60	7:51	9.6	0.0	5.0	1,440	940	1,250	****
65	2532+20	8:04	9.6	17.0	3.2	810	800	830	200
66	2532+00	8:1O	9.5	0.0	5.0	1,440	980	950	****
67	2531+50	8:27	8.2	0.0	5.0	1,440	970	640	****
68	2531+00	8:43	9.4	0.0	5.0	1,440	900	1,170	****
69	2530+50	8:59	9.2	0.0	5.0	1,440	690	1,020	****

Table 42. Estimated compressive strength at sawing for Utah test (continued).

Joint No.	Station	Cast Time [1]	Age at Sawcut, hours	Ravelled Area, sq (mm) / ft	Sawcut Rating [2]	Minimum f'c,[3] psi	f'c from Clegg,[4] psi	f'c from PV, [5] psi	f'c from NS, [6] psi
70	2530+00	9:15	9.1	0.0	5.0	1,440	970	830	288
71	2529+50	9:33	8.9	0.0	5.0	1,440	800	950	****
72	2529+00	9:50	8.7	0.0	5.0	1,440	690	830	213
73	2528+50	10:07	8.5	0.0	5.0	1,440	660	****	****
74	2528+00	10:23	8.4	0.0	5.0	1,440	780	****	155

NOTES: 1 Slabs between joints 1 and 12 paved on 8/24/90, slabs between joints 13 and 46 paved on 8/27/90, cast time unknown for slabs between joints 47 and 63, slabs between joints 64 and 74 paved on 8/29/90.

2 From equation developed in sawing slab study (chapter 4,equation 12).

3 From equation developed in sawing slab study (chapter 4, equation 16), f'c = compressive strength in psi

4 From equation developed in sawing slab study (chapter 4, equation 14).

5 From equation developed using Utah field test data; PV = pulse velocity in ft/s.

6 From equation developed using Utah field test data; NS = Nurse-Saul maturity in ^{o}F-hours.

1 ft=30.5cm
100 psi = 0.69 MPa

Table 43. Estimated compressive strength at sawing for Wisconsin test.

Joint No.	Station	Cast Time	Age at Sawcut, hours	Ravelled Area, sq (mm)/ft	Sawcut Rating[1]	f'c for Rating,[2] psi	f'c from Clegg,[3] psi	f'c from PV,[4] psi	f'c from NS,[5] psi
1	149+50	6:54	11.6	0.0	5.0	990	300	190	****
2	150+00	7:06	11.4	0.0	5.0	990	500	190	****
3	150+60	7:20	11.0	0.0	5.0	990	360	300	****
4	151+30	7:37	11.3	0.0	5.0	990	330	200	****
5	151+90	7:52	11.1	0.0	5.0	990	360	150	****
6	152+50	8:06	11.6	31.0	2.8	400	440	330	760
7	153+10	8:21	11.7	12.4	3.3	520	390	300	****
8	153+70	8:35	11.5	9.3	3.5	550	490	370	****
9	154+30	8:47	11.4	0.0	5.0	990	430	280	****
10	154+90	9:04	11.2	6.2	3.7	610	300	200	****
11	155+60	9:30	10.9	0.0	5.0	990	350	480	770
12	156+20	9:43	10.8	13.2	3.3	510	330	280	****
13	156+80	956	10.7	0.0	5.0	990	290	140	****

Table 43. Estimated compressive strength at sawing for Wisconsin test (continued).

Joint No.	Station	Cast Time	Age at Sawcut, hours	Ravelled Area, sq (mm) /ft	Sawcut Rating [1]	f'c for Rating, [2] psi	f'c from Clegg, [3] psi	f'c from PV, [4] psi	f'c from NS, [5] psi
14	157+50	10:11	11.1	0.0	5.0	990	320	300	****
15	158+10	10:24	10.9	1.6	4.3	770	310	450	****
16	156+70	10:36	10.8	12.4	3.3	520	440	330	****
17	159+30	10:49	10.7	9.3	3.5	550	460	370	****
18	160+00	11:04	10.5	1.6	4.3	770	490	350	****
19	180+60	11:17	10.4	0.0	5.0	990	570	350	****
20	161+20	11:30	10.3	0.0	5.0	990	420	350	790
21	161+80	11:44	10.1	0.0	5.0	990	500	400	****
22	162+50	12:01	9.9	3.1	4.0	690	290	400	***
23	163+10	12:16	9.8	4.7	3.8	640	520	400	****

NOTES: 1 From equation developed in sawing slab study (chapter 4,equation 12).
2 From equation developed in sawing slab study (chapter 4,equation 16); f'c = compressive strength.
3 From equation developed in sawing slab study (chapter 4)equation 14).
4 From equation developed using Wisconsin field test data; PV = pulse velocity in ft/s.
5 From equation developed using Wisconsin field test data; NS = Nurse-Saul maturity in ^{0}F-hours.

1 ft=30.5cm
100 psi = 0.69 MPa

APPENDIX E: FIELD LOAD TESTING DATA

Table 44. Regression analysis of laboratory modulus of elasticity on compressive strength for Iowa field test.

Cylinder No.	Test Age, days	Cylinder Ec, [1] million psi	Cylinder f'c, [2] psi	Ec from f'c, [3] million psi	Prediction Error, percent
7	1 .00	4.10	3750	4.12	0.6
10	1.17	4.15	3880	4.17	0.5
12	0.79	3.95	3690	4.10	3.9
14	2.00	4.25	4230	4.29	0.9
16	2.17	4.25	4400	4.34	2.2
18	1.79	4.55	4260	4.30	-5.6
19	3.00	4.20	4930	4.51	7.3
22	2.79	4.65	5250	4.60	-1.0
23	6.18	4.85	5510	4.66	-3.5
26	14.22	4.85	7070	5.10	5.2
27	17.22	5.10	7580	5.23	2.5
29	31.30	5.55	8130	5.36	-3.4
30	31.30	5.65	8250	5.39	-4.6
32	2.00	3.70	1820	3.33	-10.0
33	2.50	3.10	1600	3.22	3.8
34	5.00	3.65	2260	3.54	-3.0
35	5.50	3.65	3180	3.92	7.3

NOTES: 1 Ec = concrete modulus of elasticity in psi

2 f'c = compressive strength in psi

3 Prediction equation: Ec = 1.508 + 0.0427 * sqrt(f'c)

1 million psi = 6895 MPa

Table 45. Regression analysis of laboratory modulus of elasticity on compressive strength for Utah field test.

Cylinder No.	Test Age, days	Cylinder Ec, [1] million psi	Cylinder f'c,[2] psi	Ec from f'c [3] million psi	Prediction Error, percent
6	1.03	2.00	1470	2.04	1.8
8	1.21	2.35	1890	2.31	-1.7
9	1.39	2.60	2380	2.59	-0.3
10	2.13	3.45	3220	3.01	-12.6
11	2.38	2.95	3150	2.98	1.1
12	2.96	3.25	3810	3.28	0.9
13	3.38	3.00	3530	3.16	5.2
14	4.04	3.05	4300	3.48	14.2
15	4.36	3.45	4050	3.38	-2.0
16	4.97	3.45	4460	3.55	2.8
17	5.51	3.55	4470	3.55	0.0
18	6.08	3.35	4470	3.55	6.0
19	7.02	3.50	5100	3.79	8.4
20	7.03	3.35	4820	3.69	10.1
21	41.13	4.25	6640	4.33	1.8
22	41.13	4.75	6900	4.41	-7.1
23	41.13	4.70	7040	4.46	-5.2
24	41.13	4.80	6850	4.40	-8.4

NOTES: 1 Ec = concrete modulus of elasticity in million psi

2 f'c = compressive strength in psi

3 Prediction equation: Ec = 0.0531 * sqrt(f'c)

1 million psi = 6895 MPa

Table 46. Regression analysis of laboratory modulus of elasticity on compressive strength for Wisconsin field test.

Cylinder No.	Test Age, days	Cylinder Ec, [1] million psi	Cylinder PC, [2] psi	Ec from f'c, [3] million psi	Prediction Error, percent
18	3.12	3.40	3500	3.86	13.5
1	3.12	3.15	2970	3.55	12.8
37	2.90	3.15	2970	3.55	12.8
39	3.76	3.25	3430	3.82	17.5
21	7.08	3.70	4090	4.17	12.7
22	7.08	3.50	3600	3.91	11.8
4	14.08	3.75	4190	4.22	12.6
19	14.08	3.85	4400	4.33	12.4
17	28.08	4.00	4520	4.38	9.6
2	28.08	3.80	3580	3.90	2.7
20	28.08	3.75	3330	3.76	0.4
23	28.08	3.85	4240	4.25	10.3

NOTES: 1 EC = concrete modulus of elasticity in million psi

2 f'c = compressive strength in psi

3 Prediction equation: Ec = 0.0652 * sqrt(f'c)

1 million psi = 6895 MPa

Table 47. Single-axle load truck data.

	Iowa	Utah
Axle Spacing, in	168	155
Axle Length (c-c duals)	72	72
Dual Tire Spacing	12.75	13
Tire Type	10.00 - 20.0	11 R22.5
Front Axle Load, kips	9.6	7.5
Rear Axle Load, kips	20.1	20

100 in = 2.54 m, 10 kips = 4540 kg

Table 48. Iowa load test response for slab 1 at 2 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	11:30 Strain [4]	13:30 Strain [4]	14:00 Strain [4]	15:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	37	39	39	41	39
2	Creep	18	Slab Midlength	26	31	30	34	30
3	Creep	18	Slab Edge at Midlength	21	25	23		23
4	Creep	30	Slab Midlength	26	27	28		27
5	Creep	72	Slab interior	18	25	22		22
6	Creep	30	Transverse Joint	8	10	8		9
7	Creep	72	Transverse Joint	14	10	10		11
8	static	2	Slab Edge at Midlength	48	46	49		48
9	Static	2	Edge 1 ft From Load	36	37	42		38
10	static	2	Edge 2 ft From Load	22	22	28		24

NOTES:
1 See figures 3 - 12 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from free edge to tire edge.
4 Measured strain in millionths under 20.1 kip single axle load.

10 in = 25.4 cm, 1 ft = 30 cm, 1 mph = 1.6 km/h, 20.1 kip = 9125 kg

Table 49. Iowa load test response for slab 1 at 3 days.

Load Case[1]	Load Type[2]	Wheel Path, in[3]	Slab Location	8:00 Strain[4]	9:30 Strain[4]	11:30 Strain[4]	14:00 Strain[4]	Average Strain
1	Creep	2	Slab Edge at Midlength	36	36	35	34	35
2	Creep	18	Slab Midlength	29	31	32	27	30
3	Creep	18	Slab Edge at Midlength	23	22	23	23	23
4	Creep	30	Slab Midlength	25	24	29	24	26
5	Creep	72	Slab Interior	20	24	22	18	21
6	Creep	30	Transverse Joint	7	9	8	7	8
7	Creep	72	Transverse Joint	19	19	13	8	15
8	Static	2	Slab Edge at Midlength	50	46	51	49	49
9	Static	2	Edge 1 ft From Load	39	47	43	44	43
10	Static	2	Edge 2 ft From Load	27	24	30	22	26

NOTE:
1 See figures 3 - 12 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from free edge to tire edge.
4 Measured strain in millionths under 20.1 kip single axle load.

10 in = 25.4 cm, 1 ft = 30 cm, 1 mph = 1.6 km/h, 20.1 hip = 9125 kg

Table 50. Iowa load test response for slab 2 at 7 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	11:30 Strain [4]	13:30 Strain [4]	14:00 Strain [4]	15:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	24	27	25	29	26
2	Creep	18	Slab Midlength	20	23	24	20	22
3	Creep	18	Slab Edge at Midlength	14	17	17	-	16
4	Creep	30	Slab Midlength	19	18	20	-	19
5	Creep	72	Slab interior	14	17	19	-	17
6	Creep	30	Transverse Joint	9	7	7	-	8
7	Creep	72	Transverse Joint	13	9	10		11
8	Static	2	Slab Edge at Midlength	30	45	41		39
9	Static	2	Edge 1 ft From Load	19	27	29		25
10	Static	2	Edge 2 ft From Load	12	16	15	-	14

NOTES:
1 See figures 3 - 12 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from free edge to tire edge.
4 Measured strain in millionths under 20.1 kip single axle load.

10in=25.4cm,1ft=30cm,1 mph=1.6km/h,20.1 kip=9125kg

Table 51. Iowa test response for slab 2 at 8 days.

Load Case[1]	Load Type [2]	Wheel Path in [3]	Slab Location	8:00 Strain [4]	9:30 Strain [4]	11:30 Strain [4]	14:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	25	28	26	28	27
2	Creep	18	Slab Midlength	23	21	22	23	22
3	Creep	18	Slab Edge at Midlength	16	18	14	17	16
4	Creep	30	Slab Midlength	18	17	19	16	18
5	Creep	72	Slab Interior	17	16	17	15	16
6	Creep	30	Transverse Joint	6	6	8	6	7
7	Creep	72	Transverse Joint	9	11	12	8	10
8	Static	2	Slab Edge at Midlength	34	36	38	35	36
9	Static	2	Edge 1 ft From Load	24	24	26	24	25
10	Static	2	Edge 2 ft From Load	10	12	14	19	14

NOTES:
1 See Figures 3-12 in appendix E for wheel and strain location.
2 Creep load of 2 to 3 mph.
3 Distance from edge to tire edge.
4 Measured strain in millionths under 20.1 kip single axle load.

10 in = 25.4 cm, 1ft = 30 cm, 1 mph = 1.6 km/h, 20.1 kip = 9125 kg

Table 52. Utah load test response for slab 1 at 3 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	13:30 Strain [4]	15:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	6	5	5
2	Creep	18	Slab Midlength	6	7	7
3	Creep	18	Slab Edge at Midlength	2	3	3
5	Creep	2	Free Shoulder Edge	13	16	15
10	Creep	30	Transverse Joint	4	5	5
16	Static	2	Free Shoulder Edge	21	19	20
19	Static	30	Loaded Transverse Joint	6	6	6
20	Static	30	Unloaded Transverse Joint	6	4	5

NOTES:
1 See figures 13 - 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 in = 25.4 cm, 1 mph = 1.6 km/h, 20 kip = 9080 kg

Table 53. Utah load test response for slab 2 at 4 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	11:00 Strain [4]	14:00 Strain [4]	15:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	9	9	7	8
2	Creep	18	Slab Midlength	10	11	9	10
3	Creep	18	Slab Edge at Midlength	4	4	5	4
8	Creep	30	Slab Midlength	11	9	7	9
9	Creep	72	Slab Interior	9	7	9	8
10	Creep	30	Transverse Joint	5	5	5	5
11	Creep	72	Transverse Joint	10	4	6	7
12	Static	2	Slab Edge at Midlength	12	11	12	12
13	Static	2	Edge 1 ft from Load	7	6	6	6
14	Static	2	Edge 2 ft from Load	4	3	3	3
15	Static	2	Unloaded Shoulder	7	7	8	7
19	Static	30	Loaded Transverse Joint	7	6	6	6
3	Static	30	Unloaded Transverse Joint	3	3	2	3

NOTES:
1 See figures 13 - 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 in = 25.4 cm, 1 ft = 30 cm, 1 mph = 1.6 km/h, 20 kip = 9080 kg

Table 54. Utah load test response for slab 3 at 5 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	11:30 Strain [4]	14:00 Strain [4]	15:30 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	7	8	8	8
2	Creep	18	Slab Midlength	8	6	6	7
3	Creep	18	Slab Edge at Midlength	4	6	3	4
4	Creep	2	Unloaded Shoulder	6	6	6	6
5	Creep	2	Free Shoulder Edge	12	10	11	11
6	Creep	2	Free Edge 1 ft from Mid.	12	15	14	14
7	Creep	2	Free Edge 2 ft from Mid.	16	20	22	19
12	Static	2	Slab Edge at Midlength	11	12	11	11
15	Static	2	Unloaded Shoulder	7	7	6	7
16	Static	2	Free Shoulder Edge	20	23	22	21
17	Static	2	Free Edge 1 ft from Load	9	11	12	11
18	Static	2	Free Edge 2 ft from Load	6	6	6	6

NOTES:
1 See figures 13 - 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 in = 25.4 cm, 1 ft = 30 cm, 1 mph = 1.6 km/h, 20 kip = **9080** kg

Table 55. Utah load test response for slab 1 at 6 days.

Load Case[1]	Load Type[2]	Wheel Path, in[3]	Slab Location	9:00 Strain[4]	11:30 Strain[4]	13:30 Strain[4]	16:00 Strain[4]	Average Strain
1	Creep	2	Slab Edge at Midlength	7	5	7	5	6
2	Creep	18	Slab Midlength	3	4	4	4	4
3	Creep	18	Slab Edge at Midlength	3	2	3	4	3
5	Creep	2	Free Shoulder Edge	30	28	19	15	23
10	Creep	30	Transverse Joint	5	6	6	7	6
12	Static	2	Slab Edge at Midlength	9	9	9	11	9
16	Static	2	Free Shoulder Edge	58	47	22	24	38
19	Static	30	Loaded Transverse Joint	6	6	7	7	7
20	Static	30	Unloaded Transverse Joint	4	4	3	2	3

NOTES:
1 See figures 13 - 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 in = 25.4 cm, 1 mph = 1.6 km/h, 20 kip = 9080 kg

Table 56. Utah load test response for slab 2 at 7 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	7:30 Strain [4]	11:00 Strain [4]	13:00 Strain [4]	14:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	6	7	7	7	7
2	Creep	18	Slab Midlength	5	7	6	7	6
3	Creep	18	Slab Edge at Midlength	4	5	4	6	5
4	Creep	2	Unloaded Shoulder	6	7	6	7	6
8	Creep	30	Slab Midlength	5	8	8	9	8
9	Creep	72	Slab Interior	7	8	8	10	8
10	Creep	30	Transverse Joint	6	5	6	6	6
11	Creep	72	Transverse Joint	4	5	7	7	6
12	Static	2	Slab Edge at Midlength	9	11	10	12	10
13	Static	2	Edge 1 ft from Load	7	7	7	7	7
14	Static	2	Edge 2 ft from Load	5	5	4	4	4
15	Static	2	Unloaded Shoulder	6	8	8	7	7
19	Static	30	Loaded Transverse Joint	7	6	7	8	7
20	Static	30	Unloaded Transverse Joint	1	1	2	2	2

NOTES:
1 See figures 13 - 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 cm = 25.4 cm,1 ft=30cm,1 mph=1.6 km/h, 20 kip = 9080 kg

Table 57. Utah load test response for slab 3 at 8 days.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	8:00 Strain [4]	11:30 Strain [4]	13:30 Strain [4]	14:30 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	7	8	8	8	8
2	Creep	18	Slab Midlength	8	9	7	9	8
3	Creep	18	Slab Edge at Midlength	3	5	4	6	5
4	Creep	2	Unloaded Shoulder	4	5	6	6	5
5	Creep	2	Free Shoulder Edge	17	12	15	13	14
6	Creep	2	Free Edge 1 ft from Mid.	21	15	15	14	16
7	Creep	2	Free Edge 2 ft from Mid.	20	15	15	15	16
12	Static	2	Slab Edge at Midlength	9	9	10	8	9
15	Static	2	Unloaded Shoulder	5	4	6	5	5
16	Static	2	Free Shoulder Edge	24	24	20	20	22
17	Static	2	Free Edge 1 ft from Load	18	11	13	12	13
18	Static	2	Free Edge 2 ft from Load	11	6	4	6	7

NOTES:
1 See figures 13 - 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 in = 25.4 cm, 1 ft = 30 cm, 1 mph = 1.6 km/h, 20 kip = 9080 kg

Table 58. Utah load test response for slab 4 at 1 year.

Load Case [1]	Load Type [2]	Wheel Path, in [3]	Slab Location	7:00 Strain [4]	8:30 Strain [4]	10:30 Strain [4]	12:30 Strain [4]	14:00 Strain [4]	15:00 Strain [4]	Average Strain
1	Creep	2	Slab Edge at Midlength	12	12	12	11	15	14	13
2	Creep	18	Slab Midlength	10	7	8	12	11	12	10
3	Creep	18	Slab Edge at Midlength	4	3	4	6	7	8	5
8	Creep	30	Slab Midlength	6	6	7	10	9	10	8
9	Creep	72	Slab Interior	9	5	8	9	11	9	9
10	Creep	30	Transverse Joint	14	16	13	9	9	9	12
11	Creep	72	Transverse Joint	9	3	4	4	7	6	6
12	Static	2	Slab Edge at Midlength	17	16	15	16	16	15	16
13	Static	2	Edge 1 ft from Load	11	8	8	7	9	9	8
14	Static	2	Edge 2 ft from Load	4	2	3	3	5	6	4
15	Static	2	Unloaded Shoulder	8	7	8	6	6	7	7
19	Static	30	Loaded Transverse Joint	17	14	12	20	8	8	13
20	Static	30	Unloaded Transverse Joint	4	4	3	4	6	6	5
21	Static	72	Loaded Transverse Joint	6	6	5	3	3	2	4
22	Static	72	Unloaded Transverse Joint	2	2	2	4	4	4	3

NOTES:
1 See figures 13- 34 in appendix E for wheel and strain locations.
2 Creep load of 2 to 3 mph.
3 Distance from lane - concrete shoulder joint or free edge to tire edge.
4 Measured strain in millionths under 20.0 kip single axle load.

10 in = 25.4 cm, 1 ft = 30 cm, 1 mph = 1.6 km/h, 20 kip = 9080 kg

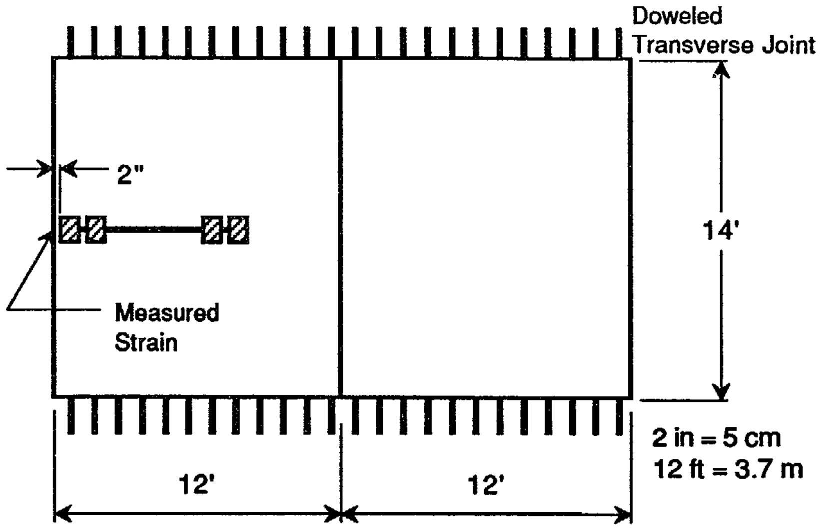


Figure 3. Iowa load case 1 creep speed.

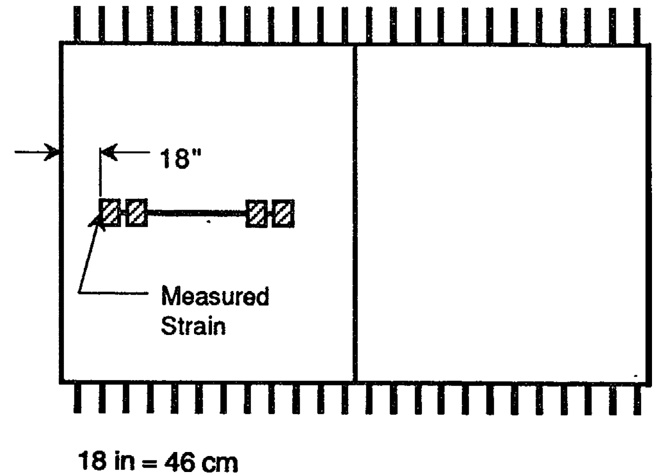


Figure 4. Iowa load case 2 creep speed.

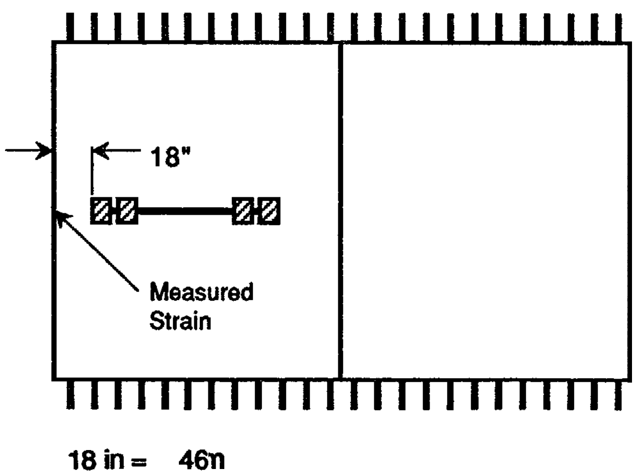


Figure 5. Iowa load case 3 creep speed.

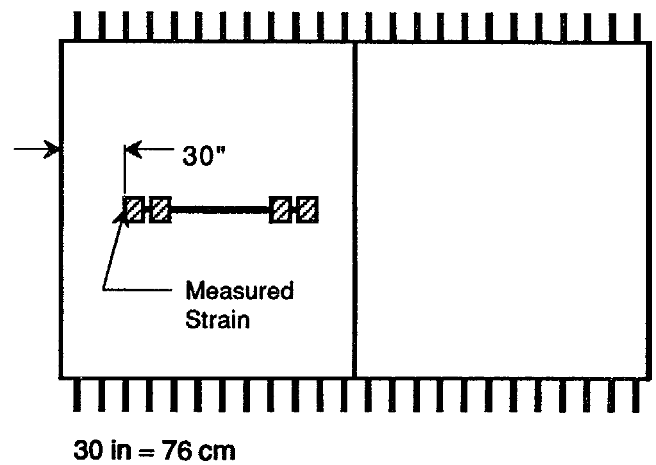


Figure 6. Iowa load case 4 creep speed.

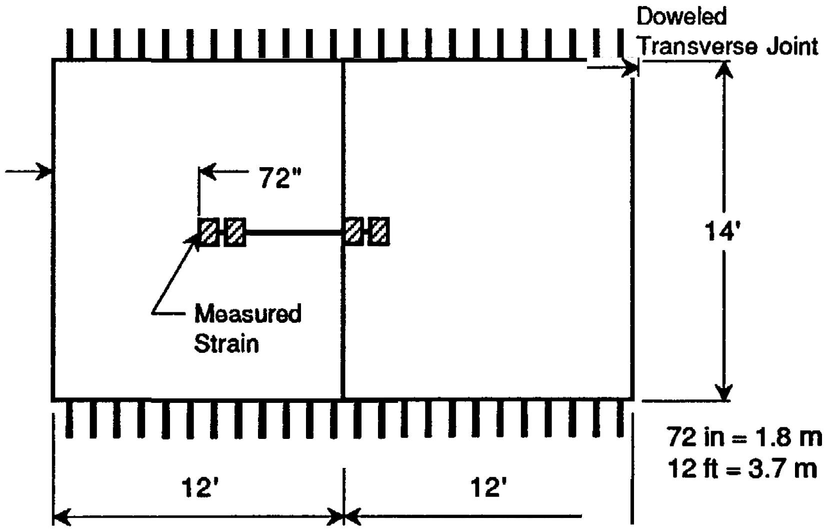


Figure 7. Iowa load case 5 creep speed.

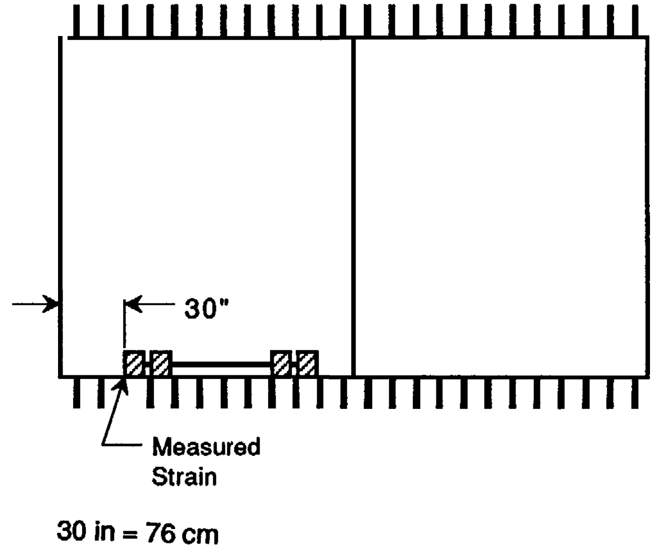


Figure 8. Iowa load case 6 creep speed.

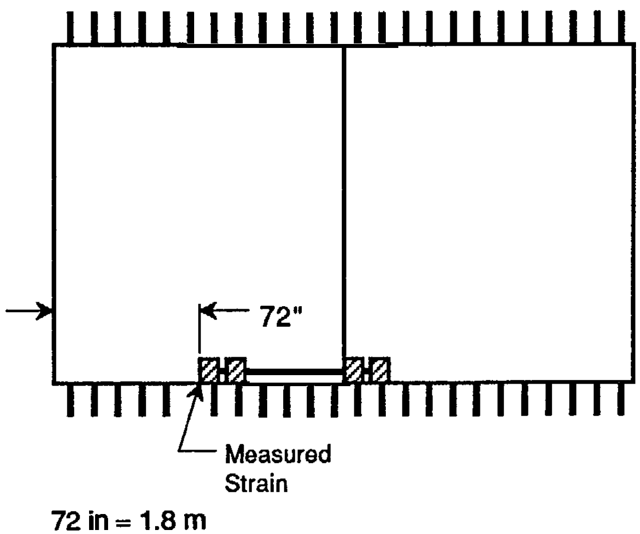


Figure 9. Iowa load case 7 creep speed.

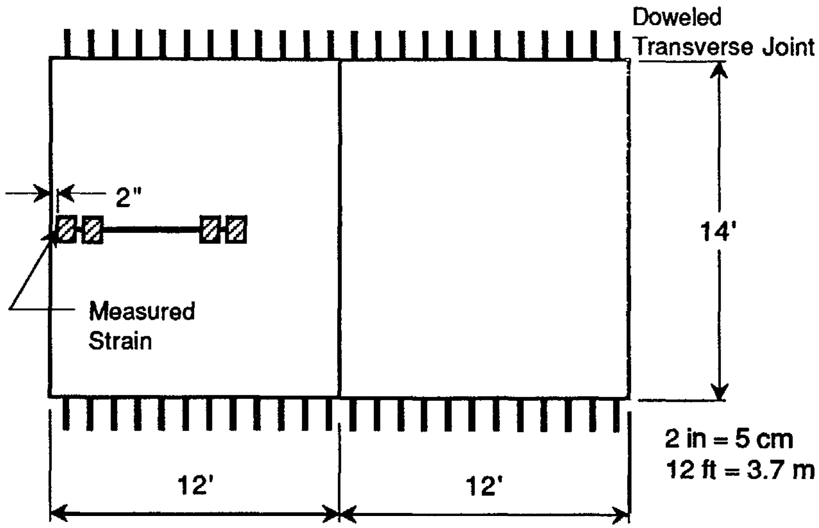


Figure 10. Iowa load case 8 static.

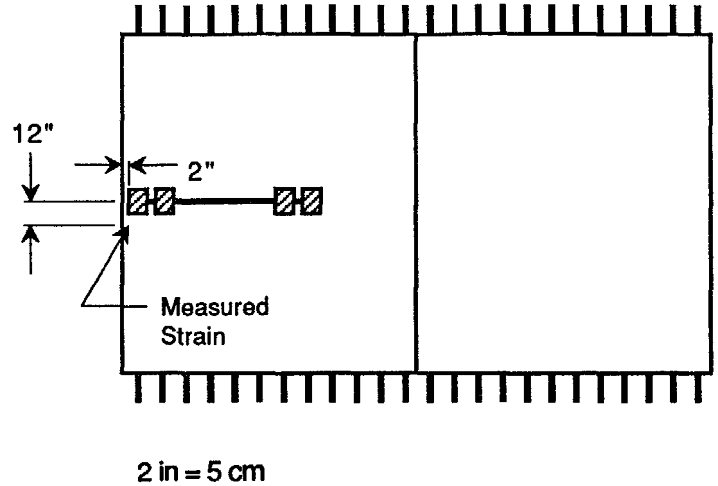


Figure 11. Iowa load case 9 static.

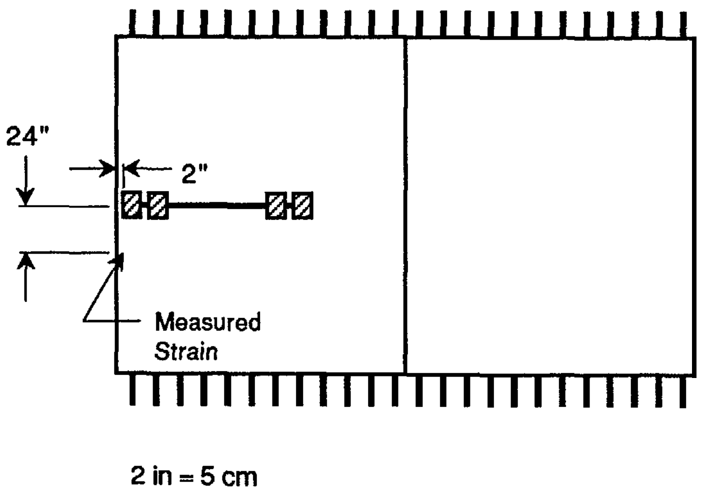


Figure 12. Iowa load case 10 static.

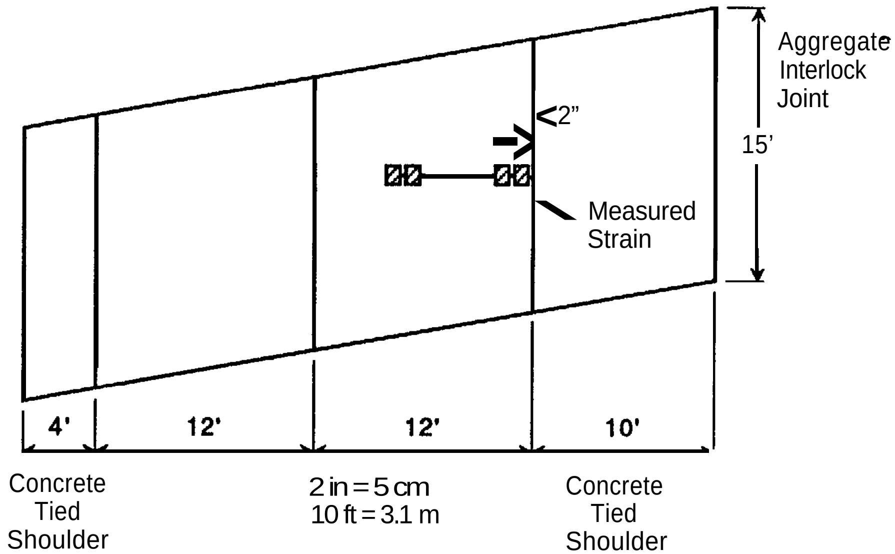


Figure 13. Utah load case 1 creep speed.

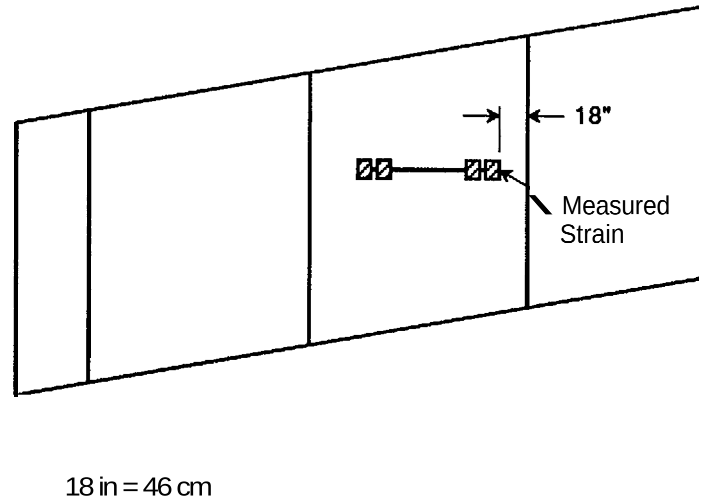


Figure 14. Utah load case 2 creep speed.

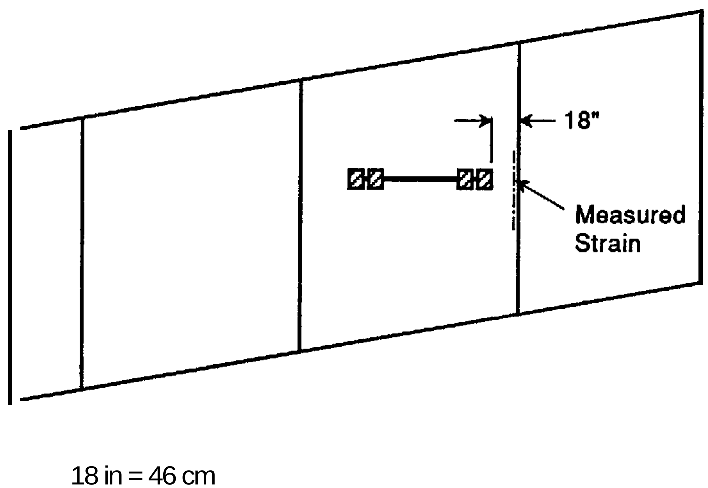


Figure 15. Utah load case 3 creep speed.

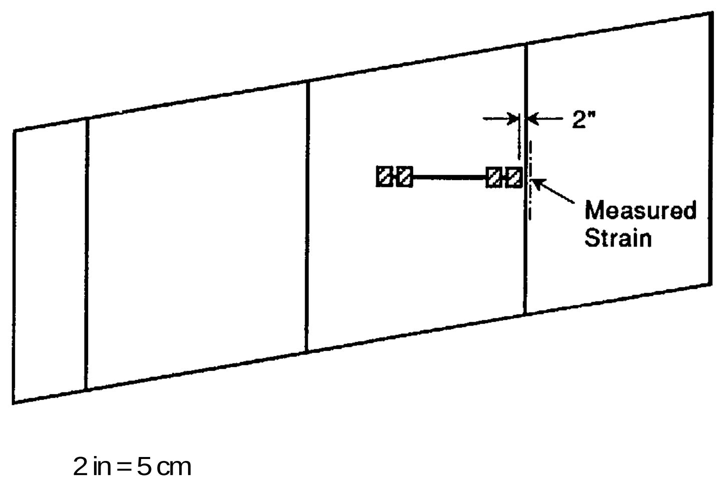


Figure 16. Utah load case 4 creep speed.

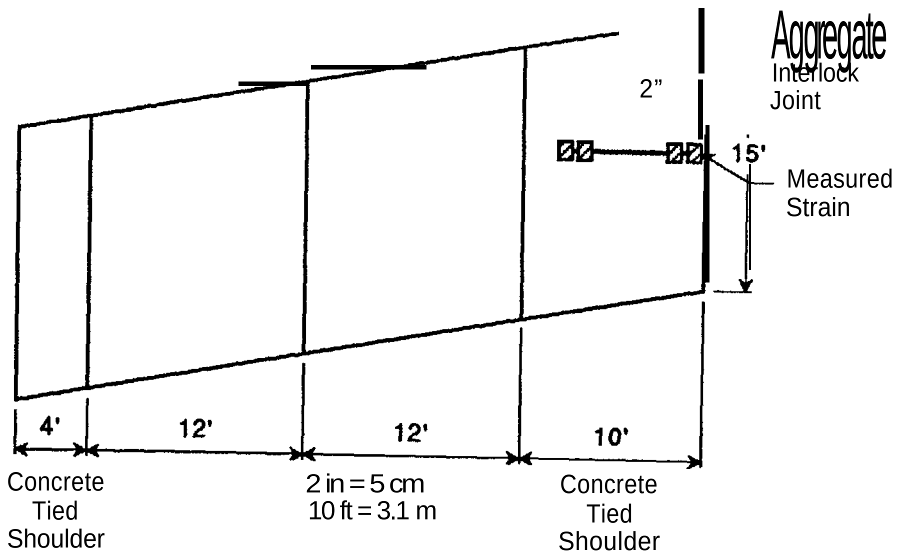


Figure 17. Utah load case 5 creep speed.

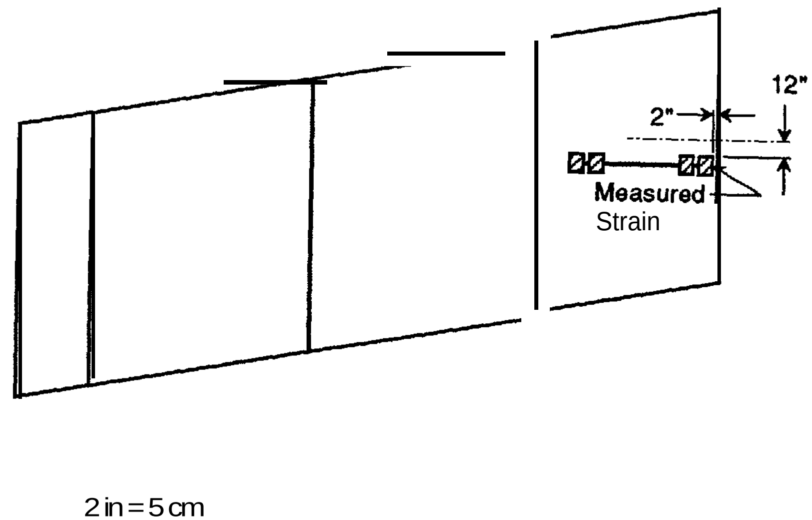


Figure 18. Utah load case 8 creep speed.

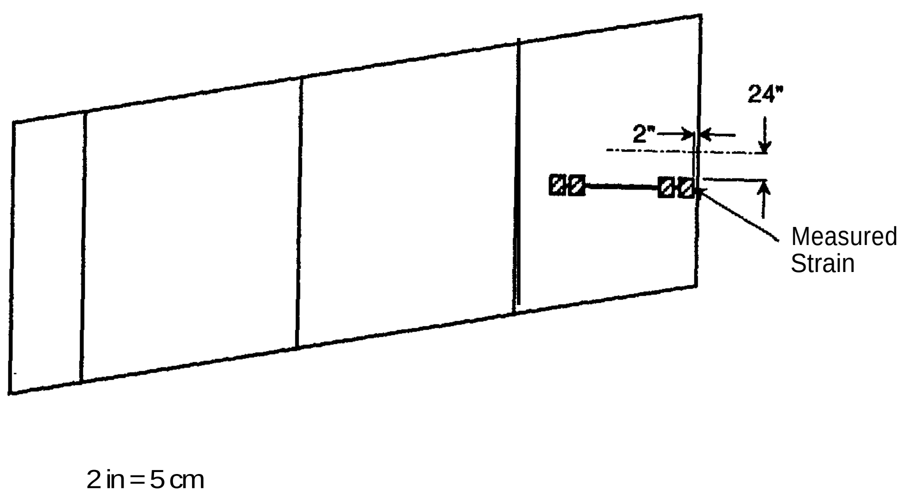


Figure 19. Utah load case 7 creep speed.

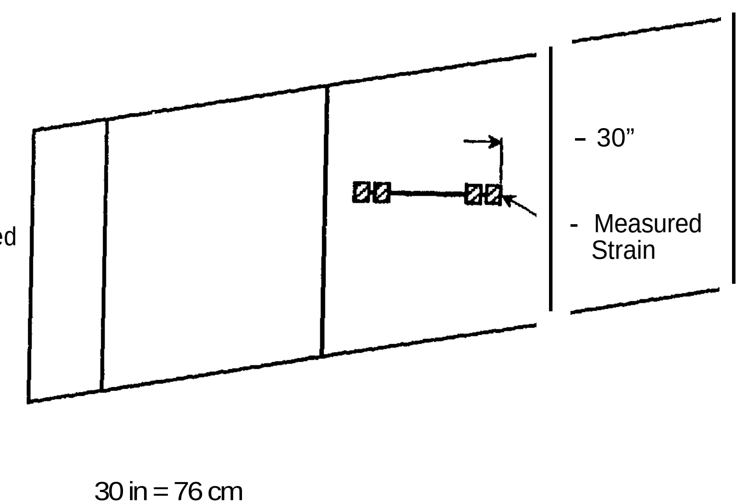


Figure 20. Utah load case 8 creep speed.

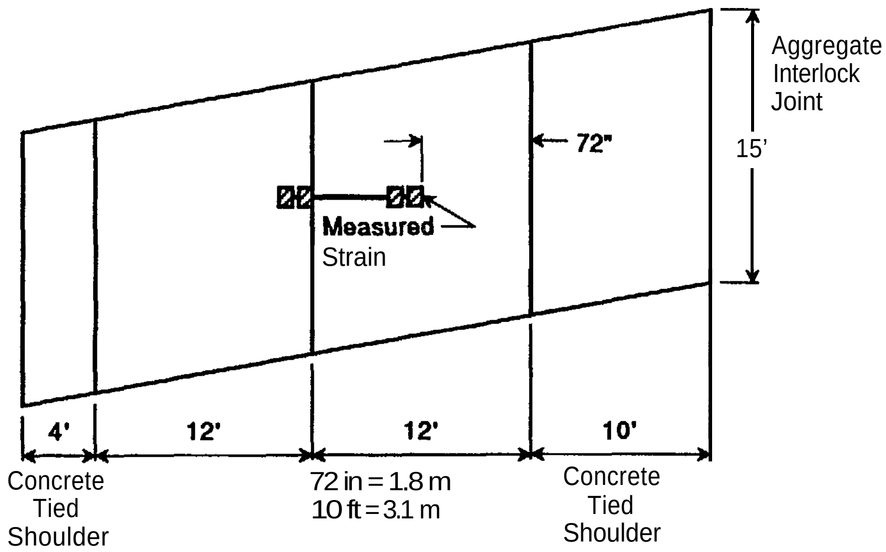
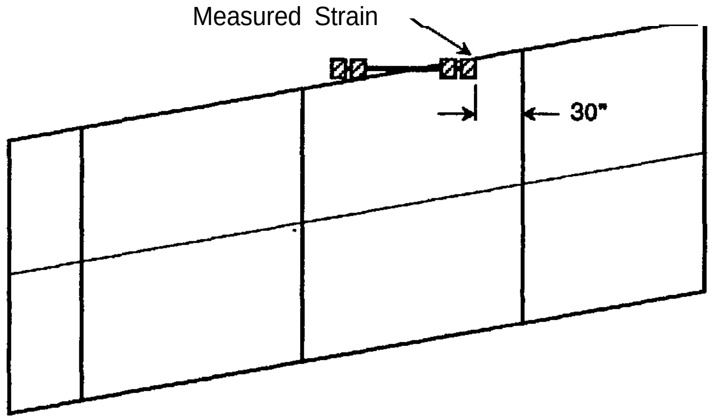
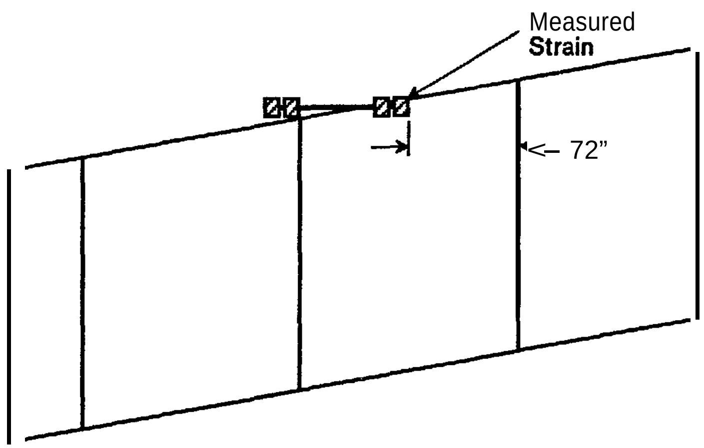


Figure 21. Utah load case 9 creep speed.



30 in = 76 cm

Figure 22. Utah load case 10 creep speed.



72 in = 1.8 m

Figure 23. Utah load case 11 creep speed.

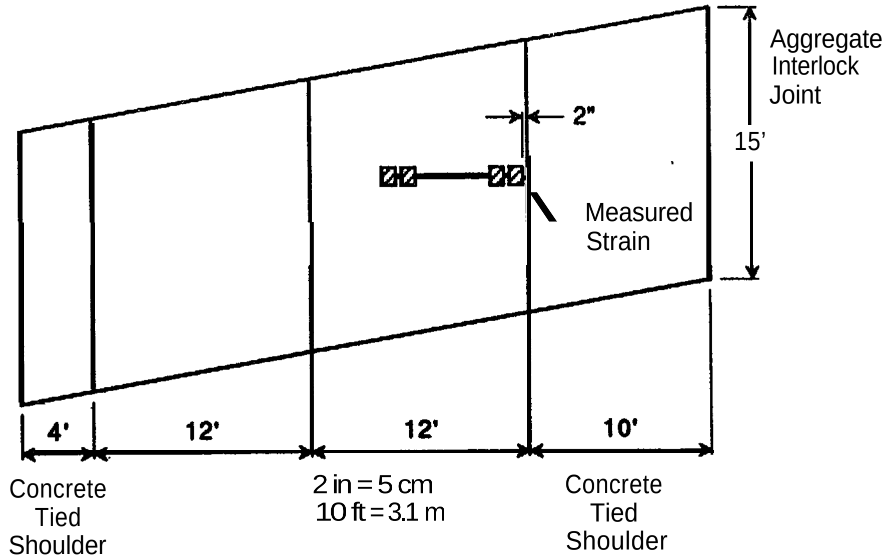


Figure 24. Utah load case 12 static.

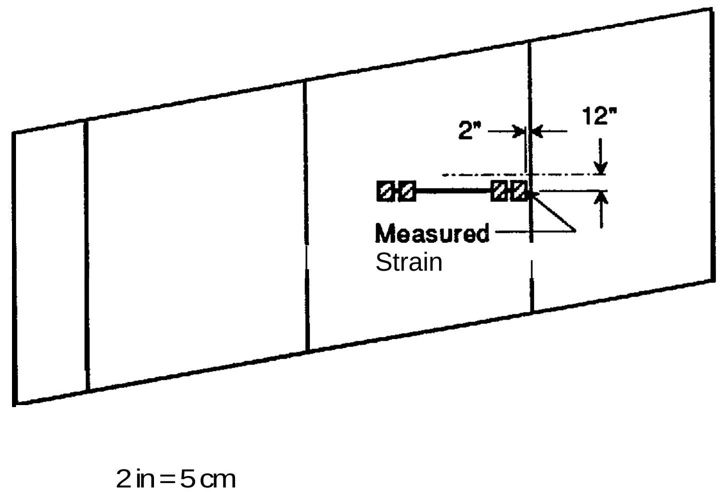


Figure 25. Utah load case 13 static.

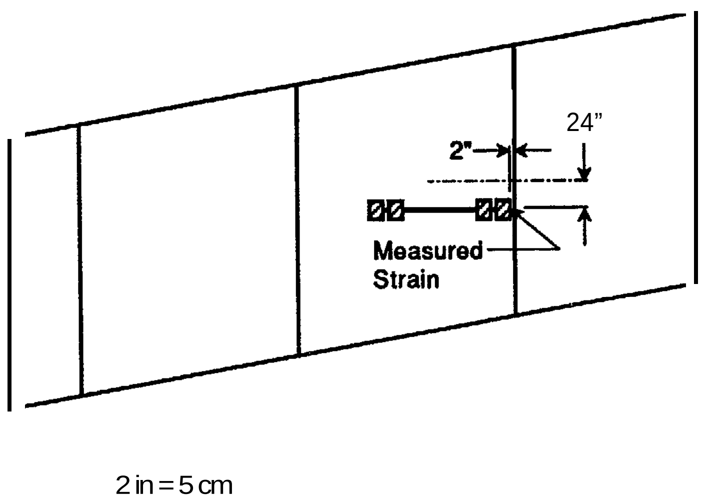


Figure 26. Utah load case 14 static.

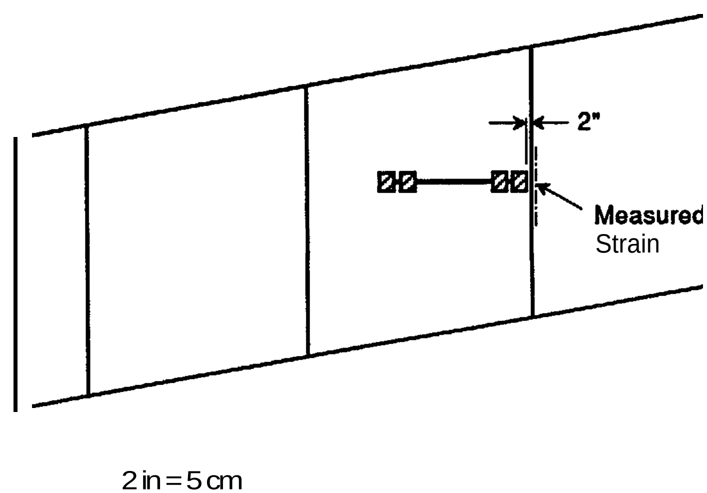


Figure 27. Utah load case 15 static.

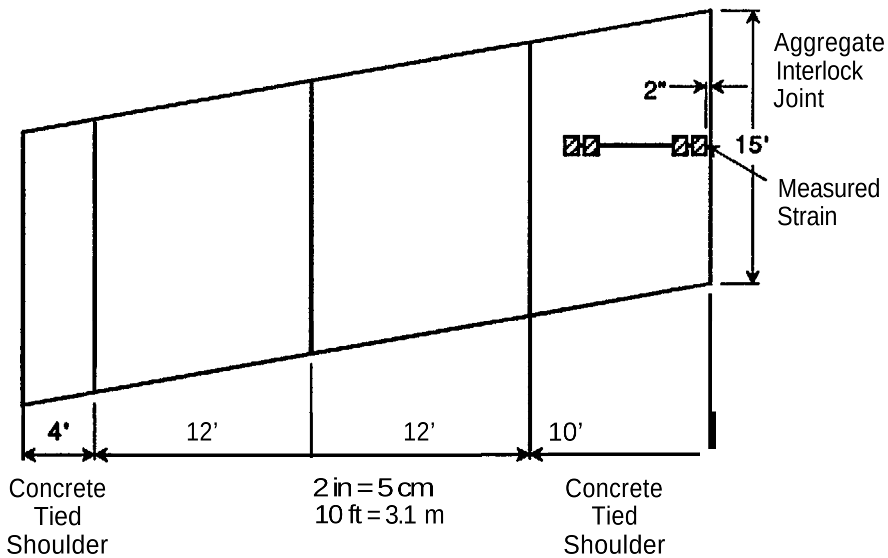


Figure 28. Utah load case 16 static.

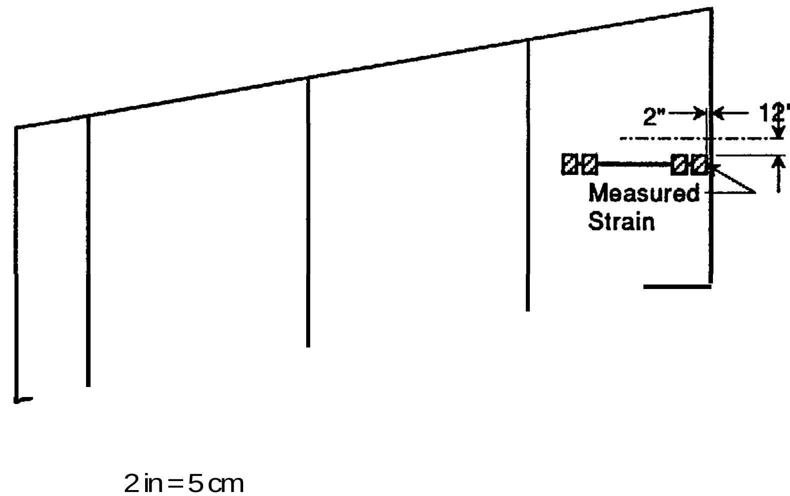


Figure 29. Utah load case 17 static.

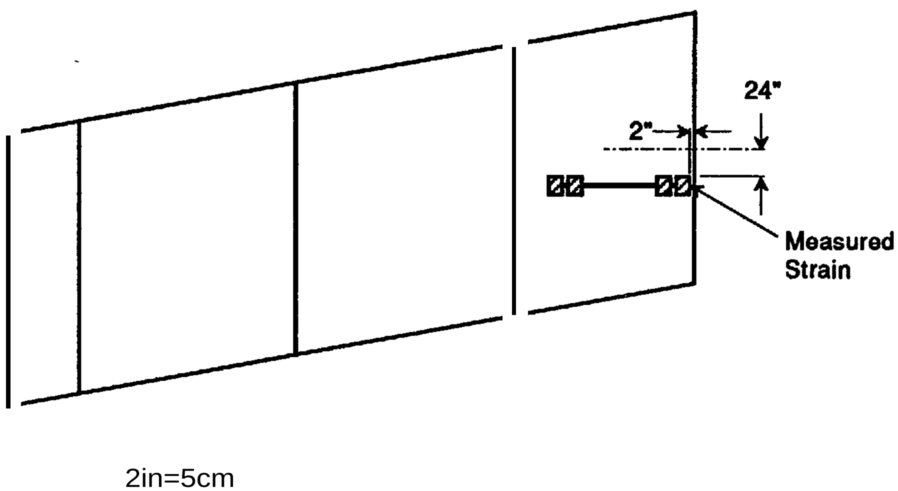


Figure 30. Utah load case 18 static.

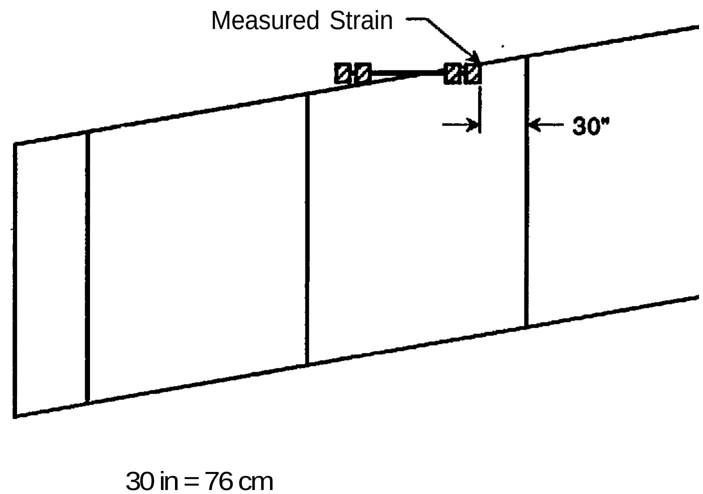


Figure 31. Utah load case 19 static.

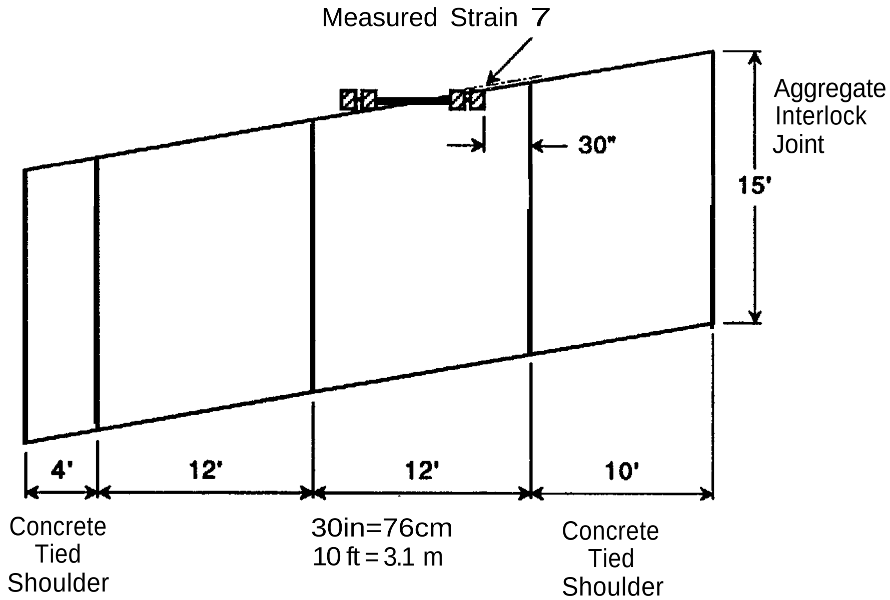


Figure 32. Utah load case 20 static.

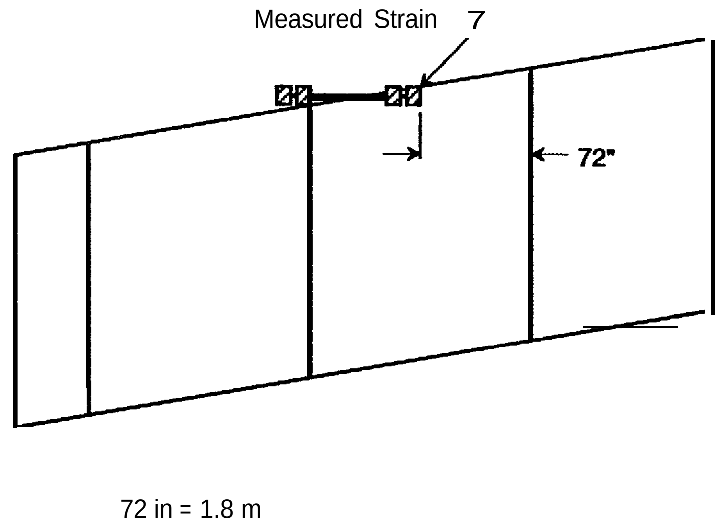


Figure 33. Utah load case 21 static.

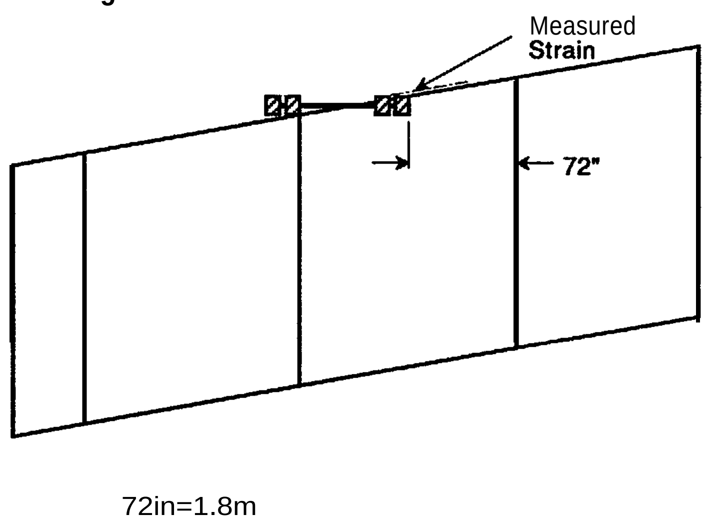


Figure 34. Utah load case 22 static.

Table 59. Summary of measured stresses and ILLI-SLAB computed stresses for Iowa load test.

Load Case	Slab 1 at 2 days			Slab 1 at 3 days			Slab 2 at 7 days			Slab 2 at 8 days		
	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi
1	117	125	6	109	126	17	64	126	42	86	126	40
2	91	80	-11	92	81	-11	70	81	11	71	81	10
3	69	55	-14	71	56	-15	51	56	5	52	56	4
4	81	73	-8	79	73	-6	61	74	13	56	74	18
5	65	68	3	65	68	3	53	69	16	52	69	17
6	26	41	15	24	41	17	25	41	16	21	41	20
7	34	47	13	46	47	1	34	48	14	32	48	16
8	143	170	27	152	171	19	124	172	48	114	172	58
9	115	86	-29	134	87	-47	80	88	8	78	88	10
10	72	25	-47	80	25	-55	46	26	-20	44	26	-18

100 psi = 0.69 MPa

Table 60. Summary of measured stresses and ILLI-SLAB computed stresses for Utah load test.

Load Case	Slab 1 at 3 days			Slab 1 at 6 days			Slab 3 at 5 days			Slab 3 at 8 days		
	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi	Measured Stress, psi	Computed Stress, psi	Pred. Error, psi
5	47	67	20	78	69	-9	36	68	32	44	69	25
6	****	****	****	****	****	****	46	39	-7	51	40	-11
7	****	****	****	****	****	****	62	15	-47	51	16	-35
16	62	106	44	129	109	-20	66	108	40	71	109	38
17	****	****	****	****	****	****	36	62	26	41	64	23
18	****	****	****	****	****	****	20	24	4	17	25	8

00 psi = 0.69 MPa

APPENDIX F: STATE-OF-THE-ART REVIEW

A summary of the literature review for determining factors to be considered for timing of control joint sawing and early loading of new concrete pavements is presented.

INTRODUCTION

This appendix provides a state-of-the-art summary on early age concrete properties, timing of control joint sawing in new concrete pavements, and on concrete properties and load factors to be considered for establishing guidelines on early use of new concrete pavements by construction traffic. The state-of-the-art review was done to establish pertinent data to be obtained from laboratory investigations and field observations of early age concrete properties and sawing of concrete pavement control joints. Early age concrete properties are investigated to determine which tests can be used for deciding when concrete pavements are ready for sawcutting joints. These tests will be correlated with concrete pavement response to sawability. Sawability is defined as the earliest time after concrete placement when control joints can be cut, using currently available wet sawing equipment, without excessive concrete ravelling at joint edges, and without excessive concrete microcracking. Joint integrity is required to assure joint sealant adhesion to joint edges and to minimize future potential joint spalling.

EARLYAGECONCRETESTRENGTHDEVELOPMENT

The purpose of joint sawing is to control cracking which occurs as a result of restrained volume changes arising from moisture and heat loss in fresh concrete. It is generally accepted that sawing cannot be performed until the concrete has set and begun to harden, typically within 4 to 24 hours after placement. To be successful, sawing must be performed before the onset of uncontrolled cracking. Sawing too early, however, before the concrete has hardened sufficiently, may result in excessive ravelling. Time window of opportunity for joint sawing is illustrated in figure 35.

Ideally, it is desirable to saw not only early enough to prevent uncontrolled cracking, but early enough to achieve sawing production rates that can keep up with the paving rate. A determination of the earliest feasible time to perform sawing therefore requires:

- A criterion for fresh concrete strength, degree of hydration, or hardness which must be achieved before sawing can be performed.
- A means of either measuring this value in the field, or estimating it as a function of mix design parameters, aggregate properties, and environmental conditions.

Hydration and Strength Gain

Hydration is a series of chemical reactions which begins immediately when portland cement is mixed with water. The reactions involving calcium aluminates (C_3A) dominate the very early stages of hydration. Initial setting of concrete, the transformation from a fluid to a solid state, occurs as C_3A and gypsum react rapidly with water to form ettringite, liberating a large amount of heat in the process. This is a diffusion-controlled process: as reaction products coat the C_3A particles, the rate of reaction slows and the rate of heat evolution drops off rapidly (within 10 to 15 minutes). The reaction proceeds slowly for the next 12 to 36 hours and peaks again as the

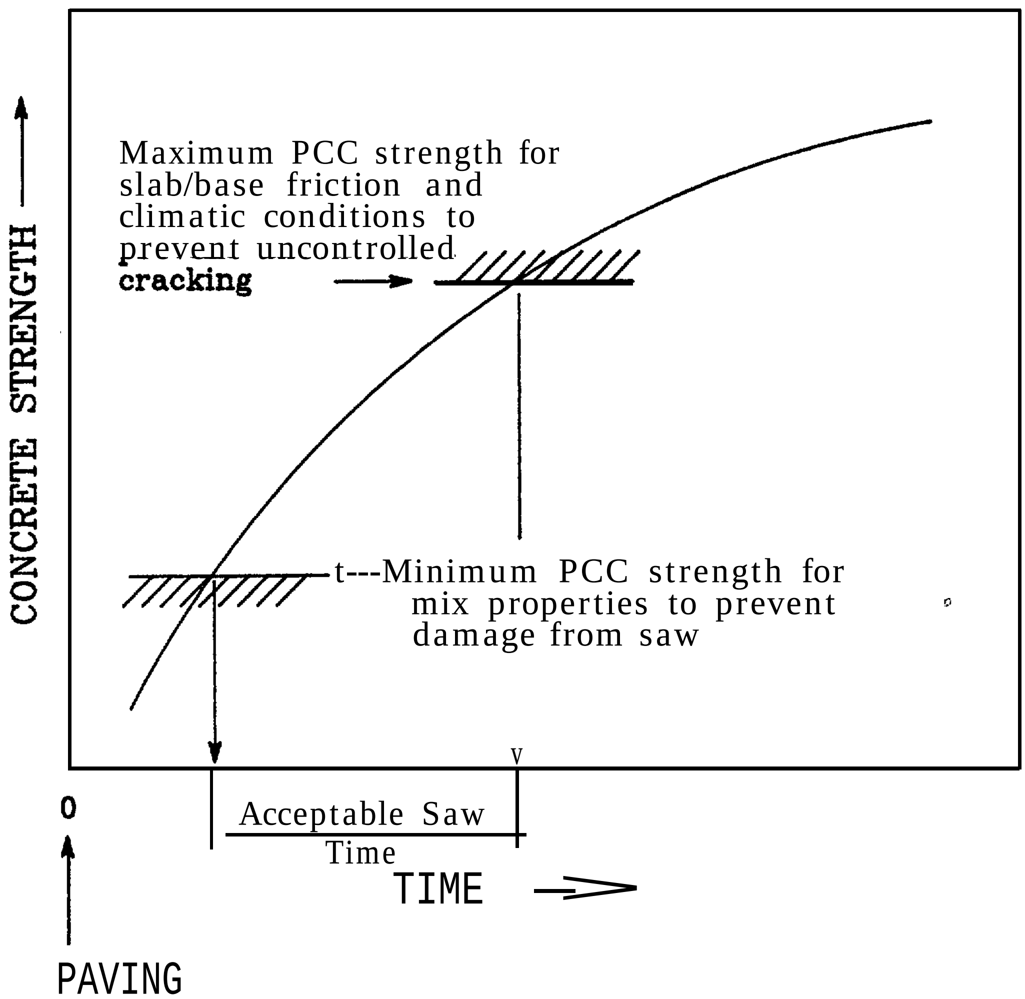


Figure 35. Illustration of acceptable sawing time.

diffusion coatings break apart and permit further C_3A hydration. Despite playing a key role in initial and final setting time, the contribution of calcium aluminate hydration to concrete's long-term strength is fairly small.

Hardening begins after setting and is associated with hydration of C_3S and C_2S to form calcium silicate hydrates (C-S-H). Since C_3S and C_2S make up 75 percent of portland cement, the calcium silicate hydrate products comprise the major fraction of the cement paste at any stage of hydration. Early strength gain (within the first 3 to 4 weeks after placement) is dependent largely on the hydration of C_3S while ultimate strength gain beyond that time depends on the contributions of both C_3S and C_2S.

The initial rapid reaction of C_3S with water, which is accompanied by liberation of a large amount of heat, is similar in nature to the C_3A reaction and lasts only about 15 minutes. This rapid initial reaction is very temperature-sensitive since the reaction rate doubles with each 20 ^{0}C (36 ^{0}F) increase in temperature. The C_3S reaction then enters a dormant stage in which C and S ions enter solution but little reactions occurs and little heat is generated. Initial setting occurs at the end of the dormant period, typically 2 to 4 hours after placement, As C and S concentrations reach critical levels, the reaction rate accelerates, reaching a maximum about 8 to 12 hours after placement, bringing about final setting and initial hardening. This reaction is also diffusion-controlled. The reaction slows as the coating of reaction products (calcium silicate hydrates) on the C_3S particles increases in thickness. Within 12 to 24 hours after placement the reaction reaches a steady state in which hydration products continue to slowly form. This process, which contributes to the long-term strength gain of the concrete, may continue for years.

The hydration of C_2S is similar to that of C_3S, but proceeds much more slowly and liberates much less heat. C_2S also contributes to ultimate strength gain, but it is really only the hydration of C_3S which controls hardening and early strength gain of the concrete.

The earliest permissible sawing time occurs sometime after final set when the concrete has attained sufficient strength to support the sawing equipment and resist damage from the sawing operation. Raveling of the sawed joint and dislodged aggregate particles can result from sawing too early. Both coarse aggregate hardness and size impact the sawability of the concrete. While the concrete may have sufficient strength to support sawing equipment the aggregates properties may influence the time at which sawing can begin without damaging the concrete. Concrete with a very hard aggregate may require greater strength gain and cement paste hardness prior to sawing than a mix with a softer aggregate to keep the aggregate particles from being dislodged during sawing. Many factors related to mix design, construction practices, and ambient conditions affect the rate of hydration and strength gain.

Influence of Environment on Hydration

Very little work has been done to quantify early strength gains in portland cement concrete. The maturity concept, which has been used to estimate strength gain in the first 28 days, has been proposed as a means of determining early (l-day) strength. Maturity is &fined as a function of the cumulative product of curing time and ambient temperature, measured in ^{0}F-hours or ^{0}F-days. The temperature is measured above a baseline experimentally found to be 11 ^{0}F (-12 ^{0}C). At temperatures below the freezing point of water and down to approximately 11 ^{0}F (-12 ^{0}C), concrete shows small increases in strength with time. This assumes that the concrete is not exposed to temperatures below freezing until it has set and gamed sufficient strength to resist frost damage, a period of approximately 24 hours. Below 11 ^{0}F (-12 ^{0}C), concrete does not appear to gain strength with time.

Strength is often a linear function of the logarithm of maturity. Thus, it is possible to express strength at any maturity as a percentage of the strength at any other maturity. The reference maturity is often taken to be 35,600 °F-hours, (19,780 °C-hours) the maturity of concrete cured at 64 °F (18 °C) for 28 days. Research shows there is an optimum temperature during the early life of concrete that will lead to the highest strength at a desired age. In laboratory studies, the optimum temperature of normal concrete has been determined to be around 55 °F (13 °C), and for rapid-hardening concrete, around 40 °F (4 °C) This is relevant only to the concrete's very early life. Once initial setting has occurred and hardening has begun, temperature influences strength according to the maturity concept: higher temperatures accelerate strength development.

A variety of computer tools exist to assist in maturity computations and interpretations, ranging from sophisticated programs to simple spreadsheets. Reference 1 demonstrates the use of PC-based spreadsheet software for quick computation of maturity as a function of date and time.

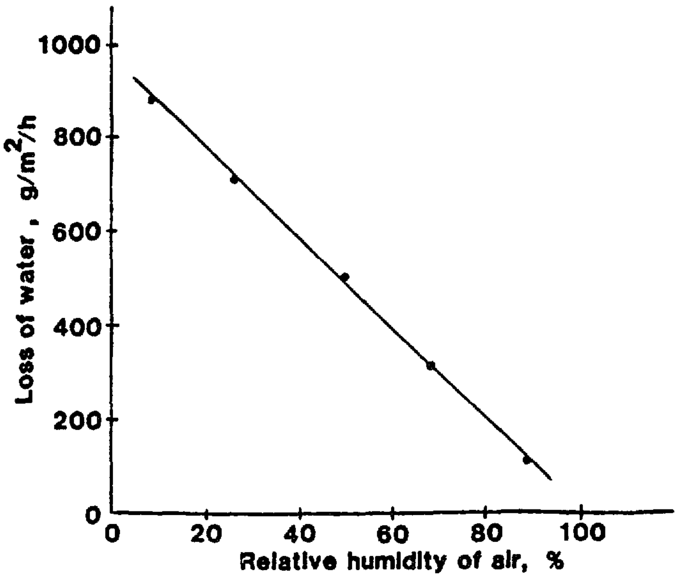
A disadvantage of the maturity concept is that it does not account for relative humidity, which has a major influence on paste porosity (hence, strength) as well as shrinkage in fresh concrete. Hydration of cement can take place only in the initially water-filled capillaries of the cement paste. The object of curing is to keep concrete as nearly saturated as possible until the water in the capillaries is replaced by reaction products to the extent necessary to provide the desired concrete strength. Excessive moisture loss through evaporation must be prevented at least until this level of strength is attained. Evaporation of water from the concrete depends on the ambient temperature, ambient relative humidity, effectiveness of curing material/procedures, solar radiation, and wind velocity, as illustrated in figure 36.(2)

Means of curing concrete pavement slabs include water spraying, ponding, covering with wet sand, sawdust, straw, burlap, waterproof paper, plastic, or canvas, or applying a membrane curing compound The last of these, the membrane compound, is the most common method in current use. The compound applied may be clear, white, or black. White compounds reflect sunlight and thus permit less temperature rise in the concrete than black or clear compounds. Curing compounds effectively retain moisture in the concrete, but do not permit entry of additional moisture into the mix, so except when used on concrete with a high water/cement ratio, membranes will generally result in slower hydration than continuous wet curing methods. In practice, however, continuous wet curing is rarely performed, addition of water to the covering is performed intermittently, which may be no more effective in keeping the concrete saturated than using a membrane. Tests for efficiency of curing compounds are given in ASTM Designation: C156-551.

Temperature at Concrete Placement

The optimum time to saw concrete strongly depends upon the environmental conditions at the time of placement and immediately afterward. This is shown by the fact that daytime or nighttime paving requites different sawing times. Concrete placed during the daytime, with very warm temperatures, will have a different sawing time than concrete placed at night, with cooler temperatures. When temperatures are high, the sawing of the concrete is critical since the potential of a large concrete temperature gradient exists (especially after solar radiation decreases) and waiting a little too long may result in uncontrolled cracking. Under cooler conditions, sawing may be accomplished within a wider time interval. Several states in dry climates require a continuous water-fog to keep the pavement cool and promote proper curing until sawing is completed.

Influence of relative humidity on loss of water from concrete in early stages after placement.



$1000\ g/m^2 = 0.2\ lb/ft^2$
$^\circ F = 1.8\ ^\circ C + 32$

Influence of air and concrete temperature on loss of water from concrete in early stages after placement.

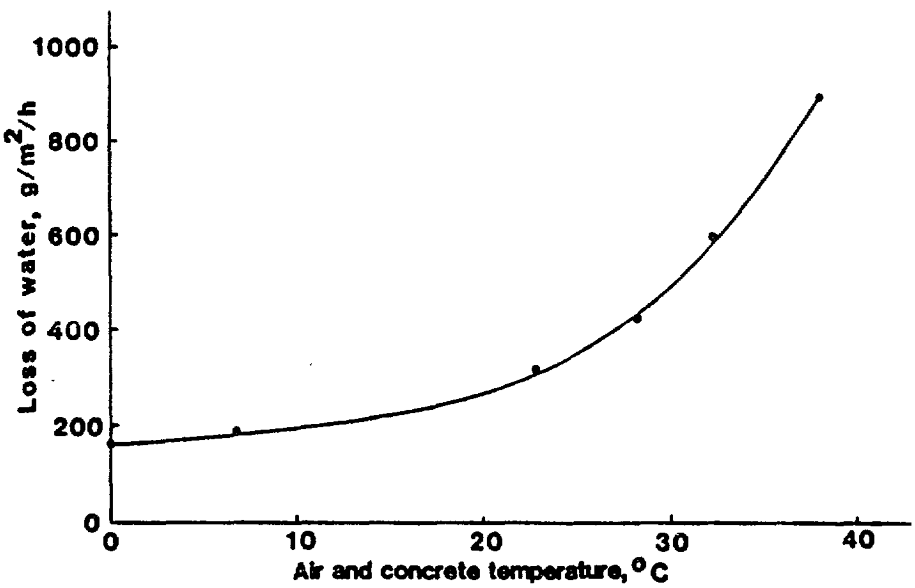
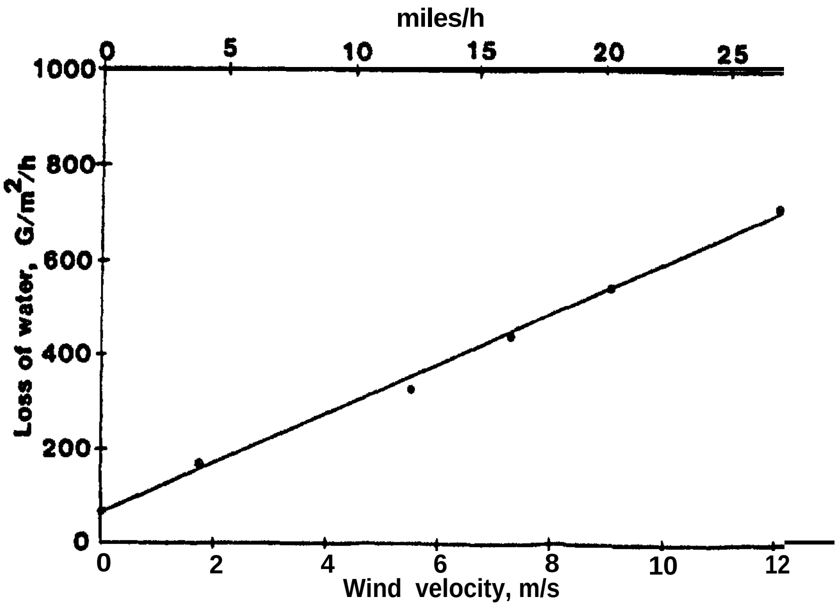


Figure 36. Factors influencing moisture loss in concrete.[2]

Influence of wind velocity on loss of water from concrete in early stages after placement.



1000 g/m2 = 0.2lb/ft^2
$^{o}F = 1.8\ ^{o}C + 32$
1 m/s = 0.31 ft/s

Figure 36. Factors influencing moisture loss in concrete (continued).[2]

Cold Weather Concreting

Concrete placed in cold temperatures may not gain strength sufficiently rapid to permit sawing at the desired time, and may even suffer frost damage. Placing concrete in cold weather therefore requires special precautions to insure durable, high-strength concrete. These precautions include increasing cement content, changing cement type, heating mixing water and aggregates, insulating concrete forms (if used), and providing external heat and cover during early curing.(3 Effects of temperatures and cement type are shown in figure 37. Effects of curing insulation provisions are shown in figures 38 through 42 and effects of temperature are shown in figure 43.

In general, the minimum acceptable temperature for concrete placement is 55 °F (13 °C) for thin slabs. Several agencies require the ambient temperature and the concrete surface temperature be recorded at frequent intervals (every 4 to 6 hours) for the first 3 to 5 days after placement. Nearly all agencies specify the concrete surface temperature be kept above 50 °F (10 °C) during the required curing period, which range from 3 to 5 days in some States to 5 to 7 days in others. A 5- to 7-day curing period is the more commonly used specification. Figure 37 illustrates the effect of cooler temperatures on strength gain, as well as the combined effects of temperature and cement type on strength gain.(4)

Hot Weather Concreting

When placing concrete in hot weather, the main concerns are increased evaporation of mixing water, reduced strength, and greater volume changes. Steps such as shading or sprinkling aggregates, cooling the mixing water, using water-reducing admixtures, erecting wind screens, and curing with wet burlap, white membrane curing compound, or plastic sheets are done to minimize hot weather effects. Applying cold water directly to a hot concrete surface is not recommended due to the likelihood of surface cracking induced by rapid temperature changes.

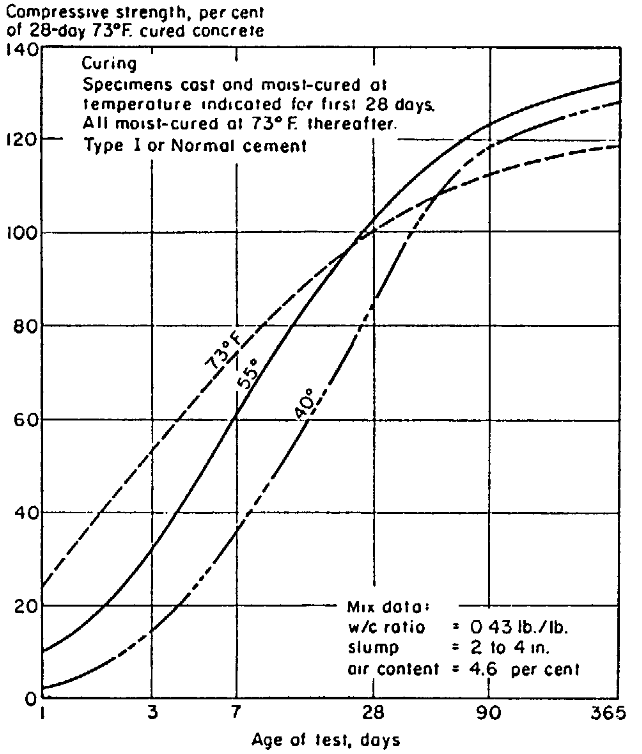
Specifications typically restrict concrete placement to times when the ambient temperature is below 90 °F (32 °C) and require keeping the concrete surface temperature below 85 °F to 90 °F (29 to 32 °C) during the curing period. Many agencies use the ACI "Recommended Practice for Hot Weather Concrete" as a standard reference.(5)

PAVEMENT TO SUBBASE FRICTION

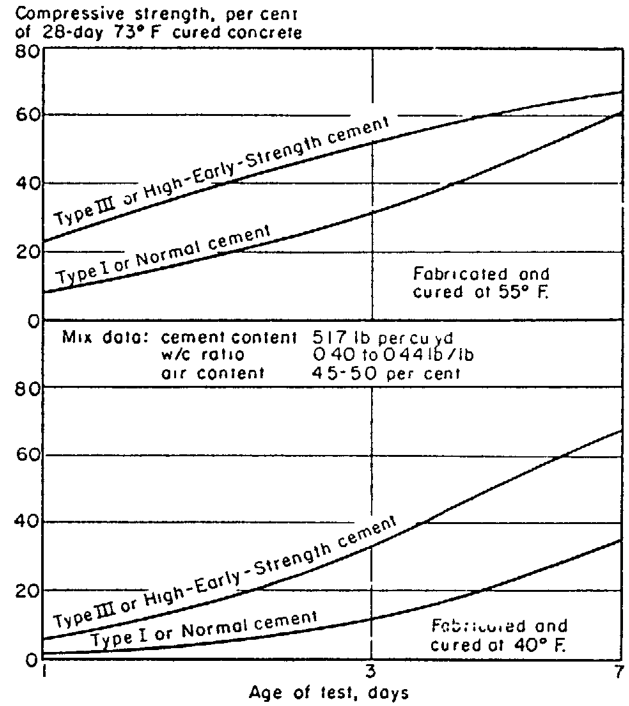
Control (contraction) joint sawing should be done within the following time limits:

- The earliest time after concrete placement when joint sawing can be done without causing excessive concrete joint (sawcut edge) damage.
- The latest time sawing can be done without occurrence of random longitudinal or transverse slab cracking that can be attributed to concrete contraction restraints or curling and warping restraining stresses.

Concrete contraction restraints occur when concrete temperature contraction or drying shrinkage are hampered or prevented by pavement to subbase friction or bond. Curling and warping restraint tensile stresses occur when slab surfaces have differential temperature and/or a greater amount of drying when compared to slab depths below top of pavement. The following discussion addresses the slab to subbase friction mobilized by horizontal slab contractions.



Effect of temperatures on concrete compressive strength at various ages



Early compressive strength relationships involving portland cement types and curing temperatures

$^{o}C = 5/9(^{o}F - 32)$
$517\ lb/yd^3 = 307\ kg/m^3$
1 kg.kg = 1 kg/kg
1 in = 2 54 cm

Figure 37. Effects of temperature and cement type on strength gain during cold weather concreting.(3)

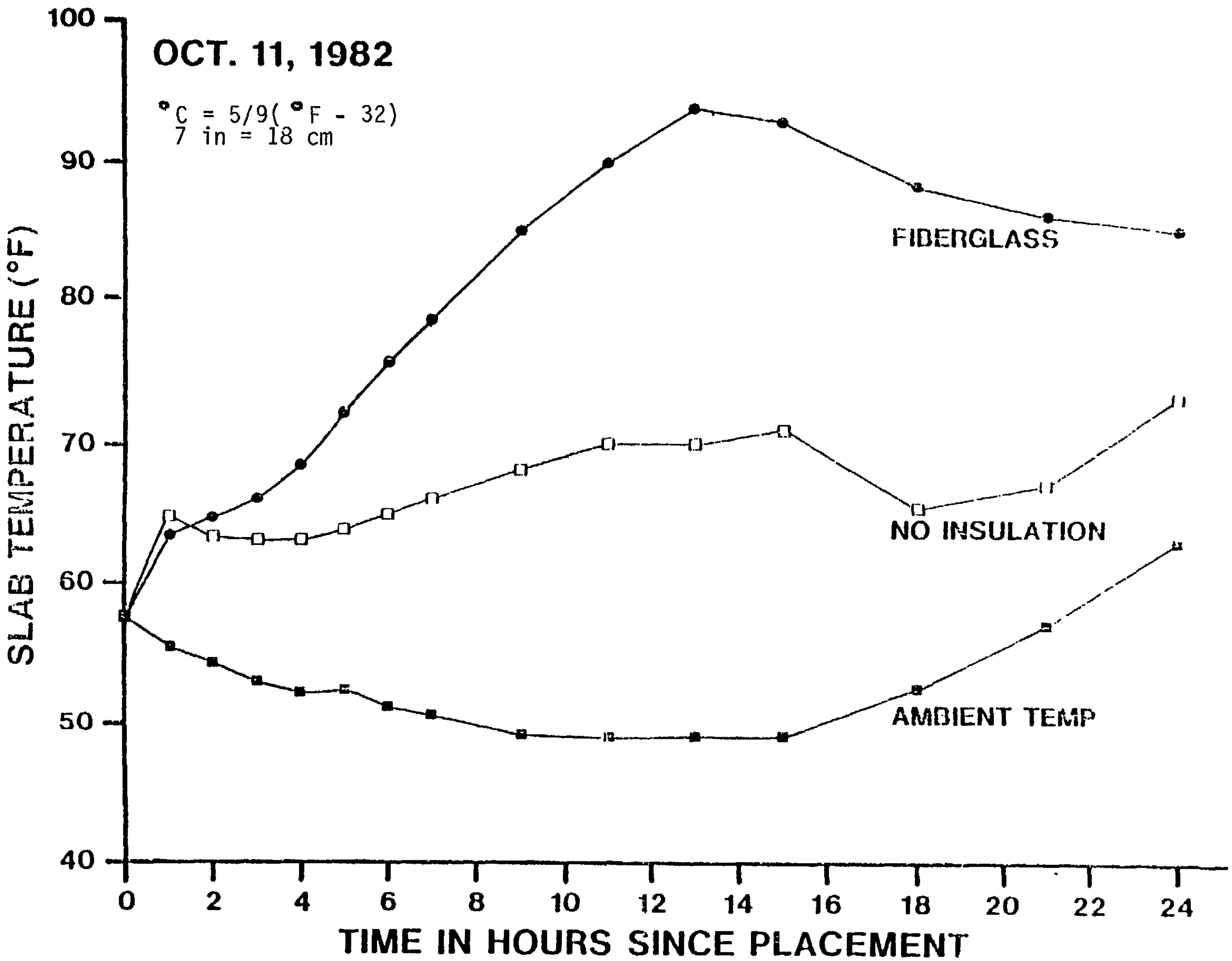


Figure 38. Temperature at mid-depth of seven-inch full-depth repair after placement - October 11, 1982.[4]

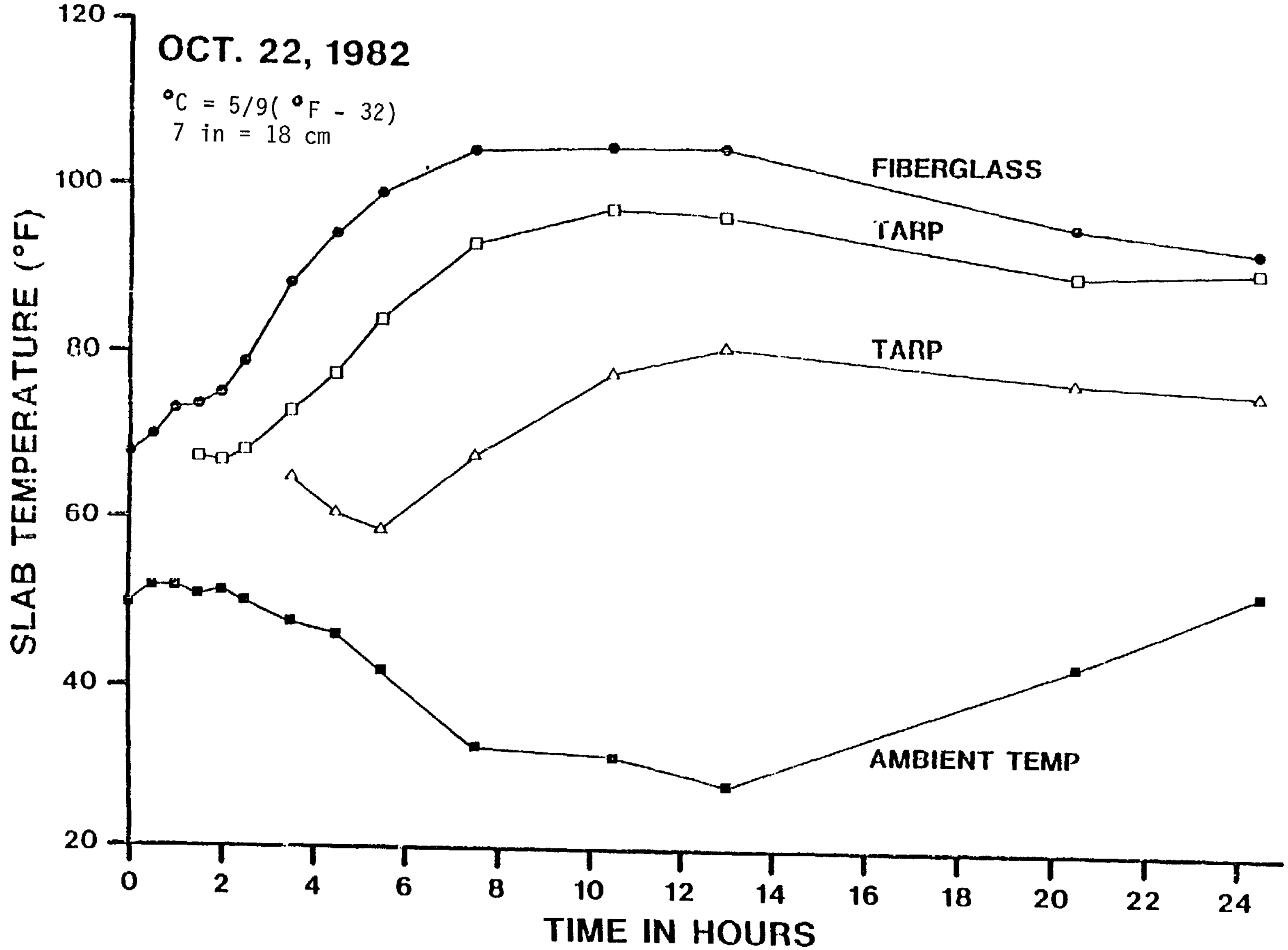
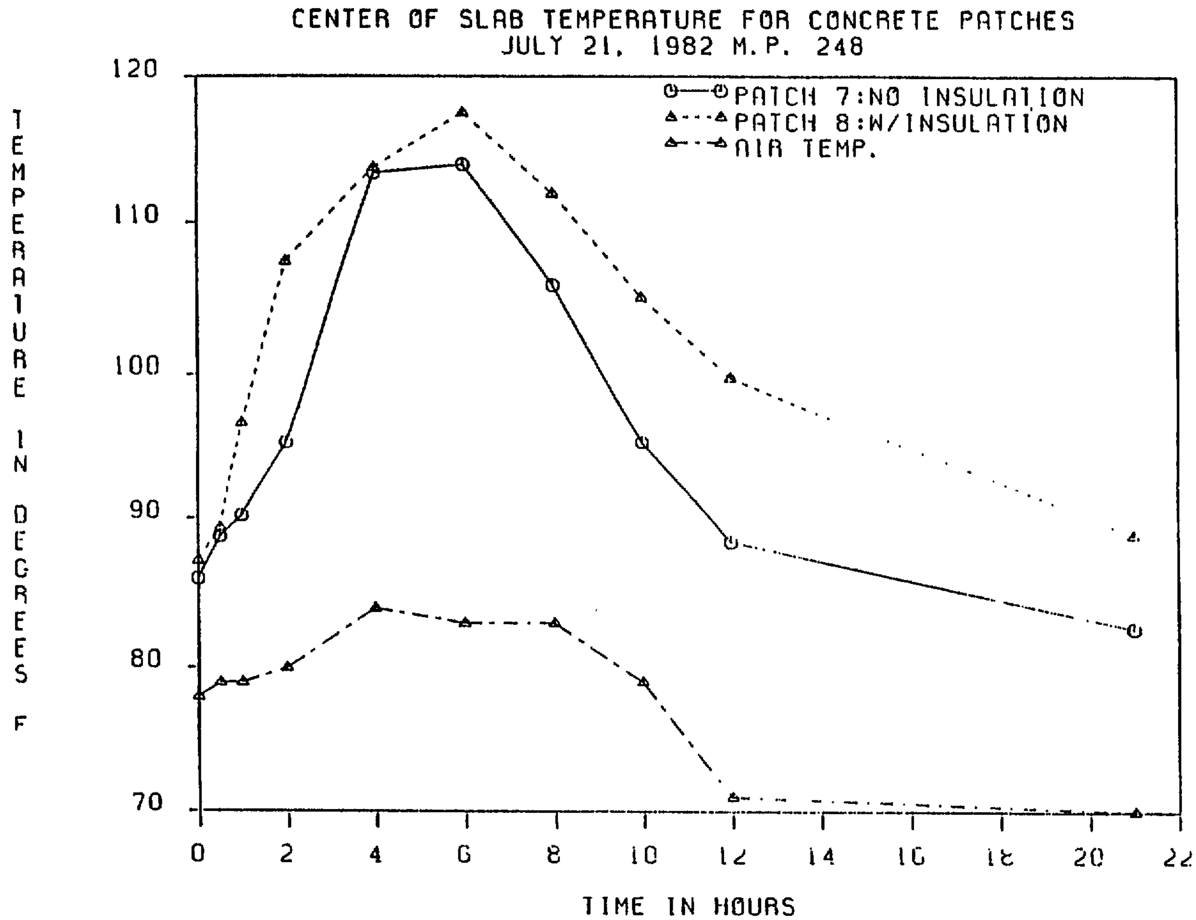


Figure 39. Temperature at mid-depth of seven-inch full-depth repair after placement - October 22, 1982.[4]



°C = 5/9(°F - 32)
7 in = 18 cm

Figure 40. Temperature at mid-depth of seven-inch full-depth repair after placement - July 21, 1982.

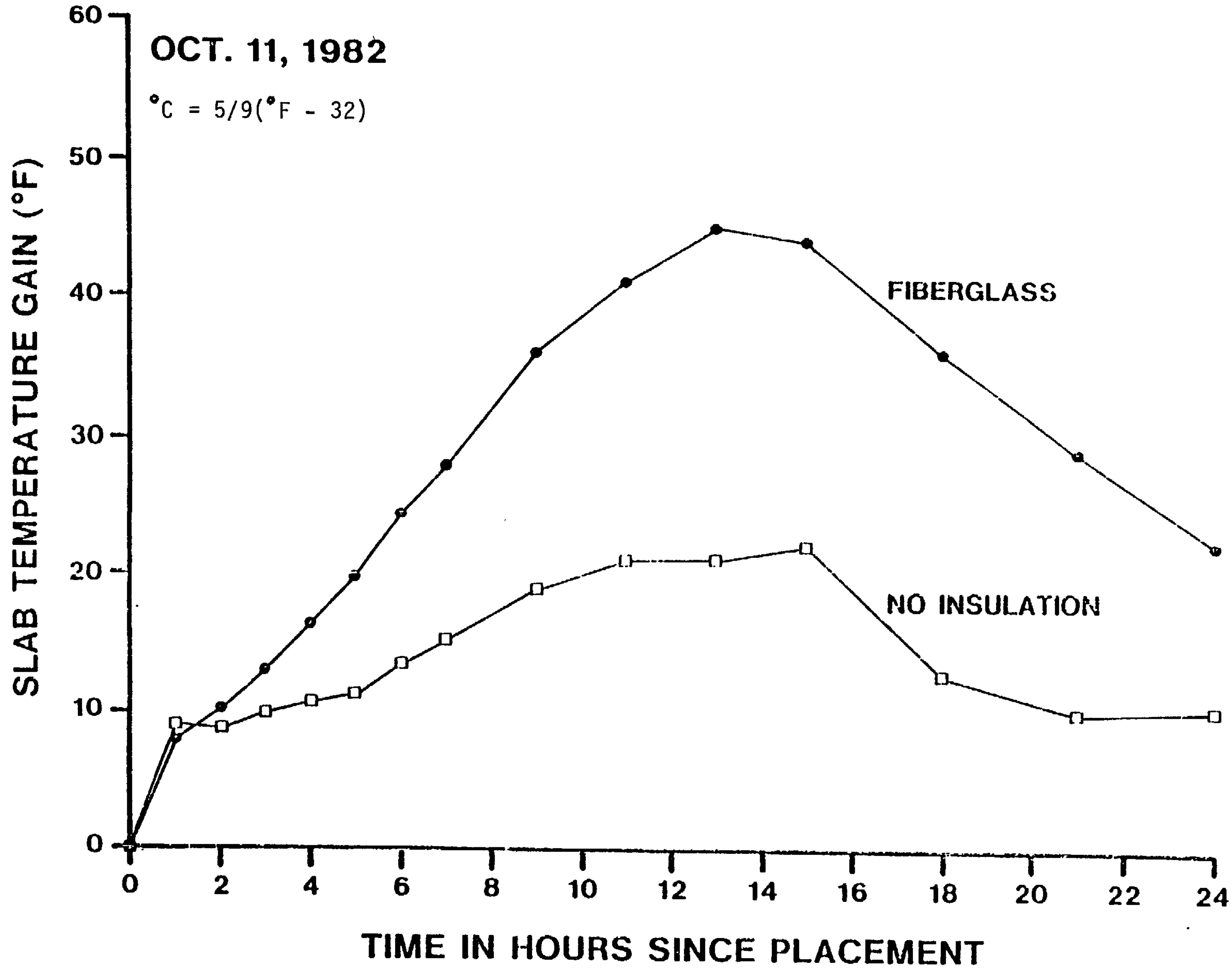
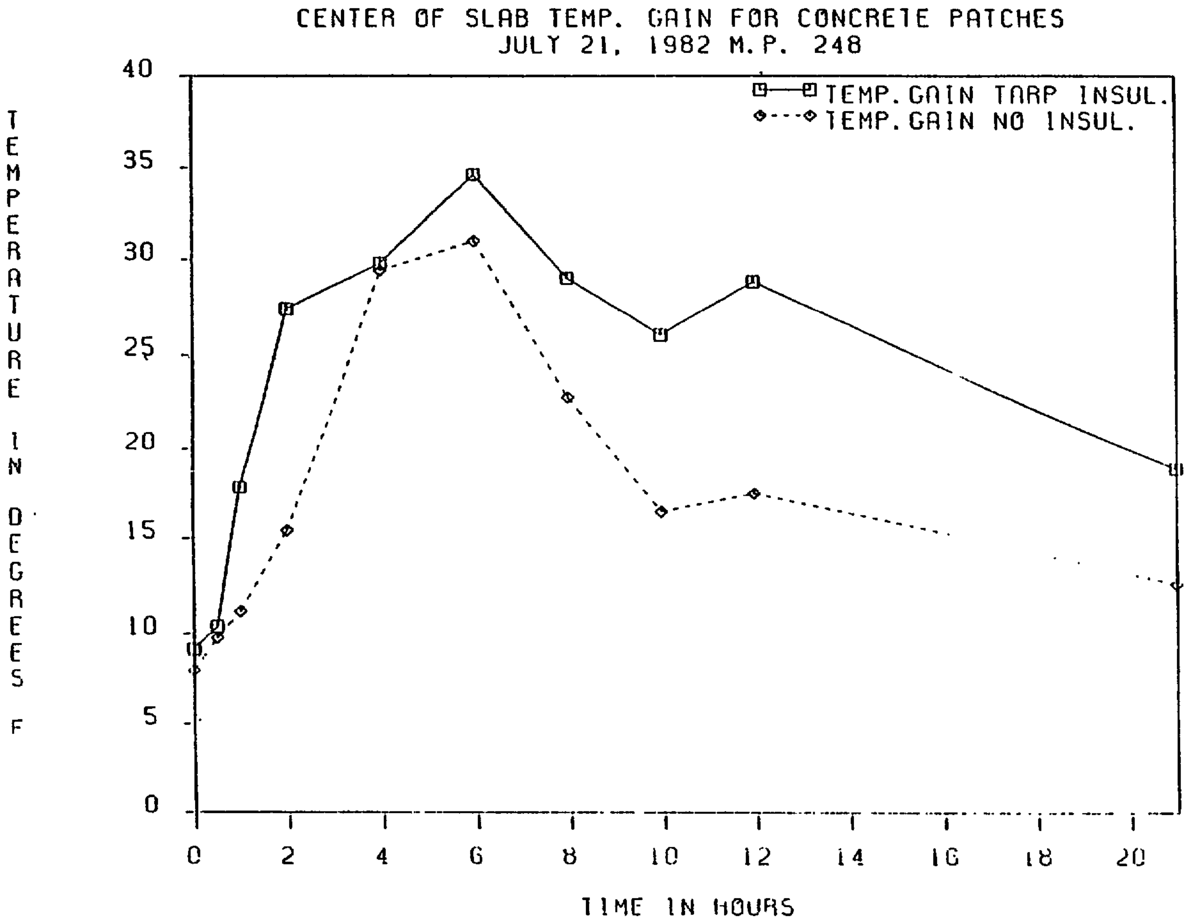
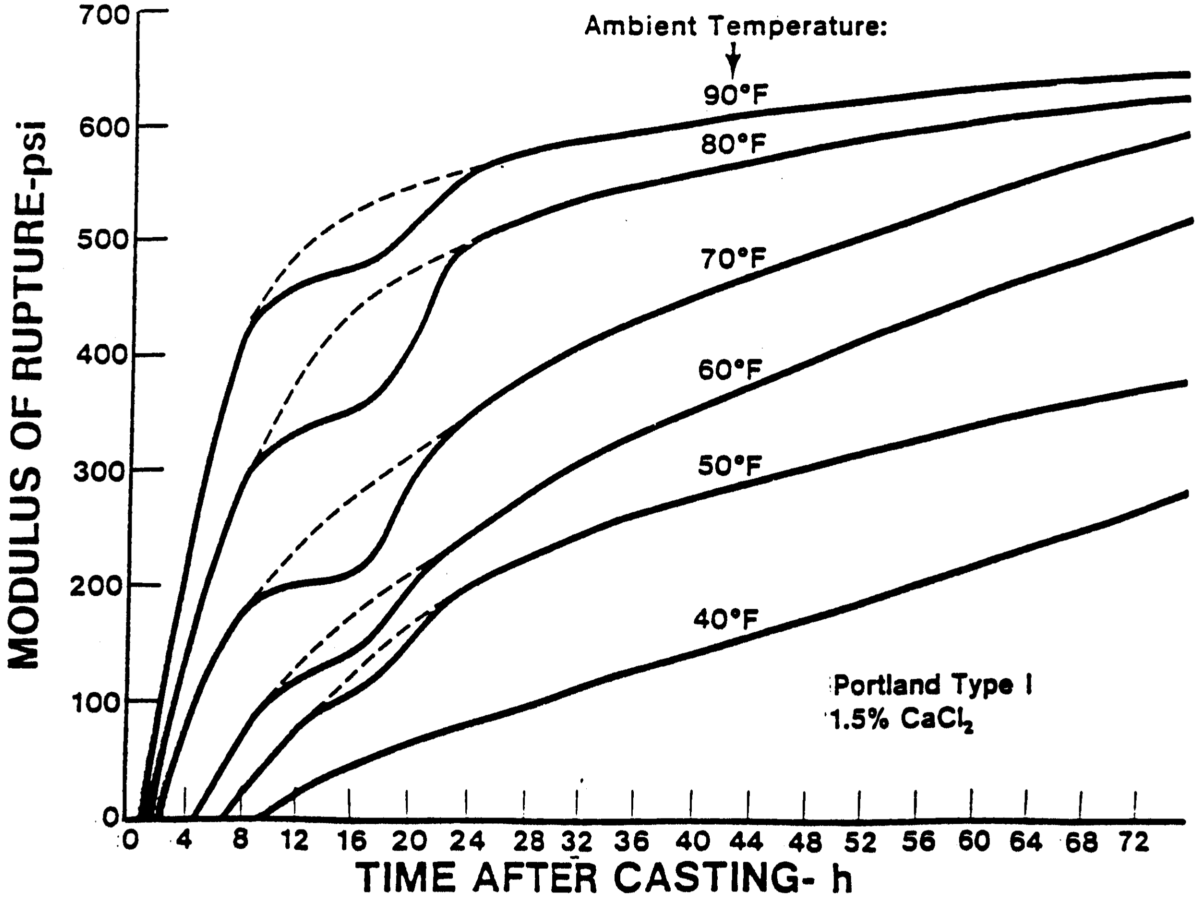


Figure 41. Temperature gain above ambient for same slab shown in figure 38.(4)



°C = 5/9(°F - 32)

Figure 42. Temperature rise above ambient for same slab shown in figure 40.



100 psi = 0.69 MPa

°C = 5/9(°F - 32)

Figure 43. Average strength gain of PCC beams cast during full-depth repair operations (temperatures on curves represent ambient temperatures at time of placement).(4)

Literature review indicates slab to subbase friction restraints are discussed in terms of slab length or width changes attributable to average through slab temperature changes. Average through slab moisture changes produce slab length or width changes and are usually expressed as equivalent temperature variations.

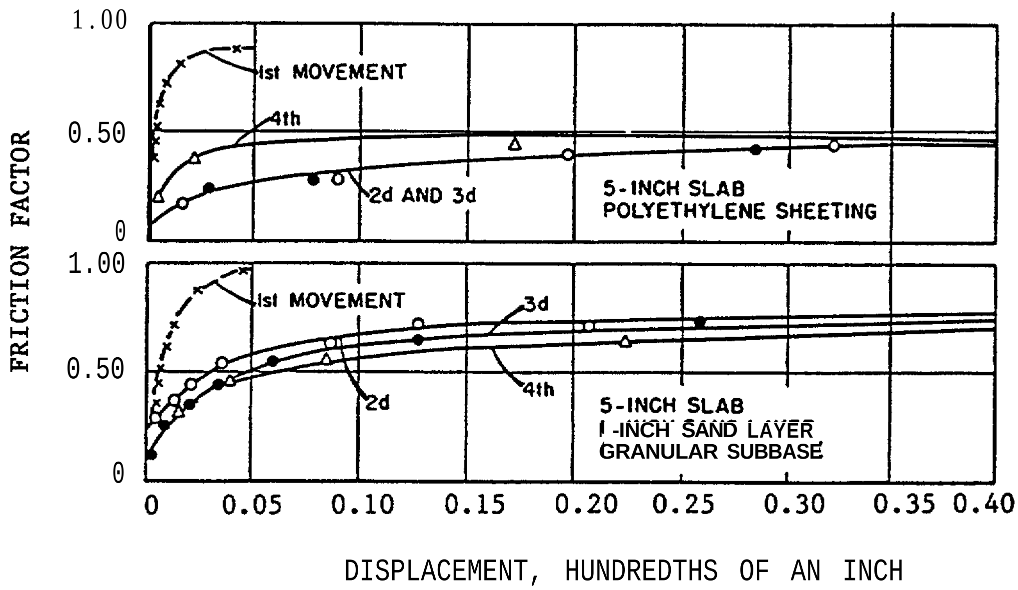
Friction Measurement

Frictional force between two slowly sliding surfaces is, according to Coulomb's Law, proportional to the normal force applied to the contact area between the two surfaces. The proportionality constant is the coefficient of friction. This coefficient may be thought of as the ratio of the horizontal resistance force to the normal force necessary to initiate sliding or cause a specified horizontal displacement. The maximum coefficient of friction value is developed at the onset of slippage between the two surfaces. The rapid buildup of friction with incipient or first slab movement is shown in figure 44. Friction coefficients for concrete pavements on subbases are generally reported as the values of friction coefficients measured at incipient movement. A lower than the incipient movement friction value is generally observed after initial slab movement has occurred The forces resisting the first movement are sometimes called the "peak restraint" and subsequent movement restraint forces are called "steady state restraint." Generally newly constructed pavements experience greater initial friction movement resistance than the friction movement experienced in subsequent pavement life. Friction associated movement restraints can be significantly changed by variations in subbase surface moisture and can be dramatically changed when this moisture freezes.

Several studies to measure frictional forces and quantify friction factors for various types of subbases and bondbreakers have been conducted over the past 65 years.[8-12] The findings are characterized by a large range in values obtained for friction factors which may be attributable to variations in testing procedures. Values for the coefficient of friction of a variety of materials range from 0.5 to 10. Friction coefficients of 1.5 and 2.0 are generally assumed for dense graded granular subbases when welded wire reinforcement dimensions arc designed using the "drag" formula. Values less than 1 .O are reported for bondbreaking pavement to subbase interface provisions such as polyethylene sheeting, fine sand, or moisture-saturated cohesive soils. Values in excess of 10 can be anticipated when partial bond between slab bottoms and treated or stablilized subbase surfaces occur. Higher values can be attributed to full bond between stabilized subbases and slab bottoms. Reported findings for various materials are summarized below.

Fine-Grained Soils: For slabs resting directly on fine-grained subgrades, resistance to movement is rarely due to friction at slab to subbase interface alone. If the material is a cohesive soil, slab movement may cause shear deformation in the soil within upper layers. The ability of the soil to resist this deformation is given by its shear strength. A cohesive soil's shear strength, and thus its cohesive resistance to slab movement, will decrease as the soil becomes saturated. While friction coefficients in the range of 1.5 to 2.0 are typical for firm, damp cohesive soils, these values may be reduced by as much as 30 percent when the soils are saturated.[6,7,10,13,14]

Unbound Granular Base: In contrast to cohesive soils, the measured friction coefficients of cohesionless materials (clean sands, gravels, and crushed stone) are in the range of 1.0 to 10 and are not significantly influenced by changes in moisture content unless freezing occurs.[6,7] Open graded crushed stone subbases without choking the subbase surface with crushed stone fines can key to slab bottoms and thus provide considerable magnitudes of equivalent friction restraint to slab movements.



1 in = 25.4 mm

Figure 44. Relationship between peak frictional restraint and steady-state frictional restraint.[6,7]

Asnhalt Subbase: High friction coefficients have been measured below concrete slabs placed on asphalt leveling courses, asphalt-treated bases, and asphalt surfacings on cement-treated bases.[12,15,16,17] Data from one study reported values between 4 and 10, in figure 45, for a range of asphalt concrete (AC) layer thicknesses and concrete slab thicknesses. These results are consistent with values measured by others. The reported data indicate the measured friction factor decreases with increasing slab thickness. This is consistent with trends observed by others for asphalt materials.

In general, asphaltic layers do not act as bondbreakers. Rather, they resist slab movements by mobilizing shear strength. This has the same effect as a high friction factor. The use of such layers is often desirable for purposes other than friction reducing layers. Asphaltic layers serve as a separation layer to minimize concrete reflection cracking. To reduce friction between concrete slab bottoms and asphalt layers, a bondbreaker such as polyethylene may be used. Friction values for bondbrealcing materials am shown in figure 46. If the purpose of the asphalt layer is to increase structural capacity, breaking the bond would decrease the structural contribution of the asphalt layer.

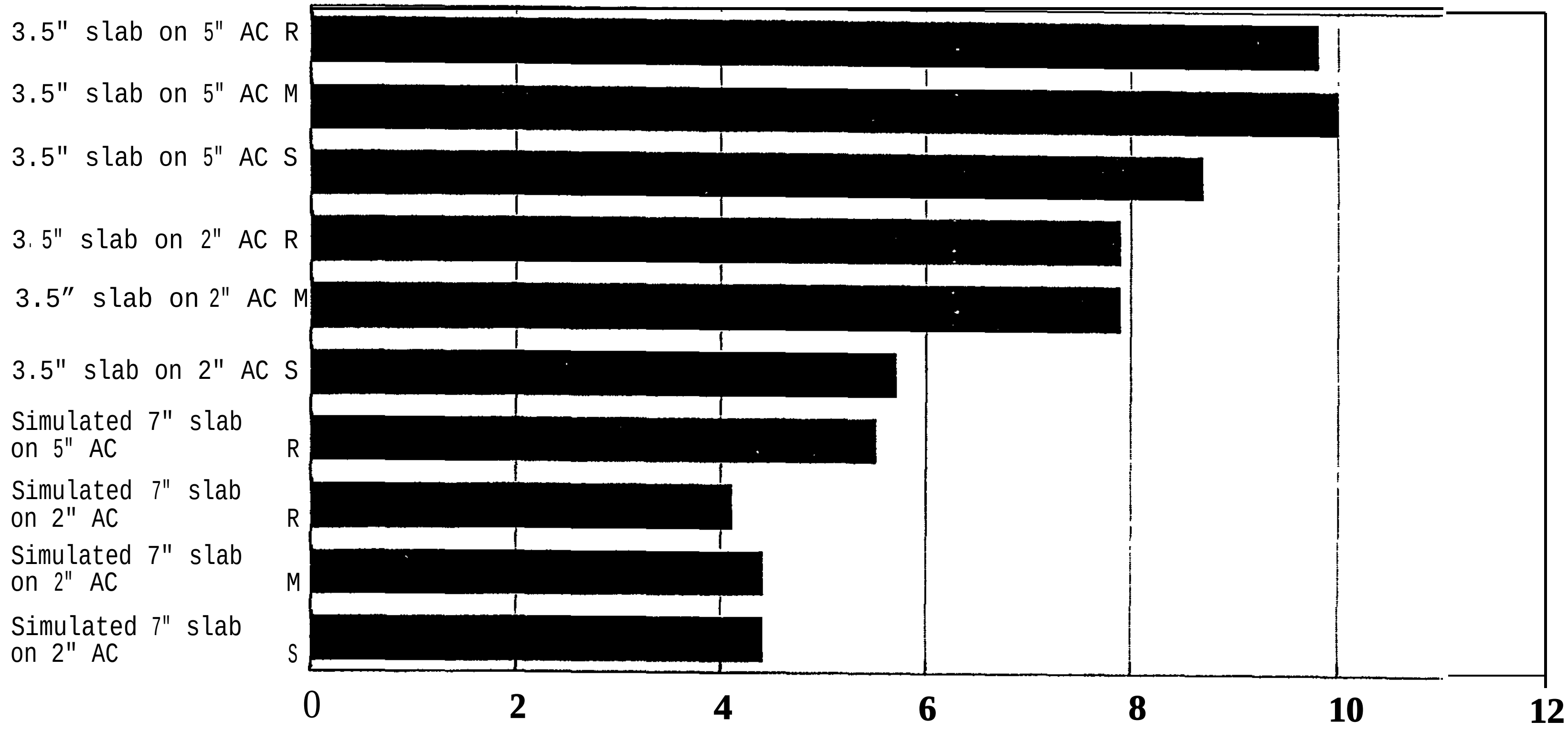
Placing a "whitewashing" or topping on an asphalt subbase reportedly has been done to reduce friction magnitude. Extent and by what mechanisms whitewashing reduces friction between the asphalt base and the surface are not known. The fine lime particles may fill in pores in the asphalt base's surface and thus change its texture. It has also been suggested that the benefit of whitewashing may be that it (1) reflects solar radiation, reducing the temperature of the asphalt base ahead of concrete placement, or (2) that it improves the stability of the asphalt near the surface. It was reported this practice reduced occurrence of cracking at many control joints. This resulted in excessive opening at those joints where cracking occurred below the sawcut control joint. Further investigation of whitewashing in both the field and laboratory is needed to better explain the role of whitewashing in reducing occurrence of cracking of concrete pavements over asphalt-treated bases.

Cement-Treated and Econocrete Subbases: Very high friction factors, ranging up to 64, have been measured for cement-treated bases, including econocrete, as shown in figure 47.[16,17,18] It should be noted the values reported in these studies include friction measured at "first movement," or initial breaking of the bond between the cement-treated subbase and the slab. As with asphalt-stabilized subbases, the purpose of cement-stabilized bases is to increase erosion resistance at slab to subbase interfaces. Bondbreakers, such as polyethylene or heavy applications of wax-based curing compounds on stabilized subbase surfaces, can greatly reduce friction magnitudes. However, with loss of bond, erosion resistance may be reduced.

Prediction of Random Pavement Cracking and Required Joint Spacing

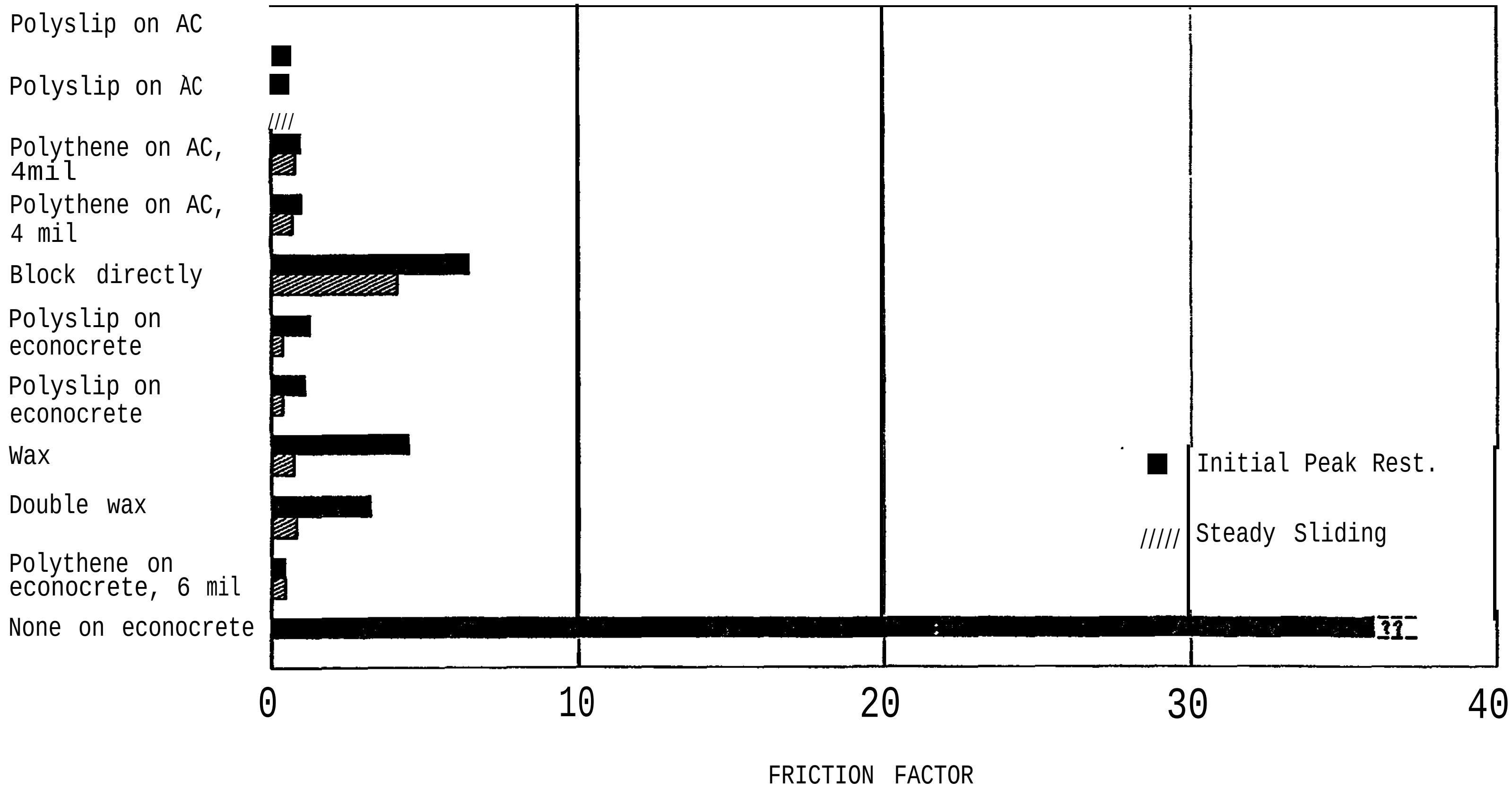
It has been proposed that the maximum tensile stress in a slab due to frictional resistance occurs at midslab.[1,20] Restraint stress is a function of the friction coefficient, unit weight of concrete, slab length, and a reduction factor to account for the nonuniformity of friction developed under the slab. Reference 15 indicates pavement tensile stress attributable to friction-associated slab movement restraints will be sufficiently large to cause cracking in slabs for the following conditions:

- Long joint spacings subjected to large temperature variations.
- Subbases with high friction coefficients.
- Newly constructed slabs that have not developed sufficient tensile stress.



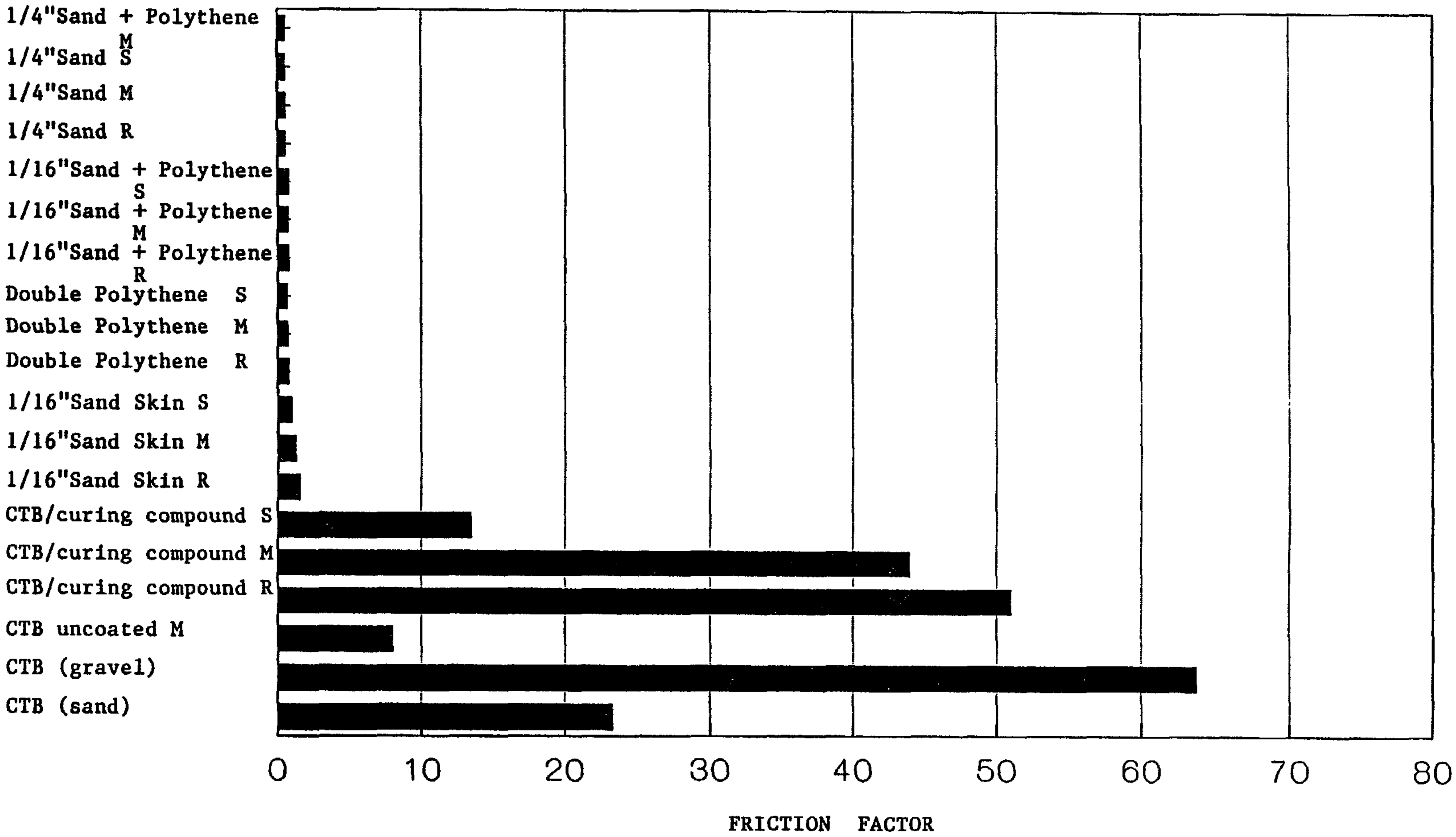
10 in = 25.4 cm

Figure 45. Friction factors measured for asphaltic layers. (6)



10 mil = 0.25 mm

Figure 46. Effect of bondbreaking layers in reducing friction factors of stabilized materiais. (6,16)



1 in = 25.4 mm

Figure 47. Friction factors measured for cement-treated bases and other materials.(6,17,18)

Thus, for a particular pavement construction project, joint spacings to prevent random slab cracking attributable by slab to subbase friction-associated tensile stresses in excess of the concrete'e early strength can be determined from knowledge of subbase type, friction coefficient, and concrete unit weight.

Effect of Subbase Type on Longitudinal Cracking

Longitudinal joint depth and spacings and the pavement to subbase friction values have a significant influence on occurrence of longitudinal cracking. Recent field data indicate base type is important to occurrence of longitudinal cracking.[21] Stabilized bases result in higher friction than nonstabilized bases. The average quantity of longitudinal cracking for several base types is summarized below for recent field data:[21]

No Base	=	86 ft/mi (16 m/km)
Lean Concrete Subbase	=	226 ft/mi (43 m/km)
Aggregate Subbase	=	228 ft/mi (43 m/km)
Asphalt-Treated Subbase	=	664 ft/mi (126 m/km)
Cement-Treated Subbase	=	729 ft/mi (138 m/km)

However, it should be recognized that construction provisions, as for example selection and coverage of curing compounds, roughness or smoothness of subbase surface texture, and subbase surface levelness may significantly alter the reported data.

Bondbreaking Materials

A variety of natural and man-made bondbreaking materials placed at slab to subbase interfaces have been tested for their ability to reduce friction between concrete slabs and their supporting layers.[7,21,22] These materials include waterproof paper, building paper, sheet asphalt, emulsified asphalt, and single- and double-layer polyethylene sheeting, among others. Some test results are reported in terms of the percent reduction in friction factor achieved with the bondbreaker for a given foundation material.

Single layers of waterproof paper and building paper reportedly reduce friction by 30 to 40 percent. Much larger reductions, as high as 70 percent, have been reported for single-layer polyethylene atop a thin layer (1 in, 25 mm) of sand, or with double-layer polyethylene. In western States, heavy applications of waxed based curing compounds are applied to lean concrete subbase surfaces immediately ahead of placing concrete for pavements. Thin layers of bituminous materials, in contrast, were not found to be effective bondbreakers; rather, they increase slab to subbase friction. These results are consistent with those found for asphalt-treated base materials. One research study reported that the friction factor for thin (up to 0.5 in, 13 mm) bituminous layers are directly proportional to rate of slab displacement and inversely proportional to layer thickness.[22] It was also reported that lower friction values exist for softer bitumen and higher temperatures. All of these observations suggest that bonding occurs between a thin bituminous layer and a concrete slab, with resistance to subsequent movement of the slab being a function of the shear resistance of the bituminous material.

Summary

The mechanism of slab to subbase friction and its role in causing random slab cracking is fairly well researched and understood. Friction coefficients for a wide variety of subbase types and interlayer materials have been determined. Typical values reported are:

- Between 1 .O and 2.0 for cohesive soils with moisture contents near optimum, falling off as much as 30 percent near saturation.
- Between 1.0 and 10 for coarse-grained materials, independent of moisture content.
- Between 4 and 10 for cement-treated material.
- As high as 64 for cement-treated materials.
- Over 30 for pavements bonded to subbases but less than 1 with polyethylene.

Bondbreaking layers such as waterproof paper and polyethylene are very effective in reducing friction. Polyethylene is generally not used as a bond breaker except in prestressed pavement construction. The benefit of using such materials with stabilized bases must be weighted against the increase in erosion and the reduction in load-bearing capacity caused by breaking the bond between the base and the concrete slab.

Most discussions of this topic address only temperature variation. For new pavement construction shrinkage must be predicted as a function of both temperature drop and moisture loss (involving water/cement ratio, ambient and environmental conditions, curing methods, etc.). If this can be done the maximum tensile stress induced in the slab by incipient movement frictional resistance to shrinkage can be determined and compared to the concrete's early strength to predict whether cracking will occur for a given slab length and width.

A higher friction factor means a more critical time interval for sawing joints. Greater temperature drops, or greater drying shrinkage will be significant to the last time within the "window of opportunity" for sawing joints.

CONCRETE SAWCUTTING BLADES

Two types of blades, abrasive and diamond impregnated blades are used for concrete sawing.

Abrasive Saw Blades

Abrasive saw blades have been used to saw concrete contraction joints in new pavement, Abrasive saw blades consist of a fabric base which is impregnated with a cutting material such as aluminum oxide, silicon carbide, or diamond. Abrasive blades can be used with or without water when sawing concrete, depending on the blade and amount of cutting required.[23]

Abrasive blades are most commonly used for quick cutting jobs on concrete that contains soft aggregate such as limestone.. They are not commonly used on large jobs where extensive sawing is required because of rapid wear: The wear characteristics of abrasive blades also make controlling the width and depth of cut difficult. As the blade wears the blade size is dim-inished. For these reasons diamond saw blades are most commonly used for sawing joints in new concrete pavement.

Diamond-Impregnated Saw Blades

Diamond impregnated saw blades are the predominant type of saw blade that is used for cutting transverse and longitudinal joints in new concrete pavements. There are many factors that are considered in the design of a diamond blade for a specific application. Properties of the diamond blade must be matched to the concrete properties to achieve good blade wear and a clean cut (no ravelling) when sawing green concrete.

There has been some research into the design parameters of diamond blades. However, there is no known documentation on the relationship between diamond blades saw blade design and the resulting quality of the concrete cut. Available literature addresses the performance of the diamond blade and is generally limited to studies on cured concrete or stone.

Diamond Saw Blade Cutting Mechanism. Diamond blades are comprised of a metal core and diamond saw blade segments that are bonded to the core by brazing. The diamond saw blade segment is comprised of a metallic bond, or matrix, impregnated with diamonds. The metallic matrix functions to hold the diamonds in place as the diamonds gradually wear away or chip during use. As the diamonds are lost to wear or fracture, the metallic matrix will also wear and expose new diamonds. The blade manufacturer can match the wear characteristics of the matrix and diamonds to the concrete properties to provide optimum blade life.

Diamond Blade Design/Selection Variables. There are many variables that need to be considered in the design and selection of a diamond blade for concrete sawing applications. These variables are a combination of the diamond blade properties and the application conditions. The properties of the diamond blade must be matched to the properties of the concrete. Table 61 presents a summary of variables that are considered in diamond blade design and selection.(24)

Material Properties. To design a diamond blade that will quickly cut and provide long life, the material properties of the concrete must be evaluated. The most important variable influencing ease of sawing is the nature of the coarse and fine aggregate used in the concrete mix. The hardness, density, and abrasiveness of the aggregates are important to the design of the saw blade. Table 62 provides a summary of how these concrete material properties affect diamond saw blade properties and design.(24)

General Electric has developed a sawability ranking of cured concrete based on aggregate size and petrographic description. The sawability ranking is presented in table 63.(25) The sawability ranking proceeds from Al, easiest to saw, to A6, most difficult to saw. Limestone is typical of an aggregate in the Al classification. Flint is typical of an aggregate in the A6 classification. It becomes more difficult to saw concrete as aggregate hardness and size increase. The General Electric study was performed on cured concrete, but it is believed the coarse aggregate properties would also dominate the sawability of green concrete because the strength and hardness of the cement past at this early age is not as developed as it is in cured concrete.(25)

Fine aggregate type also influences the ease with which concrete can be sawed A concrete mix made with an abrasive sand will be easier to cut because the sand will keep the diamond blade cutting freely. However, an abrasive sand will also result in faster blade wear and, therefore, influence the desired metal matrix properties.

Diamond Blade Properties. The main components of a diamond saw blade are the metal core, the metal matrix, and the diamonds. The properties of each of these parameters, will affect the cutting and wear characteristics of the blade. The sawblade metal core is typically constructed of steel. The performance of the blade can be affected by any imbalance of the saw blade. Sources of imbalance of the steel core include thickness differences within the core, eccentricity, and an elongated or out of round arbor hole.(26)

Circular saw blades are tensioned to run true when they are cutting. Blades that are not properly tensioned or balanced may result in instability during sawing and vibrations in the sawing machine. This was found to be a function of the rigidity of the sawing machine. The more rigid the sawing machine the less of an effect saw blade imbalance has on the performance of the saw blade. Tests on stability have shown imbalance has a negligible effect on saw blade

Table 61. Diamond saw blade design and selection variables.[24]

Application Conditions:

- Material Properties
  - Size
  - Shape
  - Hardness
  - Density
  - Particle Sizes
  - Abrasiveness
  - Chemical Composition
- Customer Considerations
  - Cutting Rate
  - Blade Life
  - Blade Cost
- **Operating Conditions**
  - **Machine Type**
  - Machine Conditions
  - Operating Speed
  - Cutting Rate
  - Horsepower
  - Coolant
  - cutting Depth

Diamond Blade Properties

- Diamonds
  - Grit Size
  - origin
  - Type
  - Shape
  - Quality
- Metal Core
  - Thickness
  - Tensioning
  - Slot Design
- Metal Bond
  - Type
  - Density
  - Hardness
  - Tensile Strength

Table 62. General relationship between concrete material properties and diamond blade properties.

Concrete Material Properties		Basic Diamond Blade Properties		
		Diamond Size	Bond Concentration	Bond Hardness
Hardness:	Hard	Fine	Low	Soft
	Soft	Coarse	High	Hard
Density:	High	Fine	Low	Soft
	Low	**Coarse**	**High**	**Hard**
Abrasive:	Low	Fine	**Low**	**Soft**
	High	**Coarse**	**High**	**Hard**

Table 63. Sawability of concrete based on aggregate group classification.[25]

Petrographic Description	Aggregate Size		
	l/8 3/4 in	3/4 2 in	Greater than 2in
Limestone	Al	Al	Al
Crushed stone or river gravel containing basalt, andesite, shale, gneiss, siltstone, and minor quantities of granite	A2	A2	A2
Crushed stone or river gravel containing medium-hard granite, trachyte, and minor quantities of quartzite	A3	A3	A3
Crushed stone or river gravel containing primarily hard granite and quartz	A4	A4	A4
Flint chert	A5	A5	A5

KEY: Al - Easiest to saw.
A6 - Most difficult to saw.

1 in = 25 mm

performance on a machine that is very rigid and in good mechanical condition.[27] Effects on a concrete joint that is sawed with an unbalanced, or improperly tensioned blade have not been documented.

There are several factors that may influence the choice of metal core slot geometry. These factors include cost, concrete properties, required quantity of diamonds, fatigue of the steel core, noise, and quality of the cut. Figure 48 illustrates the slot configurations that are common1y used for sawing concrete. These include a keyhole slot, wide slot, and nonstandard slot.[16]

The effect of slot geometry on the quality of the cut has been researched and is relevant to concrete joint sawing operations. Green concrete is a very abrasive material that can shorten blade life. Therefore, a wider slot is more desirable because it allows more water to flow into the cut. This will provide more efficient flushing of the residue from the cut and potentially provide greater blade life. However, a wider slot can result in ravelling green concrete. A conflict can arise between obtaining both a smooth finish on the concrete and acceptable diamond blade life. (26)

Metal Matrix. The metal matrix of a diamond saw blade provides the bond to hold the diamonds in place. The matrix must hold the diamonds so that they are not pulled out or pushed deeper while the blade is cutting.[28]

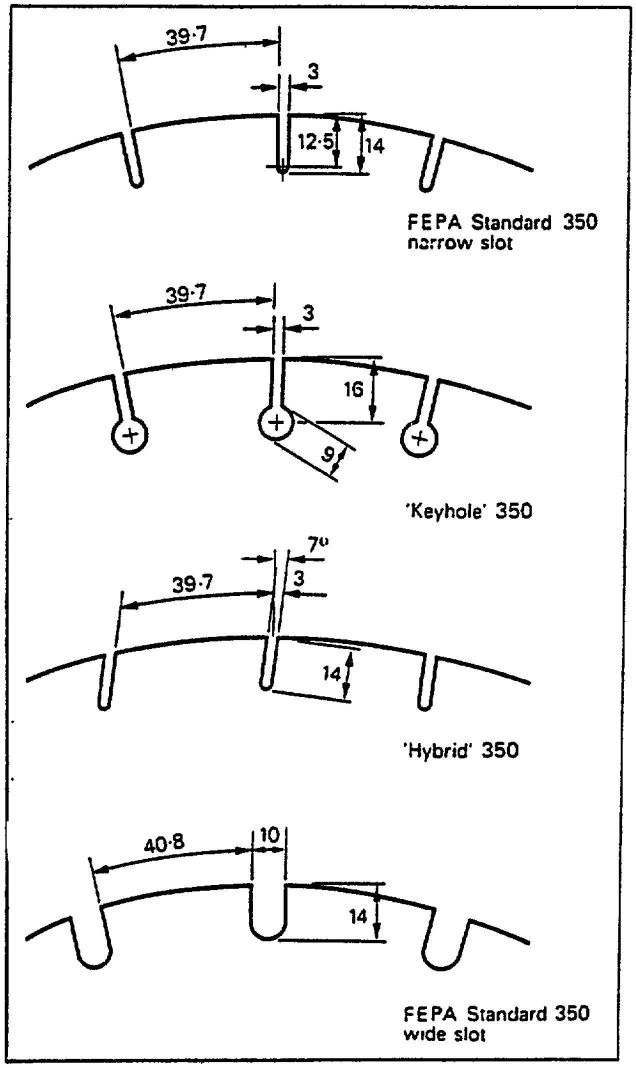
The matrix must also wear at a rate to keep the diamonds exposed. A matrix that is too hard or wear resistant will not be removed quickly enough to provide exposed diamonds. This may cause the matrix surface to polish. When this happens, very few diamonds are exposed and the cutting efficiency of the blade is reduced. If the saw operator continues sawing at the same rate the saw may begin to ride out of the cut. A matrix that is too soft may wear quickly and result in excessive exposure of the diamonds. Ideally, the metal matrix around the diamonds should be removed at a rate that keeps the diamonds exposed but prevents them from being removed from the matrix. The wear characteristics of the metal matrix, diamonds, and concrete must be matched to provide optimum performance of the diamond blade in terms of wear characteristics and desired cutting rate. [28]

There appears to be a number of proprietary matrix compositions and manufacturing processes that are currently used to fabricate diamond segments. The metal matrix is typically comprised of tungsten, tungsten carbide, and bond alloys that may include cobalt, nickel, copper, and iron among others. The metal matrix mixtures are fabricated into diamond segments through a hot press or press/sinter process. The press/sinter process is the most common method used for fabricating diamond saw segments.[28]

The optimum metal matrix composition for a concrete cutting application is normally determined through trial and error. The saw operator or contractor collects information about the concrete, such as type of aggregate (size, shape, origin), type of sand, and saw equipment characteristics and transmits this information to a blade supplier. The supplier would typically recommend a blade that has worked in similar applications. The blade would be tried in the field, and, if needed, modifications to the segment design can be made according to field performance.[27]

Diamonds. The diamond properties that are of concern in design are diamond size, shape, friability, thermal stability, consistency, and cost.

Diamond size is specified according to standard grit sizes.[29] Coarser grits allow faster cutting rates. Finer grits provide better finish. Finer grits are typically used to meet finish specifications for some cutting and grinding applications.



10 mm = 0.4 in

Figure 48. Illustration of typical slot configurations used for sawing concrete.

The diamond's shape influences its strength. Spherically shaped diamonds are generally the strongest.[29]

Friability is a measure of the impact strength of the diamond. This is based on the proportion of particles that break down into smaller sizes.[29]

Saw segments can be inspected after use to determine diamond particle wear. Diamond condition can be classified as good, flat, rough, broken, orpulled-out. Once the factors that are predominantly responsible for the wear are determined, the design of the blade and metal matrix can be modified to obtain the desired results in terms of blade wear and concrete surface finish.[29]

Diamond blade cost is primarily dependent on diamond content, A blade that has a high diamond concentration will not necessarily provide better performance than a blade with a lower diamond concentration. For each application, there is a combination of diamond concentration, diamond size, metal matrix properties, and operating conditions that will provide optimum performance in terms of cutting rate and blade wear. These factors can also be varied to obtain a clean surface cut.[24]

Operating Considerations. The operating conditions listed in table 64 ate considered when selecting a diamond blade to cut concrete. Each of these operating conditions will have an effect on the diamond saw blade. A soft blade is one that results in a shorter blade life and faster cutting rate. A hard blade is one that results in a longer blade life and slower cutting rate. Table 64 shows the general effects of operating'conditions on the diamond saw blade. Each of these factors are considered during blade selection to achieve the desired performance in terms of cutting rate, concrete surface finish, and blade life.(M)

The operating speed and cutting rate will affect blade performance. Recommended operating speeds range from 8,000 to 11,000 surface ft/min (2440 to 3355 m/min) (S.F.P.M. = pi x diameter in feet x spindle speed [RPM]). Lower speeds are recommended for green concrete and concrete with hard aggregate. Higher speeds are recommended for mature concrete.

The "area cutting rate" developed by General Electric is also used to measure the rate of sawing.[25] The "area cutting rate" is the product of the depth of cut and traverse cutting rate in square inches per minute. For example, a blade that is cutting at a depth of 3 in with a traverse rate of 3 ft/min (91 cm/min) has an "area cutting rate" of 108 in^2/min (697 cm^2/min).

Customer Considerations. Cutting rate, blade life, and blade cost are the primary customer considerations. A higher or faster cutting rate will reduce labor costs. A longer blade life reduces blade costs. Unfortunately, there is an inverse relationship between cutting rate and blade life. Generally, a blade that has a very hard matrix will not cut very fast, but it will have a longer life than a blade that has a shorter matrix and a faster cutting rate. Based on whether cutting rate or blade life is more important to the contractor, the blade selection and design can be adjusted accordingly.[24]

Diamond Blade Performance. Most of the research that has been performed on diamond saw blades has been concerned with the wear characteristics and life of the diamond blade rather than the effect of diamond blade design on the quality of the concrete cut. Known research has also been limited to tests on cured concrete.

The performance and wear characteristics of diamond blades are dependent on the rotational speed of the blade. As the cutting rate increases a faster blade speed generally provides better wear. Mechanical loading and impact forces are the major wear mechanisms that are a function of the rotational blade speed. At high blade speeds, impact between the diamonds and the concrete account for most of the blade wear. If the blade speed is reduced and the cutting rate

Table 64. Effect of operating conditions on diamond blade action.[24]

Operating Condition	Basic Diamond Blade Properties		
	Blade Action*	Life	Cutting Rate
Machine: Old	Softer	Shorter	Faster
Machine: New	Harder	Longer	Slower
operating speed: High	Harder	Longer	Faster
operating speed: Low	Softer	Longer	Slower
Cutting Rate: Fast	Softer	Shorter	Faster
Cutting Rate: Low	Harder	Longer	Slower
Horsepower: Fast	Softer	Shorter	Faster
Horsepower: LOW	Harder	Longer	Slower
Coolant Volume: High	Harder	Longer	Slower
Coolant Volume: Low	Softer	Shorter	Faster
Cutting Depth: Shallow	Softer	Shorter	Faster
Cutting Depth: Deep	Harder	Longer	Slower

* A harder blade action results in longer life, but a slow cutting rate. A softer blade action results in shorter life, but a faster cutting rate.

remains the same, the amount of concrete to be removed by each particle increases. This increases the mechanical loading on the diamonds and may tend to pull them out of the matrix.[30]

The diamond concentration also affects the wear characteristics of the blade. A higher diamond concentration results in decreased blade wear.[31]

Sources of Performance Variation. Variation of the operating conditions and diamond blade design for an application can affect the results that are achieved between blades of the same design. Table 65 lists possible sources of variation relating to the application of diamond blades. Two diamond blades of the same design may perform differently in the field because of the variability of the factors listed in table 65. With controls on the blade manufacturing process and application environment, an expected performance range could be estimated.

Conclusions

There are obviously a number of factors that are considered in the design of diamond saw blades. Research into diamond blade design has concentrated on the effect of design parameters on the performance of the diamond blade in terms of obtaining optimum wear and cutting characteristics. With the exception of the design of the metal core slot, there is little known information on the effect of these design parameters on the concrete surface finish after cutting.

Because of the number of variables involved in the design of diamond saw blades and the proprietary manufacturing processes, specifications on the components of blade design to meet a green concrete cutting application would not appear to be effective or practical. Any number of blades could be designed to successfully meet a specific application. The selection of a blade could vary from one that provides a fast cutting rate and poor wear characteristics to one that will provide long wear but a slow cutting rate. Rather than specifying diamond blade design, specifications in terms of an acceptable finish, or damage, to the joint should be considered.

EARLY LOADING OF CONCRETE

Early loading of concrete pavements can lead to slab cracking and may affect future load carrying ability and load transfer across cracks. Fatigue damage in the slab from early opening may not be readily evident and the effect may manifest several years later as a full-depth crack.

Work performed at the University of Illinois shows that concrete slabs subjected to early loading from traffic are susceptible to fatigue damage and cracking.[4] In addition to construcion traffic loads, there has been concern that concrete joint sawing equipment may cause structural damage to the new concrete during the sawing operation. Fatigue damage is greatly influenced by the ratio of flexural stress due to traffic loading to concrete strength at time of loading. The lower the concrete strength, the higher the stress ratio, and therefore the higher the fatigue damage. The longer the pavement is allowed to cure and harden (gain strength) before being subjected to loadings, the less likelihood of structural fatigue damage and subsequent cracking.

Early Loading Evaluation

The objective of this evaluation was to determine the damage potential to new concrete during the first 28 days after placement. The types of traffic and loadings that the pavement is subjected to at an early age were categorized to determine the damage potential at different concrete strengths.

Table 65. Sources of diamond blade variation.

1. Diamond Blade Diamonds	Powdered Metal	Processing
Origin Friability Hardness Internal structure Processing Sizing Ovalizing Tabling Sorting Grading	Particle sizes Particle size distribution Physical properties Chemical properties Flow rate	Weighing Mixing Pressing pressure Processing temperatures Finished dimensions Tensioning Core quality Hardness
2. Operating Conditions Machine	Operator	Purchaser
Speed Feed Horsepower Type Power source Condition **Coolant volume**	Skill Temperment Objectivity	Flexibility Communicativeness

Reference 24.

The approach followed to evaluate the damage potential of early loading of concrete is described below:

1. Typical construction equipment was identified and categorized. This includes joint sawing equipment and construction equipment trafficking the pavement during the first 28 days after concrete placement.

2. Typical concrete properties such as modulus of elasticity (E), modulus of rupture and compressive strength were determined for various time intervals after placement of the concrete.

3. The finite element computer program ILLISLAB was used to determine the resulting stresses in the slab for a given age, temperature, and loading condition[32].

4. The structural damage potential was evaluated in terms of fatigue damage for a given age and loading condition.

Construction Equipment

Information was collected on joint sawing and construction equipment that is commonly moved or driven across new concrete (in the first 28 days after placement). This information was obtained from manufacturers literature and results of questionnaires distributed to paving contractors and State highway officials. Separate questionnaires were developed for concrete sawing equipment and construction equipment. The information obtained on sawing equipment and construction equipment is discussed in the following sections.

Joint Sawing Equipment

Concrete saws that are normally used on large paving jobs include walk-behind saws of 35 to 65 horsepower (26 to 48 kw), spansaws for cutting transverse joints, and longitudinal saws. Smaller saws are available for sawing concrete, however, they are not commonly used on large paving jobs where a high production rate is desired.

Walk-Behind Saws

Walk-behind saws may be used on any size job. The most common walk-behind saws used on paving jobs are self-propelled and have engines capable of producing 35 to 65 horsepower (26 to 48 kW). Table 66 summarizes the operating characteristics for some commercially available 35 to 65 horsepower (26 to 48 kW) saws. The operating weight of the saws range from approximately 900 lb (410 kg) for a 35 horsepower (26 kW) saw to approximately 1,300 lb (590 kg) for a 65 horsepower (48 kW) saw.

The 35 to 65 horsepower (26 to 48 kW) saws have two axles with a typical axle spacing of approximately 23 inches (58 cm) when the saw is in the cutting position. The axle spacing may vary when the front of the machine is raised out of the cut. Solid rubber tires are used on the front and rear wheels to provide stability. Most saws operate in a down-cut mode and have a standard blade shaft speed. The blade shaft speed can be modified on most machines to accommodate a range of blade sixes. Typical blade operating speeds and maximum cutting depth are summarized in table 67.

Spansawa

Spansaws for sawing transverse joints have higher production rates than walk-behind saws, and are typically used on jobs where high volume sawing is required. Spansaws are

Table 66. Sawing equipment data.

Model	Horsepower	Wght.	Axle Spacing (in.)	Wheel Spacing (in.)	Tire Size Front (in.)	Tire Size Rear (in.)	Max. Forward Speed ft/min	Blade Speed (RPM)	Direction of Cut
Longyear 6500 RW	65	1,320	N.A.	N.A.	8 x 2	10 x 3	200	1300-3100	Down-cut
Target Super Quadramatic	65	1,275	23.0	24.0	8 x 2	9 X 2.5	200	N.A.	Down-cut
Target Pro 65	65	1,345	23.0	24.0	8X3	10 x 3	150	1265-2500	Down-cut
Magnum PS-6585	65	1,300	23.0	28.0	8X3	10 x 3	200	1800-2950	Down-cut
Sanders Saws 6514	65	1,200	22.5	24.0	10 X 2.5	10 X 2.5	N.A.	N.A.	Down-cut, Up-cut
Longyear 3535 WU	35	900	N.A.	N.A.	6X2	8 X 2.5	200	3400	up-cut
Longyear 3535 WC	35	900	N.A.	N.A.	6X2	8 X 2.5	200	1500-3400	Down-cut
Target Super Concrete Saw	35	905	23.0	24.0	6X2	8X2	200	N.A.	Down-cut
Target Pm-35 11	35	905	23.0	24.0	6X2	8X2	200	N.A.	Down-cut
Magnum ES-3785	37	1,040	23.0	28.0	8X3	10 x 3	200	1800-2950	Down-cut
Sanders saws SS-3507	35	934	22.5	24.0	6X2	8X2	150	N.A.	Down-cut, Up-cut

N.A. =Not Avahble. 10 in = 25 cm, 1000 ft/min = 305 m/min, 1000 lb = 454 kg, 100 hp = 75 kW

Table 67. Typical sawcutting blade speeds and maximum cutting depth.

Blade Diameter, in	Blade Speed, rpm	Maximum Depth of Cut, in
14	3100	4-7/8
18	2450	6-7/8
20	2300	7-3/4
26	1900	10-1/8

Note: 10 in = 25 cm

capable of cutting transverse joints to a width of up to 54 ft (16.5 m) and are also adaptable to skewed joints and a flat or crowned concrete slab profile. Cutting is accomplished by hydraulic drive blades at a rate of up to 24 ft/min (7.3 m/mm) Both upcut and downcut blade rotation are available. Blade speed can also be varied. Spansaw weights range from 8,000 to 14,500 lb (3630 to 6580 kg). The weight is supported by four rubber wheels.

Longitudinal Saws

Longitudinal saws are capable of sawing longitudinal centerline and lane-shoulder joints on large paving jobs which require high production rates. Gross operating weights are around 3,100 lb (1407 kg). The weight is supported by four pneumatic tires. Cutting is accomplished by hydraulic drive cutting arbors. The cutting rate for longitudinal saws is variable.

Construction Equipment

Many types of construction equipment are moved and driven across new concrete pavement. Table 68 is a partial list of the type of equipment that could be expected to use the new concrete (less than 28 days old) pavement. To assess the potential for structural damage to new concrete pavement, the evaluation of construction traffic was limited to single-axle and tandem-axle loads.

Early Age Concrete Broperties

There are many factors such as mix design, temperature at placement and curing conditions that greatly impact the rate of strength gain of new concrete. These factors have been previously discussed. A typical paving concrete mix design was used to evaluate concrete properties as the concrete aged and gained strength. The following mix design properties were used:

- Cement Content: 650 lb/yd^3 (386 kg/m^3).
- Water/Cement Ratio: 0.40.
- Superplasticizer: None.
- Calcium Chloride: None.
- Curing Method: Membrane Compound.
- Ambient Temperature: 70 ^{0}F (21 ^{0}C)

A relationship developed at the University of Illinois was used to determine the concrete properties for this mix design for any desired age.[4] An interactive computer program was developed from this work to determine strength for different Portland cement concrete mixtures, curing conditions, and time after placement. The concrete compressive strength was obtained from the program and the following relation was used to obtain the concrete modulus of elasticity **E:**[33]

$$E = 57{,}000 \times f_c^{1/2} \quad (1)$$

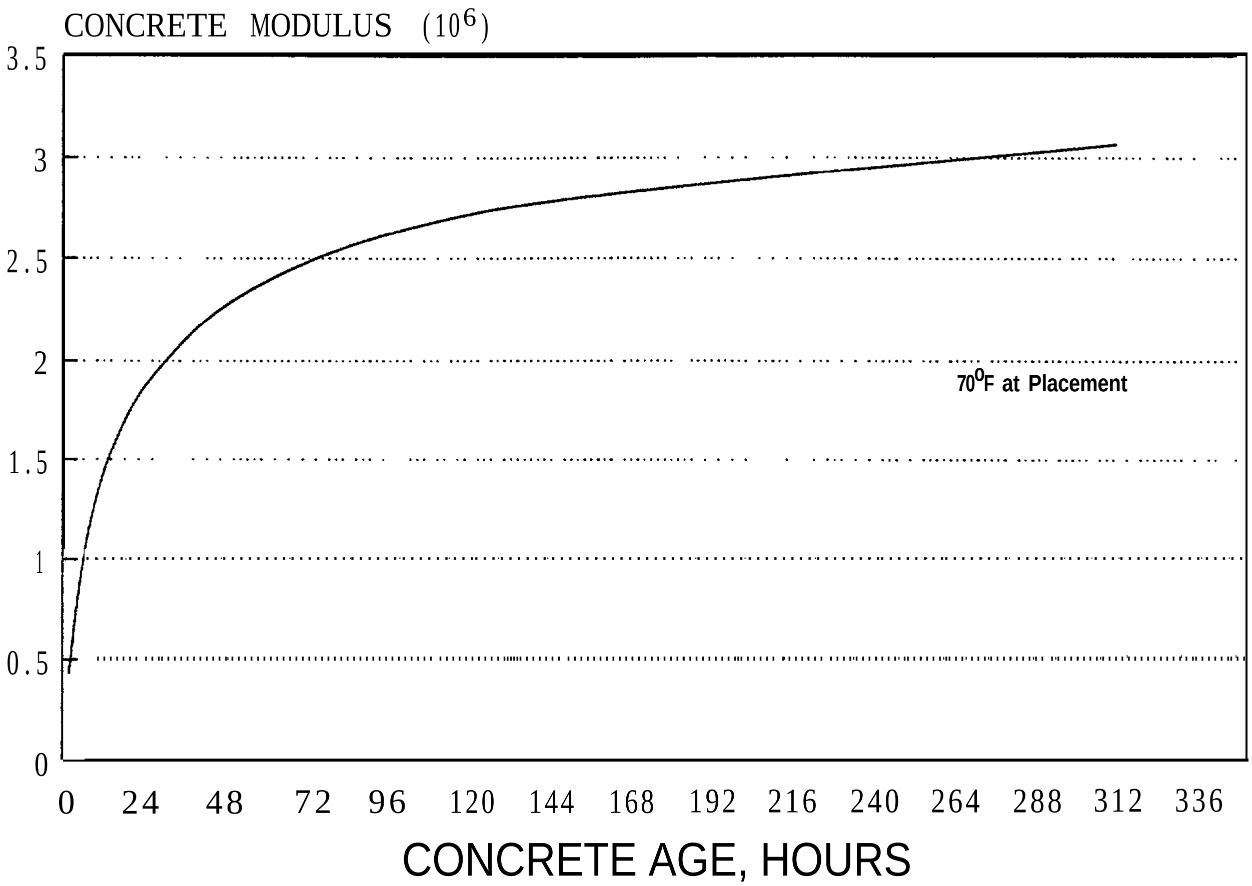
where

E = concrete modulus of elasticity, psi
f_c = concrete compressive strength psi

Figure 49 illustrates the resulting slab concrete E as a function of age for this mix design and ambient temperature of 70 ^{0}F (21 ^{0}C) during placement. Figure 50 illustrates the resulting concrete modulus of rupture obtained from the early opening program as a function of age. This

Table 68. Typical construction equipment moved/driven across concrete pavements.

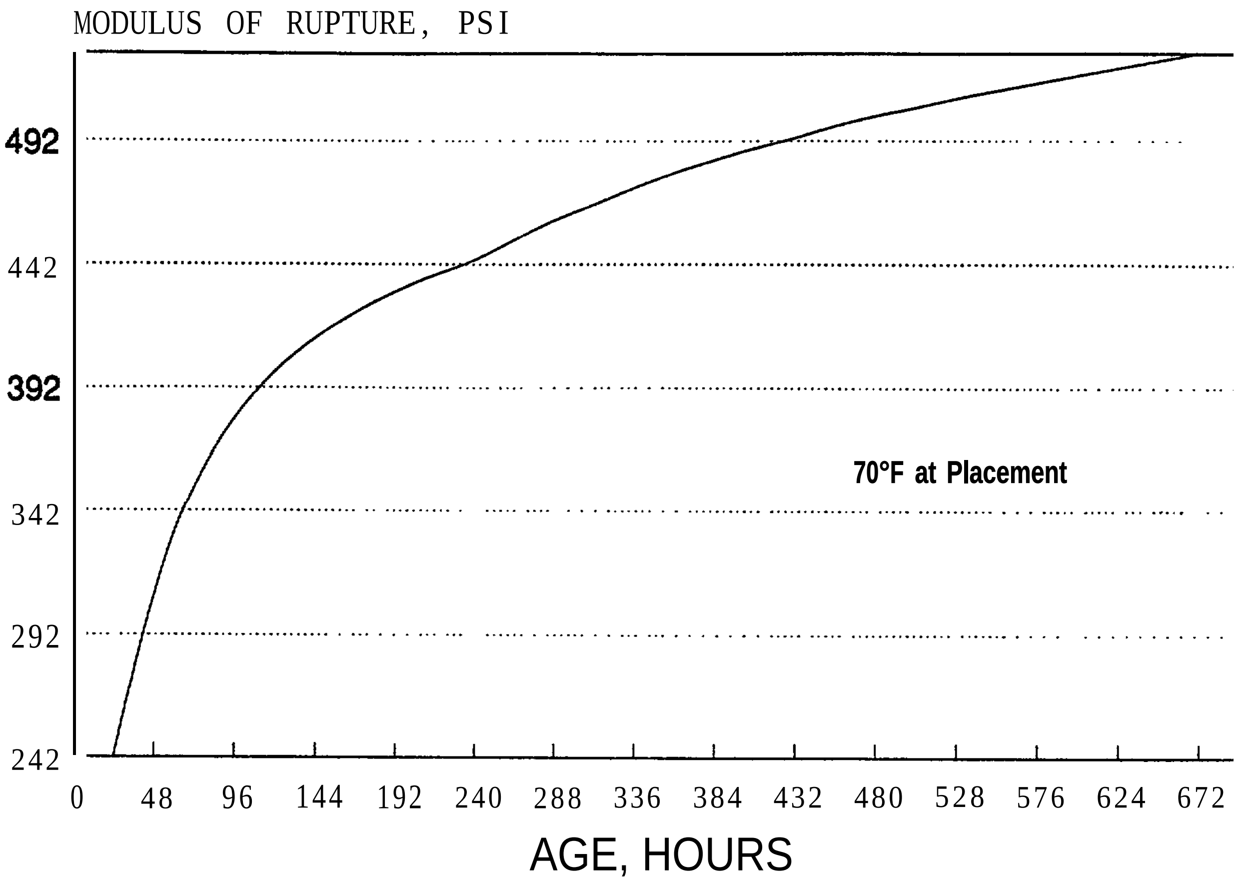
Equipment Type	Typical Axle Load (lbs)
• Caterpillar 613 Scraper	29,000 (13,170 kg)
• Caterpillar 12G and 140G Motor Graders	9,900 (4,500 kg)
• Caterpillar 916 and 926 Wheel Loaders	10,500 (4,770 kg)
• Rollers, Smooth	
• CMI suburban Paver	
• Gomaco Paver	
• CMI Belt Placer	
• Rex Belt Placer	
• CMI Tube Finisher	
• Dump Trucks, Tandem (Legal Loads)	34,000 (15,440 kg)
• Water trucks, Single (Legal Loads)	18,000 (8,170 kg)
• Concrete Transports (Legal Loads)	
• Pickups	
• Cars	
• Service Trucks	



1 million psi = 6895 MPa

70 oF = 21 oC

Figure 49. Concrete elastic modulus versus time.



100 psi = 0.69 MPa
70 °F = 21 °C

Figure 50. Flexural strength development slab with time.

procedure utilized field beam strength and temperature data to develop predictive models. These concrete properties were then used along with the resulting pavement stresses for a given loading condition to evaluate the potential for structural damage.

Pavement Design Parameters

A 9-in (23-cm) non-reinforced concrete pavement placed on top of a base with an effective k value of 200 lb/in3 (54 MPa/m) was used for this evaluation; The computer program ILLI-SLAB was used to determine critical slab tensile stresses for a given loading condition. ILLI-SLAB is a finite element structural analysis computer program developed at the University of Illinois for the analysis of rigid pavements. Using load, design and material properties information, the stresses and deflections are calculated for the given slab configurations and loading conditions.

Loads in Cracking Prediction,

Several prediction models have been developed that relate the ratio of flexural stress and concrete strength to number of load repetitions to cracking.[34-39] These models, illustrated in figure 51, are based either on flexural loading of unsupported beam specimens or full-scale field testing of fully supported slabs. The Portland Cement Association (PCA) and Zero Maintenance (ZMAN) models are based on beam data. The other models are based on field slab data

The Corps of Engineers (CORPS) and ERES models are based on data from 51 full-scale field test sections that were conducted between 1943 and 1973 at various locations.[40] There were actually a total of 60 sections, but all of the sections that did not reach failure (e.g. 50 percent slabs cracked) were excluded as these would bias the results.

The ERES coverage prediction model was developed in 1982 as part of a pavement evaluation study for the Waterways Experiment Station.[41] This model has been used extensively for rigid pavement evaluation and design. Recently a review of the field data was performed and an improved prediction model that fit the data slightly better was obtained.[42] This model is shown in figure 5 1 and was used in the early loading analysis to determine the allowable number of coverages. This model was used because it is believed that (1) field slab cracking is more realistic than beam loading and (2) many of the slabs were loaded with very high stresses that approach or exceed the concrete strength, which is similar to early loading conditions of interest.

The ERES prediction model is as follows:

$$\log_{10} N = 2.13\,(MR/\sigma)^{1.2} \qquad (2)$$

where

N = number of coverages to 50 percent cracked slabs
MR = modulus of rupture, psi (third-point loading)
σ = 3/4 x free edge stress, psi (stress reduction for load transfer)
Statistics: R^2 = 60 percent
SEE = 0.58
n = 51 sections

When the stress ratio is greater than or equal to 1, a crack will result from one loading. These methods are based on unsupported flexural beam data. The ERES coverage prediction model is based on actual field slab tests where the stress ratio was greater than 1 for a number of sections. For these data points, cracking was not observed at the surface after one loading and

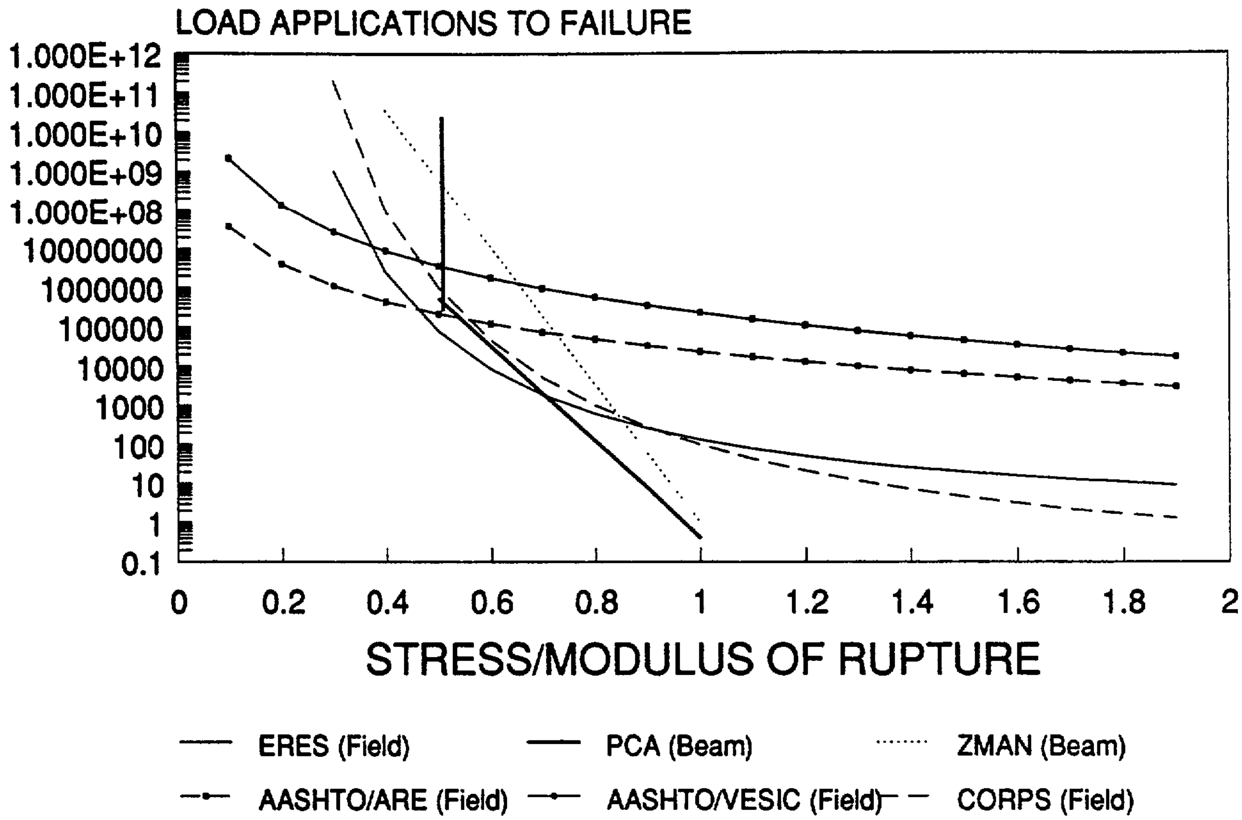


Figure 51. Stress ratios and load to cracking.

many slabs were subjected to over 100 coverages before cracking was observed. For a supported slab, a crack could initiate at the bottom of the slab after one loading. However, the fully supported slab could withstand many more loadings until the crack progresses through the slab and is observable on the surface. The differences between the beam and field testing procedures (unsupported and supported) account for the difference in the predicted number of coverages until cracking. For the following discussion of early pavement loading conditions and pavement flexural stresses, the ERES prediction model was used within the following limitations:

- Stress ratio of 0.8 or less

- Fatigue damage to slab of less than 0.10 for the anticipated number of axle loads.

Spansaw Loading Condition

A typical spansaw was modeled on the pavement as it would be positioned during sawing of transverse joints on a 24-ft (7.3-m) wide pavement section. The loading condition is illustrated in figure 52. A gross weight of 14,500 lb (6580 kg) was evenly distributed among four solid rubber tires. The contact area per tire was approximately 50 in^2 (323 cm^2) resulting in a contact pressure of 72 psi (496 kPa).

The pavement response to the spansaw loading was determined at one hour intervals after concrete placement. The critical tensile stress at the bottom of the concrete slab and the resulting fatigue damage were determined for each time interval. The critical slab stresses and concrete properties for selected pavement ages are summarized in table 69.

The spansaw loading results in low pavement stresses; approximately 60 to 70 psi (414 to 483 kpa) during expected sawing times. The resulting structural fatigue damage from one pass of a spansaw at 4 hr after placement for an assumed 70 ^oF (21 ^oC) curing condition is calculated to be negligible for stress ratios (pavement stress to concrete strength) less than one.

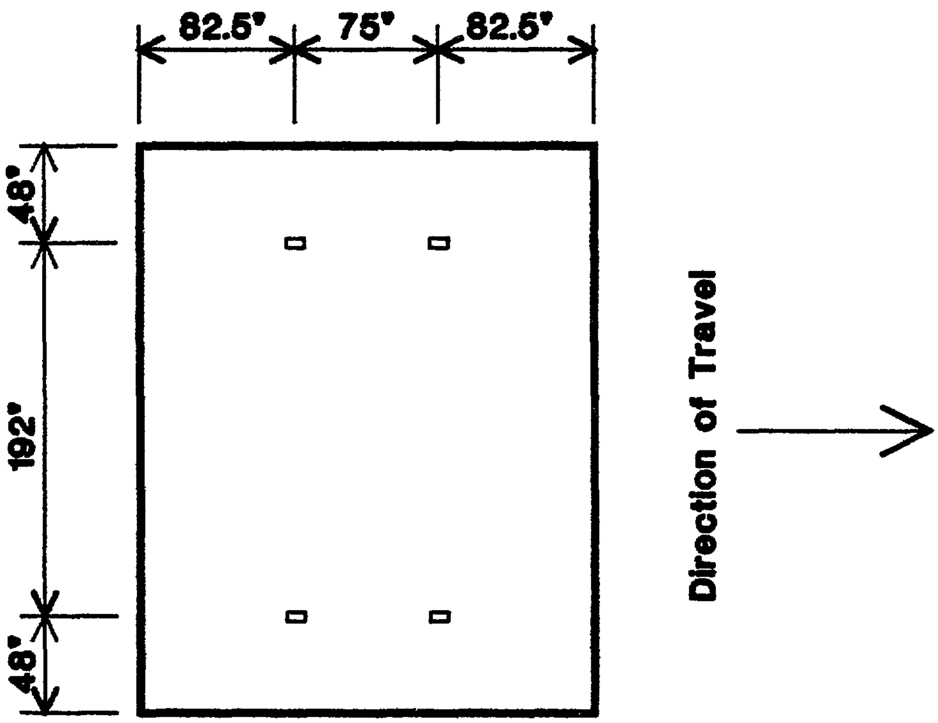
There are a number of factors that will affect how rapidly new concrete gains strength. It appears that the resulting structural damage to the new concrete pavement will be negligible from 1 coverage of a spansaw during sawing operations. However, during cold temperatures, sawing to control cracking may be required before the new concrete has gained sufficient strength to support spansaws.

Longitudinal Saw Loading Condition

A typical longitudinal saw was modeled on the pavement as it would be positioned during sawing of a longitudinal centerline joint on a 24-ft (7.3-m) wide pavement section. The loading condition is illustrated in figure 53. A gross weight of 3,100 lb (1407 kg) was evenly distributed among four pneumatic tires. The tire pressure was 80 psi (550 kPa), and the contact area per tire was approximately 9.7 in^2 (62.6 cm^2).

The pavement response to the longitudinal saw loading was determined at 1 hour intervals after concrete placement. The critical tensile stress at the bottom of the concrete slab and the resulting fatigue damage were determined for each time interval. The critical slab stresses and concrete properties for selected ages are summarized in table 70.

Longitudinal joints are normally sawed after the transverse joints have been sawed. This may be immediately after completing the transverse joints cuts. If longitudinal sawcutting is delayed, it may occur in much higher pavement strengths than can be expected at the time that transverse joints are sawed. Also, at time of longitudinal joint sawing, the saw loading is at the



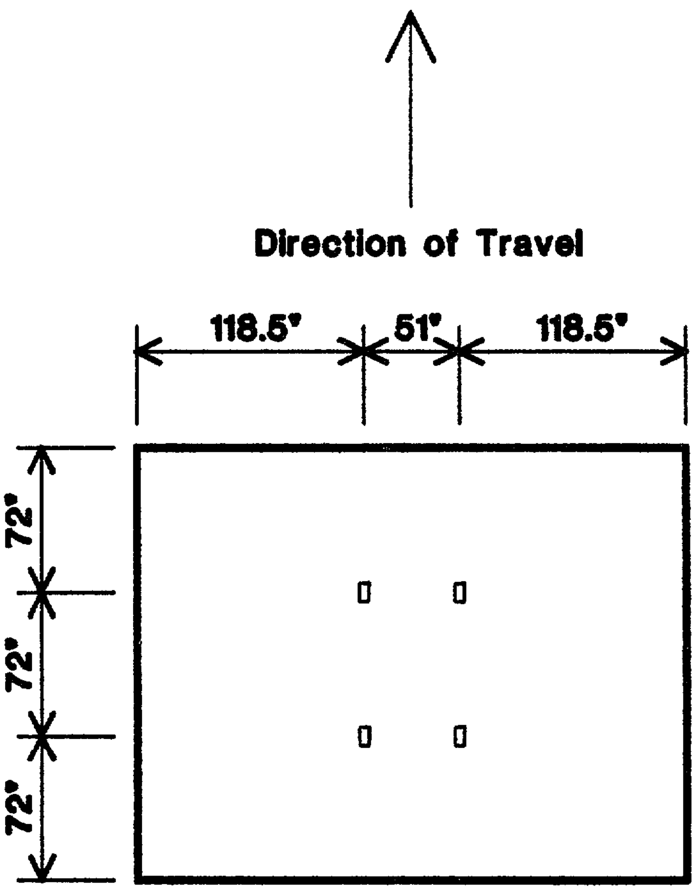
100 in = 2.54 m

Figure 52. Spansaw load pattern

Table 69. Spansaw fatigue loading damage.

Age, h	Modulus of Elasticity, psi	Flexural Stress, psi	Modulus of Rupture, psi	Stress Ratio Stress/M R	Fatigue Damage for 1 Coverage	Number of Loads to Cause Cracking
4	762,600	62	73	0.85	0.003	399
5	888,500	63	89	0.71	0.000	1676
10	1,312,200	66	151	0.44	0.000	562,879
15	1,574,500	67	192	0.35	0.000	30E+06
24	1,875,800	69	242	0.29	0.000	43E+08

1000 psi = 6.9 MPa



100 in = 2.54 m

Figure 53. Longitudinal saw load pattern.

Table 70. Longitudinal spansaw fatigue loading damage.

Age, h	Modulus of Elasticity, psi	Flexural Stress, psi	Modulus of Rupture, psi	Stress Ratio Stress/MR	Fatigue Damage for 1 Coverage
2	430,300	14	34	0.41	0.000
3	613,900	14	55	0.25	0.000
4	762,600	15	73	0.21	0.000
5	888,500	15	89	0.17	0.000
10	1,312,200	15	151	0.10	0.000
15	1,574,500	16	192	0.08	0.000
24	1,875,800	16	242	0.07	0.000

1000 psi = 6.9 MPa

pavement interior position. The longitudinal saw loading results in very low calculated pavement stresses. Therefore, the resulting structural fatigue damage from 1 pass of a longitudinal saw is negligible.

Walk-Behind Saw Loading Condition

There are many walk-behind saws that are used for sawing joints in new concrete pavements. Most saws have operating weights in the range of approximately 900 lb (410 kg) for the 35-horsepower (26-kW) saw to approximately 1,300 lb (590 kg) for the 65-horsepower (48-kW) saw. A typical 65-horsepower (48-kW) saw was modeled on the pavement as it would be positioned during sawing of a transverse joint. Pavement stresses were determined for the interior and edge loading conditions. When the saws are cutting, the weight is not evenly distributed between the front and rear wheels. Most of the weight is on the front wheels when sawing. A gross weight of 1,200 lb (545 kg) was evenly distributed among four pneumatic tires for the static condition resulting in a contact pressure of 98 psi (676 kPa) for each wheel. For the sawing condition, a contact pressure of 150 psi (1034 kPa) was used for the front wheels and 46 psi (317 kPa) for the rear wheels. The contact area was approximately 3.1 in^2 (20 cm^2).

The pavement response to the saw loading was determined at l-hour intervals after concrete placement. The critical edge loading tensile stress at the bottom of the concrete slab and the resulting fatigue damage were determined for each loading and sawing condition for various concrete ages. The edge loading condition during sawing was determined to be critical. The critical pavement stresses at the bottom of the concrete slab arc shown in table 71 for the sawing and static edge loading conditions.

The critical pavement stresses for the edge loading condition during sawing, concrete properties for selected ages and resulting fatigue damage are shown in table 72.

The critical slab stresses for a 65-horsepower (48-kW) walk-behind saw are small and result in negligible structural fatigue damage to the new concrete pavement.

Construction Traffic Single-Axle Loading

A 17,300-lb (7850-kg) single-axle load was modeled on a 24-ft (7.3-m) wide pavement section. Edge and interior loading conditions were evaluated. The critical stresses for each loading condition are shown in table 73.

The edge loading condition resulted in the highest slab stresses. The stresses for the edge loading condition were determined at 24-hour intervals up to 672 hours (28 days). The critical stresses and the resulting structural fatigue damage at the slab edge to the new concrete are shown in table 74.

Depending on the number of coverages and the concrete strength at the time of each coverage, there appears to be potential for structural fatigue damage to new concrete. However, not all passes of construction traffic will result in an edge loading condition. The fatigue damage for interior loading would be much less.

The critical stresses and the resulting structural fatigue damage calculated for 17,300-lb (7850-kg) single-axle loads to the new 9-in (23-cm) thick concrete pavement for the interior loading condition are shown in table 75.

The stress ratios for the interior loading condition are lower than the edge loading condition and therefore result in negligible structural fatigue damage for 100 coverages.

Table 71. Walk-behind saw edge loading condition.

Age, h	Flexural Stress, psi Static Edge Load	Flexural Stress, psi Sawing Edge Load
2	15	21
3	16	22
4	17	23
5	17	24
10	19	25
15	19	26
24	20	27

100 psi = 0.69 M Pa

Table 72. Walk-behind saw fatigue loading damage.

Age, h	Concrete E, psi	Flexural Stress, psi	Modulus of Rupture, psi	Stress Ratio Stress/MR	Fatigue Damage for 1 Coverage
2	430,300	21	34	0.62	0.000
3	613,900	22	55	0.40	0.000
4	762,600	23	73	0.32	0.000
5	888,500	24	89	0.27	0.000
10	1,312,200	25	151	0.17	0.000
15	1,574,500	26	192	0.13	0.000
24	1,875,800	27	242	0.11	0.000

1000 psi = 6.9 M Pa

Table 73. Single-axle loading condition.

Age, h	Flexural Stress, psi	
	Edge	Interior
24	275	140
48	282	142
72	286	143
96	289	144

100 psi = 0.69 MPa

Table 74. Singleaxle load fatigue edge loading damage.

Age, h	Concrete E, psi	Flexural Stress, psi	Modulus of Rupture, psi	Stress Ratio Stress/MR	Fatigue Damage for No. of Coverages 1	10	100
120	2,724,100	289	399	0.72	0.001	0.007	0.074
144	2,793,600	292	412	0.71	0.001	0.006	0.061
168	2,847,1OO	293	423	0.69	0.000	0.005	0.049
192	2,889,1OO	292	431	0.68	0.000	0.004	0.040

1000 psi = 6.9 MPa

Table 75. Single-axle load fatigue interior loading damage.

Age, h	Concrete E, psi	Flexural Stress, psi	Modulus of Rupture, psi	Stress Ratio Stress/MR	Fatigue Damage for No. of Coverages		
					1	10	100
24	1,875,800	140	242	0.58	0.000	0.000	0.008
48	2,285,000	142	315	0.45	0.000	0.000	0.000
72	2,495,700	143	355	0.40	0.000	0.000	0.000
96	2,630,600	144	380	0.38	0.000	0.000	0.000

1000 psi = 6.9 MPa

Construction Traffic Tandem-Axle Loading

A 34,600-lb (15,700-kg) tandem-axle load was modeled on a 24-ft (7.3-m) wide pavement section. Edge and interior loading conditions were evaluated. The critical stresses for each loading condition are shown in table 76.

The edge condition resulted in the highest pavement stresses. The stresses for the edge loading condition were determined at 24-hour intervals up to 672 hours (28 days). The critical stresses and the resulting structural fatigue damage to the new 9-in (23-cm) thick concrete are shown in table 77.

Depending on the number of coverages and the concrete strength at the time of each coverage, there appears to be some potential for structural fatigue damage to new concrete. However, not all passes of construction traffic will result in an edge loading condition.

The critical stresses and the resulting structural fatigue damage calculated for a 34,600-lb kip (15,700-kg) tandem-axle load to the new concrete for the interior loading condition are shown in table 78.

The stress ratios for the interior loading condition are lower than the edge loading condition and therefore the fatigue damage is lower for a given concrete strength.

Summary

There are many factors that affect the time to saw and the strength gain of new concrete. Concrete subjected to early loading is susceptible to structural fatigue damage from heavily loaded traffic[(4)]. In addition to construction traffic loads, there has been concern that concrete joint sawing equipment may cause structural damage to the new concrete during the sawing operation. Fatigue damage is greatly influenced by the ratio of flexural stress due to traffic loading to concrete strength at time of loading. The lower the concrete strength, the higher the stress ratio, and therefore the higher the fatigue damage. The longer the pavement is allowed to cure and harden (gain strength) before being subjected to loadings, the less likelihood of future fatigue damage and subsequent cracking.

The following conclusions and recommendations are based on this preliminary analysis for the 9-in (23-cm) thick pavement.

- The potential for structural fatigue damage from the sawing operations is negligible. Critical pavement stresses of approximately 60 to 70 psi (414 to 483 kPa) for the spansaw, 13 to 16 psi (90 to 110 kPa) for the longitudinal saw, and 20 to 30 psi (138 to 207 kPa) for walk-behind saws were calculated for the standard 9-in (23-cm) pavement section constructed at 70 ^{0}F (21 ^{0}C) ambient temperature.

- There are many types of construction equipment that may use the new concrete pavement during the first 28 days prior to opening to traffic. Single and tandem axle loads were modeled to evaluate the potential for structural fatigue damage to the new concrete. Structural fatigue damage can potentially result from construction traffic loadings depending on load positions, strength of the concrete at the time of loading, and number of cover-ages. The free edge loading condition is the most critical and results in the most fatigue damage for a given coverage. Interior loads result in much less structural fatigue damage.

Table 76. Tandem-axle loading condition.

Age, h	Tensile Stress, psi	
	Edge	Interior
24	238	149
48	247	151
72	253	153
96	256	154

100 psi = 0.69 MPa

Table 77. Tandem-axle load fatigue edge loading damage.

Age, h	Modulus of Elasticity, psi	Flexural Stress, psi	Modulusof rupture, psi	Stress Ratio Stress/MR	Fatigue Damage for No.ofCoverages		
					1	10	100
72	2,495,700	253	355	0.71	0.001	0.006	0.064
96	2,630,600	256	380	0.67	0.000	0.004	0.039
120	2,724,1OO	257	399	0.64	0.000	0.002	0.025
144	2,793,600	259	412	0.63	0.000	0.002	0.019
168	2,847,10O	261	423	0.62	0.000	0.002	0.016
192	2,889,10O	261	431	0.61	0.000	0.001	0.013

1OOOpsi=6.9MPa

Table 78. Tandem-axle load fatigue interior loading damage.

Age, H	Modulus of Elasticity, Psi	Flexural Stress, Psi	Modulus of Rupture, Psi	Stress Ratio Stress/MR	Fatigue Damage for No. of Coverages		
					1	10	100
24	1,875,800	149	242	0.62	0.000	0.001	0.015
48	2,285,000	151	315	0.48	0.000	0.000	0.001
72	2,495,700	153	355	0.43	0.000	0.000	0.000
96	2,630,600	154	380	0.41	0.000	0.000	0.000

1000psi = 6.9 MPa

- There are a number of factors that affect the rate of strength gain in new concrete and impact the type and number of loads that could be applied to the pavement without causing damage. These factors include concrete mix design, curing condition, environmental conditions, slab thickness, and support conditions.

- Additional construction equipment can be modeled to determine pavement stresses for any desired concrete strength and pavement design. Guidelines could be developed for concrete strength and critical pavement stress to keep the resulting structural fatigue damage acceptably low.

LITERATURE REVIEW SUMMARY

From the literature review it was determined a large number of variables influence a pavement's early age sawability and ability to carry loads. The variables can be generally divided into two broad categories:

- Variables affecting concrete sawability as shown in table 79,

- Variables affecting early loading shown in table 80. Some variables affect both early joint sawing and early loading of the pavement as listed in tables 8 1 and 82. Properties that influence onset of cracking are listed in table 83. Very little data are available on very early age properties at times when joints will be sawed

Concrete Sawability

Concrete properties influencing sawability of concrete are concrete strength, coarse aggregate hardness, and bond between concrete mortar matrix and coarse aggregate particles. Variables influencing concrete strength properties, aggregate hardness, and aggregate mortar matrix bond are listed in the second column of table 79. These variables affect the concrete's ability to prevent coarse aggregates from dislodging during sawing. Dislodgement would result in a ravelled joint edge. Ideally, insitu concrete characteristics govern pavement response to early sawing and loading. However, due to difficulties of obtaining insitu specimens at early ages, cylinders and beams are commonly cast from the same mix as used for pavement placement and cured on site. Specimens should be insulated to retain heat which is generated from the hydration process. It is commonly assumed that other properties such as tensile strength, split-tensile strength, and modulus of elasticity are related to compressive or flexural strength. Cylinders are commonly tested in compression and beams in flexure (third-point loading). Split-tensile testing is an option for evaluating sawability.

The ability of the concrete pavement to undergo sawing with no detrimental effects may be related to one or a combination of compressive, flexural, and split-tensile strength. Variability due to test methods and material is generally lowest for compressive strength. Accurate determination of concrete pavement strength will be significant in establishing the earliest time the concrete can be sawed with a minimum of joint ravelling.

Concrete pavement strength gain can also be monitored using insitu nondestructive testing (NDT) techniques. The literature review identified three different NDT techniques for estimating concrete compressive strength or to monitor concrete strength gain. The three techniques are impact/rebound (Clegg Impact Hammer), ultrasonic pulse velocity, and maturity tests. These are listed in table 81 as proposed test methods. Insitu strength is quickly and indirectly estimated once a relationship is established between strength and NDT results. Test variables selected to evaluate early age concrete strength properties are listed in column 2 of table 82.

Table 79. Concrete properties that influence sawability.

Concrete Property	Variable	Classification	Relationship	Concrete Property Test Method
Strength	Cement Content	material	Decrease in setting time with higher cement factor	Compressive Strength ASTM C89-86
	Subbase Temperature	environmental	Higher early strengths required if high subbase temperatures are present	Flexural Strength C78-84
	Ambient Temperature	curing	Higher temperatures promote early strength gain	Splitting Tensile Strength ASTM C496-86
	Length of Curing	curing	Longer curing times produce higher strengths	Pulse Velocity ASTM C597-83
	Wind Velocity	curing	Winds result in higher rates of evaporation which can reduce strength gain	Maturity ASTM C1074-87
	Relative Humidity	curing	High relative humidity reduces evaporation, thus increasing early strength gain	
	Curing Material	curing	Application of curing material reduces evaporationrthus increasing strength	
Aggregate Source	Aggregate Type and Geometry	material	Round hard aggregate may dislodge easier than with soft/crushed aggregate	
Paste to Aggregate Bond	Aggregate Shape/geometry	material	Paste/aggregate bond with round aggregate is weaker than with crushed aggregate	
	Mortar Matrix Strength (paste)	material	Mortar strength influences aggregate to matrix bond	Setting Time for Mortar ASTM C403-88

Table 80. Concrete properties that influence early loading capacity.

Concrete Property	Variable	Classification	Relationship	Concrete Property Test Method
Strength	Cement Content	material	Earlier strength gain with higher cement content factor	Compressive Strength ASTM C89-86
	Ambient Temperature	curing	Higher temperatures promote early strength gain	Splitting Tensile Strength ASTM C-496-86
	Length of Curing	curing	Longer curing times produce higher strengths	Flexural Strength ASTM C78-84
	Wind Velocity	curing	Winds result in higher rates of evaporation) thus reducing strength gain	
	Relative Humidity	curing	High relative humidity reduces evaporation) thus increasing early strength gain	
	Curing Material	curing	Application of curing material reduces evaporation, thus increasing strength	
Slab Curling	Temperature Gradient	environmental	Tensile and compressive restraint stresses develop as slabs curl upward	
Slab Warping	Moisture Gradient	environmental	Surface drying results in higher shrinkage causing restraint stresses	

Table 81. Concrete properties affecting early age sawing and loading conditions.

Concrete Property	Proposed Test	Sawability Rating	Early Loading (0 to 24 hrs) Rating	Early Loading (1 to 28 days) Rating
Compressive Strength	Cylinder Tests Clegg Impact Pulse Velocity Maturity	high	medium	medium
Modulus of Elasticity		****	high	medium
Splitting-tensile Strength	Cylinder Tests	medium	high	****
Flexural Strength	Beam Tests	low	high	high

Table 82. Variables affecting early age concrete properties.

Variable	Proposed Test	Sawability Rating	Early Loading (0 to 24 hrs) Rating	Early Loading (1 to 28 days) Rating
Aggregate Type/Geometry	3 Aggregate Types Petrographic Exam Sawing Strips	high	****	****
Humidity	100% and 50% Cure	low	low	medium
Ambient Temperature	50,72,100 ^{o}F Cure (10,22,38 “C) Maturity	high	medium	medium

Table 83. Concrete properties that influence the onset of cracking.

Concrete Property	Variable	Classification	Relationship	Concrete Property Test Method
Strength	Cement Content	material	Earlier strength gain with higher cement factor, but with higher shrinkage	Compressive Strength ASTM C89-86
	Subbase Friction	environmental (of slab)	Higher early strengths required for subbases with large friction factor	Flexural Strength ASTM C78-84
	Ambient Temperature	curing	Higher temperatures promote early swength gain	Splitting Tensile Strength ASTM C-496-86
	Length of Curing	curing	Longer curing times produce higher swengths	
	Wind Velocity	curing	Winds result in higher rates of evaporation, thus reducing strength gain	
	Relative Humidity	curing	High relative humidity reduces evaporation, thus increasing early strength gain	
	Curing Material	curing	Application of curing material reduces evaporation, thus increasing strength	
Slab Curling	Temperature Gradient	environmental	Larger thermal gradients result in higher restraint stresses as slabs curl upward	
Slab Warping	Moisture Gradient	environmental	Surface drying results in higher shrinkage causing restraint stresses	
Slab Contraction	Temperature/ Drying	curing and environmental	Cement heat of hydration and environmental factors can cause slab length changes	

The time of setting for the mortar fraction of the concrete is related to strength gain. Sawability of concrete may be related to the early age concrete strength gain which depends upon initial and final setting of mortar. The time of set test has been used to determine performance specification compliance.

A second important material property to consider for sawability is aggregate type. The type of diamond blade selected and operating conditions depend on fine and coarse aggregate properties. Aggregate size, shape, hardness, and gradation need to be considered for determining earliest joint sawing time. Round hard aggregates may dislodge easier than a soft crushed aggregate under identical conditions. Concrete ravelling potential at joints is a function of paste to aggregate bond and may be indirectly related to a strength parameter. By monitoring strength, the earliest time to minimize joint ravelling due to sawing may be established.

Environmental factors affecting sawability include time and curing conditions. At ages of less than 7 days, the rate of strength gain increases with curing temperature. Curing temperature is a function of amount of cement used, time of cum, method of curing, initial concrete temperature, ambient air temperature, and solar radiation. Other curing conditions which can influence strength gain are humidity and wind. The maturity method has been successfully used to estimate the combined effects of concrete temperature and curing time on strength development for early formwork removal ages. By monitoring insitu slab temperature with time, insitu strength can be estimated. Based on strength estimates, the earliest time the concrete can be sawed without ravelling at the joint edge or damaging the surface with sawing equipment can be estimated.

Another factor affecting concrete sawability is sawing equipment. Based on concrete material properties, diamond blade properties, and operating conditions, a blade is selected to minimize joint ravelling and achieve good blade wear.

Timely Sawing to Minimize Onset of Early Pavement Cracking

Objectives of installing sawcuts or forming joint notches in concrete pavements after construction are to minimize random slab cracking and to minimize slab axial and bending restraint stresses that could otherwise lead to longitudinal or transverse random cracking. Observation of freshly placed concrete pavement performance during initial cooling periods, that is during the first evening and night following paving operations, have shown that random longitudinal or transverse cracks occur in long and wide slabs when significant cooling occurs. The cracking associated with concrete cooling can be attributed to development of high axial and bending restraint stresses. Stress levels increase with increased cooling.

The window of opportunity for sawcutting has two boundaries. The near boundary is the soonest the slab can be sawcut without unacceptable joint edge concrete ravelling. The far boundary is the latest the slab can be cut before longitudinal and/or transverse cracks occur. The cracking, based on anecdotal and experimental evidence, occurs during the early evening or night immediately following paving. Results from tests indicate that cracking occurs when concrete cooling, immediately below pavement surface, exceeds about 15 ^{o}F (8 ^{o}C). Depending on cooling rates and an adequate factor of safety, the data suggest that sawing be completed prior to concrete cooling of 7 ^{o}F (4 ^{o}C).

Stresses for cooling of 7 ^{0}F (4 ^{0}C) near surface concrete can be calculated using equations 1 and 5 in chapter 2 of volume 1 of this report for axial and bending restraint stresses, respectively. Assuming for a 10-in (25-cm) thick pavement a temperature gradient, AT= 0.5 ^{o}F/in (0.11 ^{o}C/cm), a uniform temperature change of 4 ^{0}F (2 ^{o}C), and taking the previously used concrete properties of E = 2x106 psi (13,790 MPa), a = 5.5x10-6 in/in/^{O}F (9.9 x 10-6 mm/mm/^{o}C), μ= 1.5, (wh) = 0.868.1b/in^{2} (6 kPa), and x = 19 ft (5.8 m), the combined restrained tensile stress is about 58 psi (400 kPa) Depending on concrete mix strength gain properties and ambient conditions, the concrete may or may not have adequate strength capacity to resist the 52-psi (359-kPa) stress level to be anticipated for delaying sawing until 7 ^{0}F (4 ^{0}C) cooling has occurred Data on concrete strength at early ages, 4 to 24 hours, to be determined from tests as part of this project, will permit comparisons of combined stress development with concrete strength properties for a range of mixes and curing conditions. These comparisons are anticipated to provide additional inputs towards developing guidelines defining limits of the sawing window of opportunity.

Early Loading

Concrete properties listed in table 80, column 1, that affect early loading of concrete slabs can be broadly classified into two categories: those affecting concrete strength and those affecting applied stresses. Variables affecting concrete strength gain include mix design (amount of cement and water/cement ratio), curing time, and curing conditions (temperature, humidity, wind, solar radiation). In addition to sawing equipment, loads can be applied at later ages with other construction equipment. The applied stresses and concrete flexural strength can be used to determine if there is potential for slab cracking, from overload or excessive fatigue consumption.

Environmental factors affecting early loading of concrete slabs also affect sawability of concrete. Time and curing conditions, as previously discussed, will affect early concrete strength gain. Concrete fatigue life is directly related to the ratio of concrete stress to concrete strength. Fatigue consumption increases with stress ratio. Therefore, strength at time of loading is indirectly related to the fatigue life consumed. Both compressive and flexural strength are important factors in evaluating when concrete can be loaded to minimize fatigue consumption. Flexural strength is an important factor to consider in both selection of sawing equipment and subsequent construction traffic load analyses. Since concrete has very little early age tensile strength, failure attributable to early loading occurs when flexural stresses exceed the flexural strength. Compressive strength is an important variable to consider at very early ages. If inadequate compressive strength is developed, the concrete surface may fail in crushing or abrasive wear under sawing equipment wheels. If dowel pressures under load exceed the concrete compressive strength bearing failure will occur.

As discussed for sawability, strength gain can be monitored by testing beam and cylinder specimens or by nondestructive insitu testing. At later ages, cores or beams from insitu concrete can also be tested. Cylinders or cores are tested in compression and beams in flexure. Due to difficulties in handling and testing beams, compressive or split-tensile testing may be alternative methods for determining flexural strength. Split-tensile or compressive strengths would be converted to flexural strength using previously established correlation factors. Modulus of elasticity can also be determined using previously established correlation with compressive strength.

Nondestructive insitu testing (NDT) can also be used to monitor strength gain. The impact/rebound, ultrasonic pulse velocity, and maturity test methods which show promise in evaluating very early age concrete strength can also be used for estimating strength at later ages. Strength is estimated using previously established correlations with NDT data.

Fatigue consumption is not only a function of concrete strength but of induced stress. Fatigue damage is a function of load configuration, magnitude, position, concrete modulus of elasticity, slab thickness, and subgrade support. The degree of subgrade support is dependent upon subgrade properties, amount of slab warping, and degree of curling.

As part of the literature review, a preliminary loading analysis was done to evaluate fatigue damage resulting from stresses due to sawing and construction equipment. A conventional paving concrete mix design and strength gain model was used to evaluate concrete properties as a function of time. Results were input into a finite element computer program to obtain stresses at various time intervals after concrete placement. Equipment loads were obtained from manufacturers' literature and questionnaire surveys sent to paving contractors and highway officials. A crack-coverage prediction model was used to determine fatigue consumption and allowable number of coverages. For a 9-in (23-cm) thick slab with subgrade support of 200 lb/in3 (54 MPa/m), the flexural fatigue damage from sawing equipment was negligible at ages of 4 hours or more. The most critical sawing condition was a 14,500-lb (6583-kg) spansaw at 4 hours. At the 0.85 stress ratio (flexural stress to strength), the number of loads to cause cracking is 399.

The loading analysis was also done using 17,300-lb (7850-kg) single axle and 34,600-lb (15,710-kg) tandem-axle construction traffic loads. The critical stress and the resulting structural fatigue damage calculated are summarized in table 84 for a concrete age of 72 hours (3 days). At 72 hours the predicted concrete modulus of elasticity is 2,495,700 psi (17,200 MPa) and predicted concrete modulus of rupture is 355 psi (2.4 MPa).

At 3 days there is a small amount of fatigue damage due to truckloads at the free edge. The interior loading condition theoretically results in no significant fatigue damage. At the free edge loading condition the resulting damage is approximately three times greater when loads are increased to 20,000-lb (9080-kg) single-axle load and 40,000-lb (18,160-kg) tandem-axle load Also, for 20,000-lb (9080-kg) single-axle load and 40,000-lb (18,160-kg) tandem-axle load at the slab interior there is no significant fatigue damage.

A preliminary analysis indicates that after 4 hours no significant load-associated damage occurs due to sawing equipment. Fatigue damage can potentially result from construction traffic loadings. This depends on load position, concrete flexural strength, and number of cover-ages.

These results are based on very limited concrete strength gain predictions. Based on the proposed laboratory and field test program results, the relationship used to determine concrete properties at different ages may be modified Using the established strength gain with time relationships, an in-depth fatigue analysis can be done. Variables would include load magnitude and position, slab thickness and support, number of repetitions, material properties, and concrete age.

Conclusions

Information on early concrete strength properties was collected as part of the literature review. Effects of curing conditions on concrete slab moisture losses and concrete temperatures within slabs for a range of curing protection are shown in figures 36 and 38 through 42. Concrete compressive strength and flexural strength increases for increasing ambient temperature exposure conditions are provided in figures 37 and 43, respectively. Pavement slab to subbase friction data are provided in figures 44 through 47. In our opinion, the quantitative early concrete strength data found in the literature has not been related to early concrete sawability. Early pavement load capacity calculation methods based on early concrete compressive and flexural concrete strength were presented.

The results of the literature review indicate that tests are needed to quantify concrete properties (listed in first column of tables 79 through 83), and correlate these with early saw-ability and early loading. As indicated in tables 79 through 83, the concrete properties are influenced by the variables such as cement amount, curing conditions, and aggregate type. Thus, a test program was developed to generate data needed to quantitatively relate early concrete properties as effected by material and environmental (curing) factors on early concrete sawability, early concrete cracking, and load carrying capacity. Test variables and methods of both destructive and nondestructive test methods are described in chapter 3 of the main body of this report

Table 84. Critical loading stresses at 3 days.

Load, kips	Load Position	Critical Tensile Stress, psi	Stress Ratio Stress/MR	Fatigue Damage for No. of Coverages		
				1	10	100
17.3 SAL	Interior	143	0.40	0.000	0	0
	Edge	286	0.81	0.002	0.017	0.174
34.6 TAL	Interior	153	0.43	0.000	0.000	0.000
	Edge	253	0.71	0.001	0.006	0.064

100 psi = 0.69 MPa, 17.3 kips = 7850 kg, 34.6 kips = 15,700 kg

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