STRENGTH DEVELOPMENT OF CONCRETE BASED ON MATURITY AND PULSE VELOCITY

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STRENGTH DEVELOPMENT OF CONCRETE BASED ON MATURITY AND PULSE VELOCITY

by

Chengsheng Ouyang
515-239-1088

Office of Materials
Project Development Division
Iowa Department of Transportation
Ames, Iowa 50010

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8. ABSTRACT

The effect of curing temperature, in the range of 4.4 to 22.8 degrees C (40 to 73 degrees F), on strength development was studied based on the maturity and pulse velocity measurements in this report. The strength-maturity relationships for various mixes using a Type I cement and using a Type IP cement, respectively, were experimentally developed. The similar curves for early age strength development of both the patching concrete, using a Type I cement with the addition of calcium chloride, and the fast track concrete, using a Type III cement and fly ash, have also been proposed. For the temperature ranges studied, the strength development of concrete can be determined using a pulse velocity measurement, but only for early ages up to 24 hours. These obtained relationships can be used to determine when a pavement can be opened to traffic. The amount of fly ash substitution, up to 30%, did not have a significant influence on the strength-maturity relationship.

9. KEY WORDS Compressive strength, Concrete fast track, Fly ash, maturity, Modulus of rapture, patching Pulse velocity, traffic opening strength	**10. NO. OF PAGES** 29

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DISCLAIMER

STRENGTH DEVELOPMENT OF CONCRETE BASED ON MATURITY AND PULSE VELOCITY

INTRODUCTION

There are restrictions on the use of fly ash and Types IP and I(PM) cements in concrete paving for late season work in an effort to provide adequate strength development before opening the pavement to traffic. At present, these restrictions amount to a reduction of the amount of fly ash permitted after September 15 and a total discontinuance after October 15. Similar types of restrictions are placed on the use of Types IP and I(PM) cements.

The October cut off date on the use of fly ash was selected because that is the time that normal temperatures in Central Iowa could be expected to drop to 40 degrees F. Previous research had established that a substitution of fly ash for cement would result in concrete of reduced strength at 7 days when cured at that temperature.

The concrete paving industry in Iowa has continuously requested revision of the fly ash cut-off date since there are times when weather conditions are such that the colder temperature curing conditions are not a factor. While technically there is basis to allow this, the project administration could easily become cumbersome and non-uniform throughout the state.

If there was a way to effectively determine that there was adequate strength development prior to opening to traffic under various temperatures, the use of these materials could be reconsidered. One of the ways to determine such properties is through the use of a maturity concept for the materials on the project.

On the other hand, when placing a patch or fast track overlay on the surface of an old concrete pavement, one needs to know early strength development of new concrete in order to satisfy the open traffic strength requirement. This early strength development may be determined based on maturity and on pulse velocity measurement.

The objective of this project is to determine the relationship of concrete strength to maturity and pulse velocity for several concrete mixes cured at various temperatures, and to check whether or not such a relationship developed at a certain curing temperature can apply to other curing temperatures.

Three groups of concretes were tested in this project. The first group is normal concrete, which may or may not have fly ash replacement of cement and uses either Type I or Type IP cement. This category is referred to as *the normal concrete* hereafter. The second group is concrete for patching. This concrete uses Type I cement and has the addition of calcium chloride solution. This category is referred to as *the patching concrete* hereafter. The third group is concrete using Type III cement for fast track overlay, and is referred to as *the fast track concrete* hereafter. For the normal concrete, relationships among strength development, maturity and pulse velocity up to an age of 56 days were studied, whereas for the patching and fast track concretes, similar relationships up to an age of 24 hours were studied.

MATERIALS AND MIX PROPORTIONS

The Normal Concrete

A Type I cement (R-11 Blend) and a Type IP cement from Ash Grove at Louisville, NE were used. Fly ash (Type C) used was from Ottumwa. The coarse aggregate (limestone) used was from Martin Marietta, Fort Dodge Mine (A94002), and the fine aggregate used was from Moline Consumers Co., Cordova, Illinois (AIL520).

Iowa Department of Transportation Standard Mix C-3WR was selected as the reference. The seven mixes tested are described in Table 1.

The Type I cement (R-11 Blend) was used for Mix Nos. 1-4. Mix No. 1 was the Standard C-3WR mix. Mix No. 2 was the C-3WR mix with a 15% substitution rate of fly ash for the cement. Mix No. 3 was the C-3WR mix with a 20% substitution rate of fly ash for the cement. Mix No. 4 was the C-3WR mix with a 20% cement reduction and a fly ash addition of 30%.

The Type IP cement (from Ash Grove, Louisville, NE) was used for Mix Nos. 5-7. Mix No. 5 was the Standard C-3WR mix. Mix No. 6 is the C-3WR mix with a 5% substitution rate of fly ash for the cement, whereas Mix No. 7 was the C-3WR mix with a 10% substitution rate fly ash for the cement.

The Patching Concrete

A Type I cement (R-11 Blend) were used. The coarse aggregate (limestone) used was from Martin Marietta, Fort Dodge Mine (A94002), and the fine aggregate used was from Moline Consumers Co., Cordova, Illinois (AIL520).

Iowa Department of Transportation Standard Mix M-4 was used for this concrete which is named as Mix No. 8 in Table 1. The amount of 2.75 gallons of 32% calcium chloride solution were added into a cubic yard of the concrete.

The Fast Track Concrete

A Type III cement from Lehigh, Mason City was used. A fly ash from Port Neal #4 was used. The coarse aggregate (limestone) used was from Martin Marietta (Alden, A42002), whereas the fine aggregate used was from Martin Marietta (Anderson-Popejoy, A35512).

Iowa Department of Transportation Standard Mix FF-4WR-C was used. This concrete is called Mix No. 9 in Table 1.

EXPERIMENTAL PROGRAM

The Normal Concrete

The experimental program for this group is shown in Table 2. For each mix from Nos. 1-7 given in Table 1, three 4 1/2" x 9" cylinders were tested for compressive strength at 7 days and at 28 days for each of the curing temperatures of 4.4 and 22.8 degrees C (40 and 73 degrees F), respectively. An additional cylinder was cast for monitoring internal temperature of the cylinder for each temperature using a maturity meter (Model H-2680, System 4101 from HUMBOLDT MFG. CO.). For Mix No. 3 (C-3WR with a 20% fly ash substitution) three additional cylinders were also made and tested at ages of 4, 14 and 56 days, respectively, for each curing temperature. The aggregates and cements used for making the mixes subjected to 4.4 degrees C (40 degrees F) curing were cooled to the same temperature prior to mixing.

Just prior to testing for compressive strength, a pulse velocity measurement was made for each cylinder using a pulse velocity meter (Model Mark II, James Instruments Inc.).

The Patching Concrete

The experimental program for this concrete (Mix No. 8) is shown in Table 3. Twenty-six 4 1/2" x 9" cylinders were cast. Thirteen of them were cured at the temperature of 4.4 degrees C (40 degrees F), whereas other thirteen were cured at the temperature of 22.2 degrees C (73 degrees F). For each curing temperature, three cylinders were tested for compressive strength at ages of 4, 5, 7 and 10 hours, respectively. The pulse velocity was measured prior to the test for each cylinder. One cylinder were used to continuously monitor internal temperature of the cylinder for each curing temperature.

The Fast Track Concrete

The experimental program for this concrete (Mix No. 9) is also shown in Table 3. Two types of specimens, 6 x 6 x 20 in. beam and 6 x 12 in. cylinder, were cast. All the specimens were cured at the temperature of 22.8 degrees C (73 degrees F). These two types of specimens were tested for modulus of rupture (MOR, the center-point loading) and compressive strength at ages of 5, 6, 8, 12 and 24 hours, respectively. Before each strength test, the pulse velocity was measured.

DETERMINATION OF CONCRETE MATURITY

The effect of curing temperature and age on strength development is usually described by maturity. The maturity is a function of curing age and temperature, and is usually expressed as (ASTM C1074)

$$M(t) = \sum (T - T_0)\Delta t \quad (1)$$

where M is the maturity in degree-hours (or degree-days), Δt is the time interval in hours (or days), T is the average concrete temperature during the time interval Δt, and T_0 is the datum temperature at which concrete ceases to gain strength with time. Different values for this datum temperature have been found by different investigators, these values have ranged from -10 to -20 degrees C[1]. The value of T_0 = -10 degrees C (14 degrees F), which is most commonly used, was used for all the concretes in the study. Maturity can be empirically related to strength of concrete.

The Normal Concrete

The measured relationships between specimen internal temperature and age for Mix No. 1 (Type I cement) cured at 4.4 and 22.8 degrees C (40 and 73 degrees F), respectively, are shown in Figure 1a. The specimen internal temperature initially increase from the curing temperature due to the release of hydration heat. However, the specimen internal temperature approaches the curing temperature after about 48 hours. By integrating the measured temperature-age curves based on Eq. (1), the maturity-age relationships are obtained as shown in Figure 1b for the mix subjected to both 4.4 and 22.8 degrees C (40 and 73 degrees F) curing, respectively. The obtained results indicate that the effect of initial temperature increase due to hydration of the cement on the maturity can be neglected for the concrete with an age of greater than 7 days. It was also found that the effect of fly ash substitution on the maturity is negligible. As a result, values of the maturity obtained in Figure 1b for Mix No. 1 (without fly ash substitution) was used for Mix Nos. 2, 3 and 4 which have up to 30% of fly ash substitutions. The similar observation was also made for the mixes using the Type IP cement as shown in Figure 2.

The Patching Concrete

The relationships between specimen internal temperature and age for this concrete (Mix No. 8, Type I cement with the addition of calcium chloride) cured at 4.4 and 22.8 degrees C (40 and 73 degrees F), respectively, are shown in Figure 3a. The corresponding maturity values for each curing temperatures are plotted against the specimen age in Figure 3b. The influence of heat release from cement hydration cannot be ignored for this concrete since only the maturity values up to the age of 10 hours are concerned here.

The Fast Track Concrete

The measured curve between specimen internal temperature and age for this concrete (Mix No. 9, Type III cement with 15% fly ash replacement) cured at 22.8 degrees C (73 degrees F) is shown in Figure 4a. The corresponding maturity values for each curing temperature are plotted against the specimen age in Figure 4b. Again, the influence of heat release from cement hydration cannot be ignored for this concrete since only the maturity values up to the age of 24 hours are concerned.

RESULTS AND DISCUSSION

The Normal Concrete

All the measured values of compressive strength, maturity and pulse velocity for this concrete are given in Table 2. The obtained compressive strengths for all the mixes using the Type I and Type IP cements are plotted against the maturity and pulse velocity measured in Figures 5a and b. It is seen that the data in both plots are rather scatter. This indicates that the influence of cement type should be considered, and it is not suitable to plot all the mixes with two types of cements together.

Relationships between the compressive strength and the maturity are shown in Figures 6a and b, respectively, for the mixes (Nos. 1, 2, 3 and 4) using the Type I cement and the mixes (Nos. 5, 6 and 7) using the Type IP cement. It is seen, by comparing with Figure 5a, that the scattering of the data is significantly reduced after considering the effect of cement type. Although the mixes were cured at 40 and 73 degrees F, respectively, a continuous strength-maturity curve is observed for the mixes using the same type of cement. For the mixes using the Type I cement the compressive strength, f'_c , is expressed as the following function of the maturity (see Figure 6a),

$$f'_c = 1153 \ln(M) - 6067 \tag{2}$$

where M is in degree C-hour, and f'_c is in psi. The correlation coefficient (R^2) for Eq. (2) is 0.884. For the mixes using the Type IP cement, the relationship between the compressive strength and the maturity is (see Figure 6b)

$$f'_c = 1637 \ln(M) - 11058 \tag{3}$$

The correlation coefficient (R^2) for Eq. (3) is 0.918. The above obtained result indicates that strength development under curing temperatures ranging from 40 to 70 degrees F can be accounted for by using the concept of maturity. The curves given by Eqs. (2) and (3) can be used to determine strength development of a concrete pavement based on maturity measurement.

In order to check the effect of fly ash substitution on the strength-maturity relationship, the results shown in Figure 6a is plotted again in Figure 7, where the data is re-arranged based on different amounts of fly ash substitution. Although up to 30% of fly ash substitutions were used in the Type I cement mixes (Mix Nos. 1, 2, 3 and 4), the amount of fly ash substitution has no significant influence on the strength-maturity relationship.

Relationships between the compressive strength and the pulse velocity measured are given in Figures 8a and b, respectively, for the mixes (Nos. 1, 2, 3 and 4) using the Type I cement and the mixes (Nos. 5, 6 and 7) using the Type IP cement. Since both plots are quite scattered, it is not suitable to account for the effect of curing temperature on strength development based on the measurement of pulse velocity.

The Patching Concrete

The compressive strength is plotted against the maturity in Figure 9 for the patching concrete cured under 4.4 and 22.8 degrees C (40 and 73 degrees F), respectively. This relationship can be expressed as

$$f_c' = 9.767\ M - 931.63 \tag{4}$$

The correlation coefficient (R^2) for Eq. (4) is 0.957. This result further confirms the fact, previously observed from the normal concrete, that the influence of curing temperature on concrete strength development can be described by the maturity concept.

The compressive strength is also plotted against the pulse velocity in Figure 10 for the patching concrete. Contrast to the normal concrete previously discussed, a continuous relationship between the compressive strength and the pulse velocity for specimen age up to

10 hours is observed although the tested cylinders were subjected to 4.4 and 22.8 degrees C (40 and 73 degrees F), respectively. This relationship can be described by

$$f_c' = 3.81\ \exp(0.00048c) \tag{5}$$

where c is the pulse velocity in feet/second. The correlation coefficient (R^2) for Eq. (4) is 0.931.

This observed fact for the relationship between the pulse velocity and the strength may be explained by the development of the modulus of elasticity for early age concrete. Based on elasticity, the value of pulse velocity for a solid depends primarily on values of the modulus of elasticity and density[2]. Since concrete density is basically constant regardless its age, the pulse velocity is primarily related to the modulus of elasticity. Although the compressive strength continuously increases with specimen age up to 28 days, the modulus of elasticity usually reaches approximately 80% of its 28-day value within 2 days, then keeps very slow growth[3]. Since at early age, the compressive strength and the modulus of elasticity almost simultaneously increase with increasing specimen age, the compressive strength may be also related to the pulse velocity during this early period.

The Fast Track Concrete

The measured values of the compressive strength and MOR are plotted against the maturity for the fast track concrete in Figure 11a and b, respectively. These relationships are

$$f_c = 1692\ \ln(M) - 8926 \tag{6}$$

and

$$MOR = 259 \ln(M) - 1331 \tag{7}$$

where MOR is in psi. The correlation coefficients (R^2) for Eqs. (6) and (7) are 0.974 and 0.970, respectively. It is noted that all the specimens were cured under 22.8 degrees C (73 degrees F) for this concrete.

The measured values of the compressive strength and MOR are expressed in terms of the pulse velocity in Figures 12a and b, respectively. The obtained equations for both cases are

$$f_c = 1.675 \exp(0.00063c) \tag{8}$$

and

$$MOR = 3.123 \exp(0.00042c) \tag{9}$$

The correlation coefficients (R^2) for Eqs. (8) and (9) are 0.982 and 0.990, respectively.

CONCLUSION

The effect of curing temperature, in the range of 4.4 to 22.8 degrees C (40 to 73 degrees F), on strength development can be described using the concept of maturity, provided that the strength-maturity curve is developed for mixes using the same type of cement. The strength-maturity relationships for the normal concrete mixes using a Type I cement and using a Type IP cement, respectively, have been experimentally developed. The similar curves for early age strength development of both the patching concrete, using a Type I cement with the addition of calcium chloride, and the fast track concrete, using a Type III cement and a fly ash, have also proposed. For the curing temperatures of the range of 4.4 to 22.8 degrees C (40 to 73 degrees F), the strength development of concrete at early age (approximate up to

24 hours) may also be determined using the pulse velocity. These obtained relationships can be used to determine when a pavement can be opened to traffic. It is found that the amount of fly ash substitution, up to 30%, has no significant influence on the strength-maturity relationship.

REFERENCES

1. Mindess, S., and Young, J. F., CONCRETE, Prentice-Hall, Inc., Englewood Cliffs, HJ O7632, 1982, p.390.

2. Bay, J. A., and Stokoe, K. H. II, "Field and Laboratory Determination of Elastic Properties of Portland Cement Concrete Using Seismic Techniques," Transportation Research Record 1355, 1992, pp. 67-74.

3. Hensen, W. "Static and Dynamic Elastic Modulus of Concrete as Affected by Mix Composition and Compressive Strength," Concrete at Early Ages, ACI SP-95, American Concrete Institute, Detroit, 1986, pp.115-138.

Table 1 Materials for a Cubic Yard of Concrete

Mix No.	Cement (lb)	Fly Ash (lb)	Coarse aggregate (lb)	Fine aggregate (lb)	Curing temp. (°F)	Water (lb)	Slump (in.) *	Air content (%)
1	571	0	1696	1354	40	250	2	6.0
					73	271	2	5.6
2	486	86	1696	1354	40	241	2 1/2	6.8
					73	246	2	6.4
3	457	114	1696	1354	40	237	2 1/2	6.4
					73	245	2	6.1
4	457	171	1696	1354	40	238	2	6.0
					73	246	2	6.0
5	562	0	1660	1354	40	287	2	5.8
					73	308	2	6.0
6	534	28	1660	1354	40	283	2 1/4	6.2
					73	296	2	5.8
7	506	56	1660	1354	40	281	2 1/4	6.0
					73	290	2	5.8
8	802	0	1399	1404	40	296	1 3/4	5.2
					73	296	1 3/4	5.6
9	735	83	1298	1303	73	352	2 1/4	5.7

* The accuracy of the slump measurement is a quarter of an inch.

Table 2 Test Program and Results for the Normal Concrete

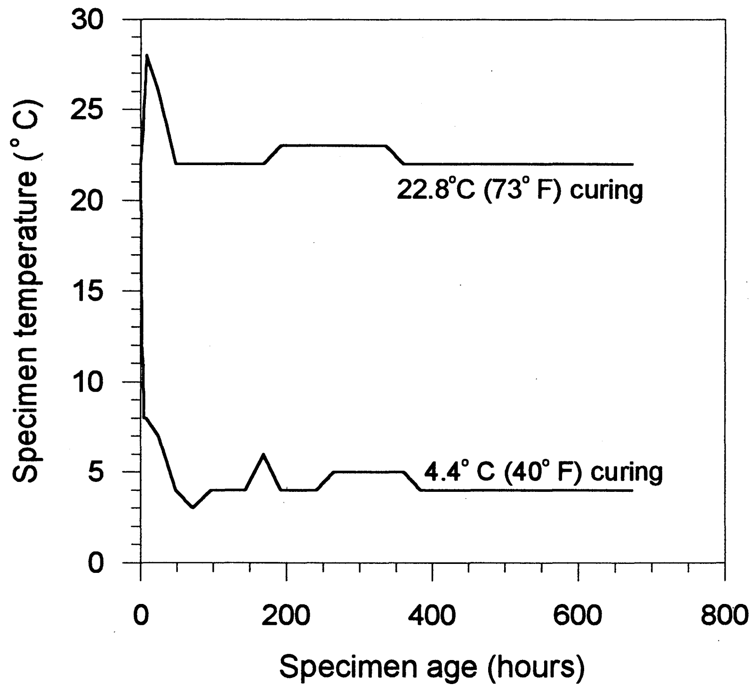
Mix No.	Curing temperature (°F)	Age (days)	Compressive strength (psi)	Maturity (°C-hour)	Pulse velocity (ft/sec.)
1	40	7	3230	2497	14079
		28	4660	9697	14780
	73	7	3270	5527	14808
		28	4910	21823	15134
2	40	7	2690	2497	14089
		28	4470	9697	14303
	73	7	3940	5527	14067
		28	4880	21823	15021
3	40	4	1650	1465	-
		7	2680	2497	-
		14	3790	4957	14687
		28	4650	9697	14706
		56	5210	19354	14795
	73	4	3530	3223	-
		7	3980	5527	-
		14	4700	11059	14507
		28	5280	21823	13276
		56	6180	44083	15421
4	40	7	3230	2497	14108
		28	5320	9697	13930
	73	7	4450	5527	13875
		28	5910	21823	15274

Table 2 Test Program and Results for the Normal Concrete (Continued)

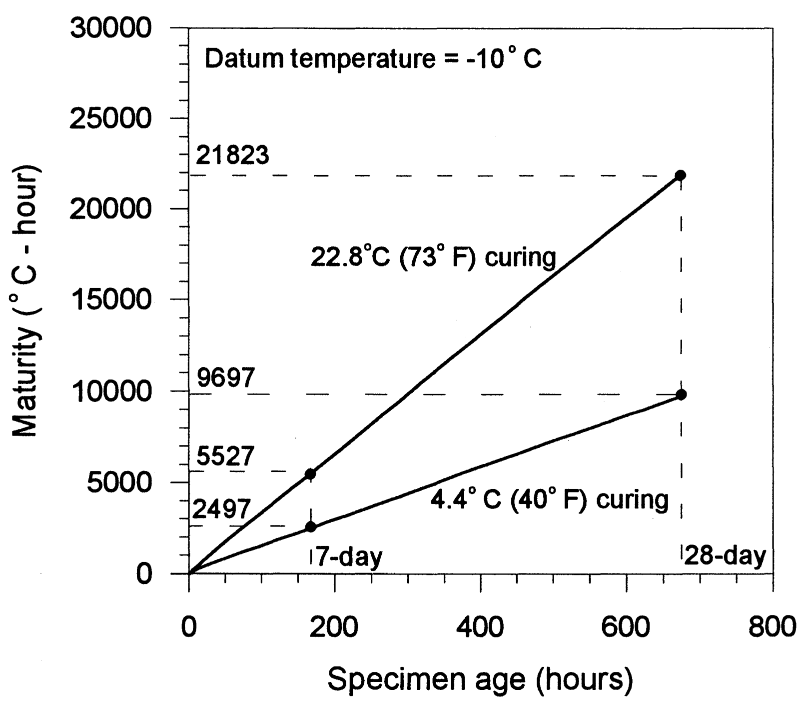
Mix No.	Curing temperature (°F)	Age (days)	Compressive strength (psi)	Maturity (°C-hour)	Pulse velocity (ft/sec.)
5	40	7	1480	2459	12725
		28	3320	9611	13467
	73	7	3750	5671	13177
		28	5240	21883	14497
6	40	7	1650	2459	9885
		28	3610	9611	13901
	73	7	3530	5571	12919
		28	5130	21883	14063
7	40	7	1520	2459	12141
		28	3560	9611	13700
	73	7	3670	5671	12276
		28	5570	21883	14544

Table 3 Test Program and Results for the Patching and Fast Track Concretes

Mix No.	Curing temperature (°F)	Age (hours)	MOR (psi)	Compressive strength (psi)	Maturity (°C-hour)	Pulse velocity (ft/sec.)
8	40	4	-	120	94	7580
		5	-	210	115	7614
		7	-	360	154	10433
		10	-	690	201	10823
	73	4	-	560	146	10112
		5	-	1040	186	11937
		7	-	1860	265	12105
		10	-	2760	379	13641
9	73	5	20	90	185	4624
		6	60	160	224	7278
		8	155	510	314	9018
		12	340	1440	517	11153
		24	435	2130	1006	11984

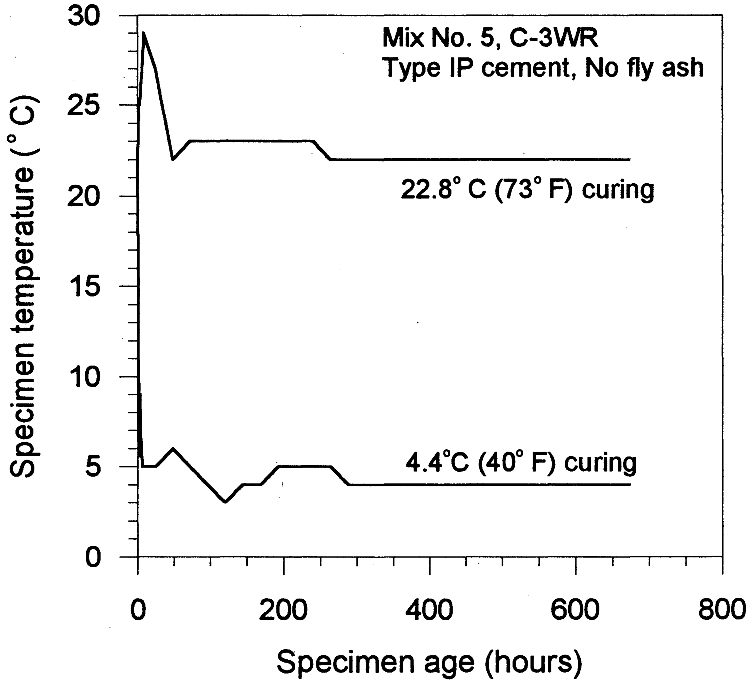


(a) Specimen temperature versus age

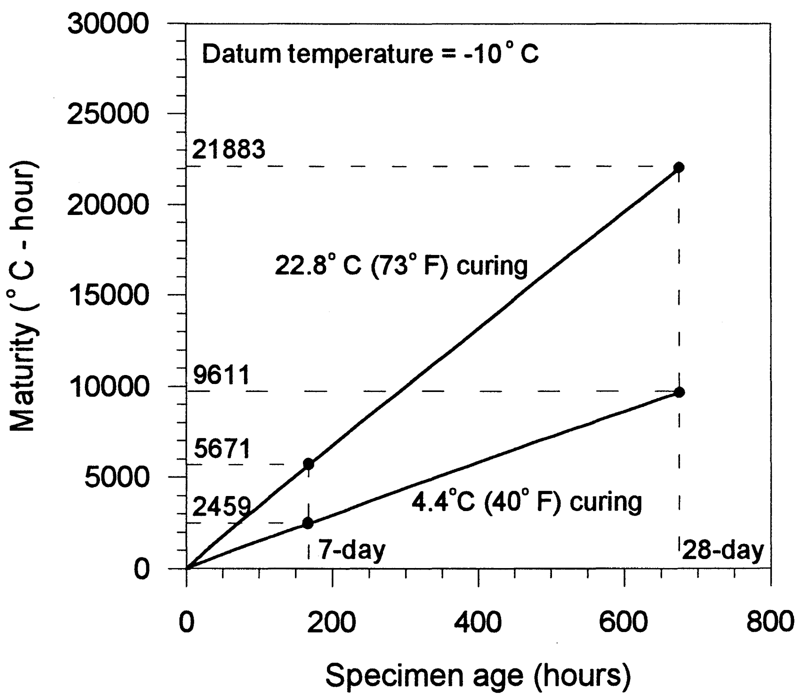


(b) Specimen maturity versus age

Fig. 1 Determination of specimen maturity based on measturements of specimen temperature for Mix No. 1 (Type I cement)

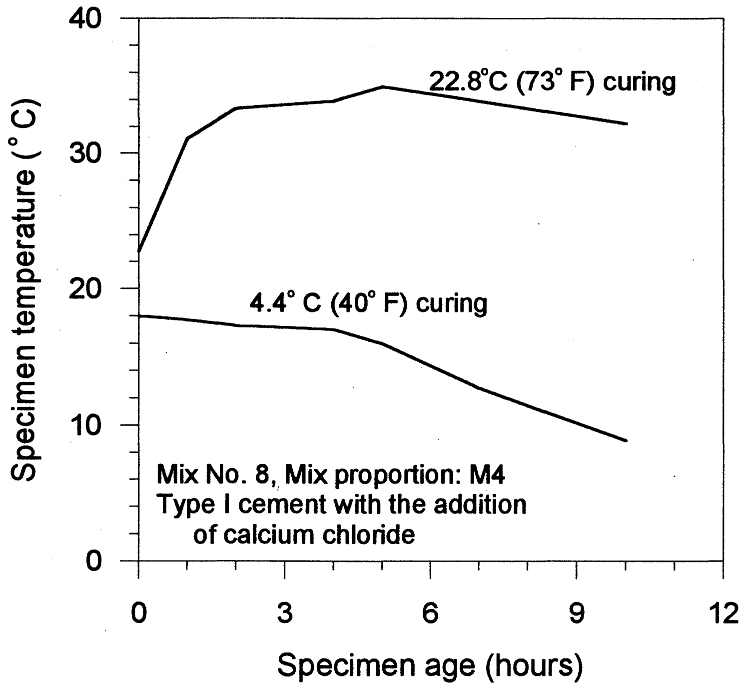


(a) Specimen temperature versus age

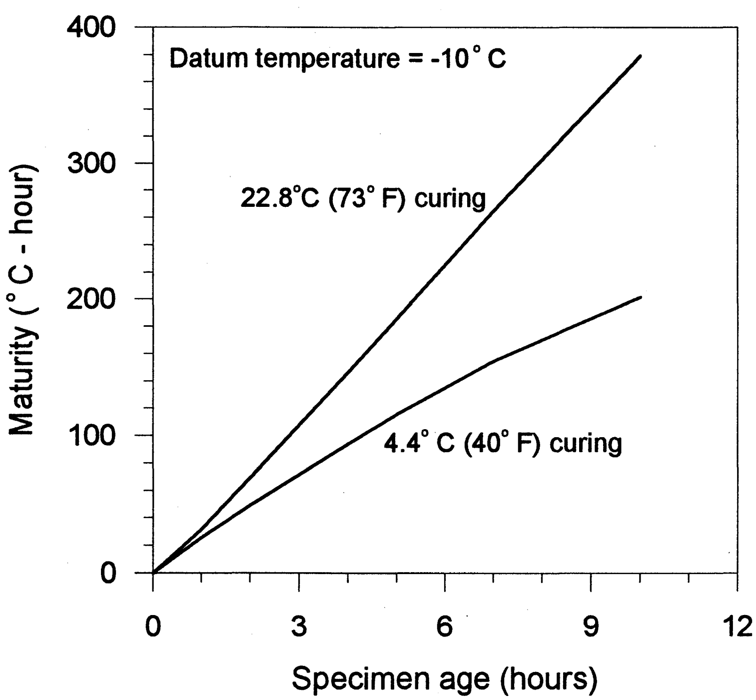


(b) Specimen maturity versus age

Fig. 2 Determination of specimen maturity based on measturements of specimen temperature for Mix No. 5 (Type IP cement)

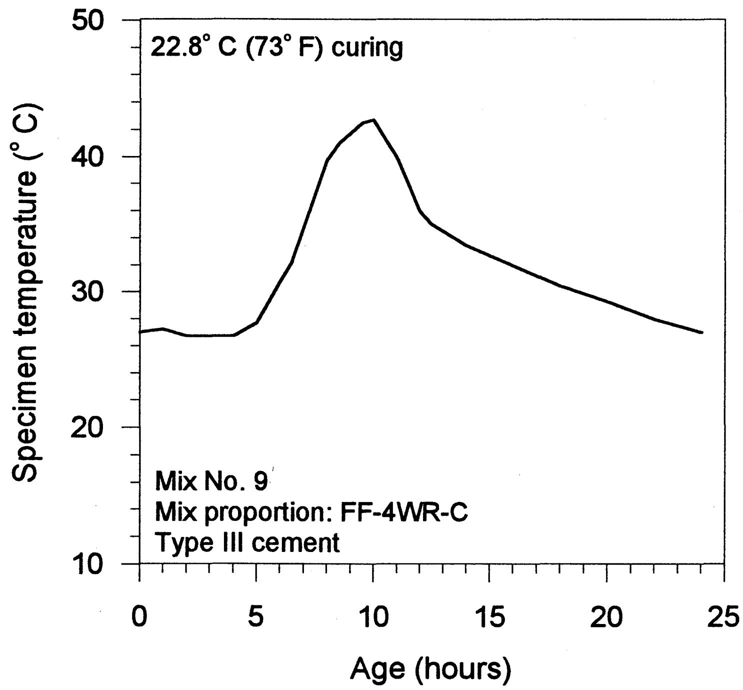


(a) Specimen temperature versus age

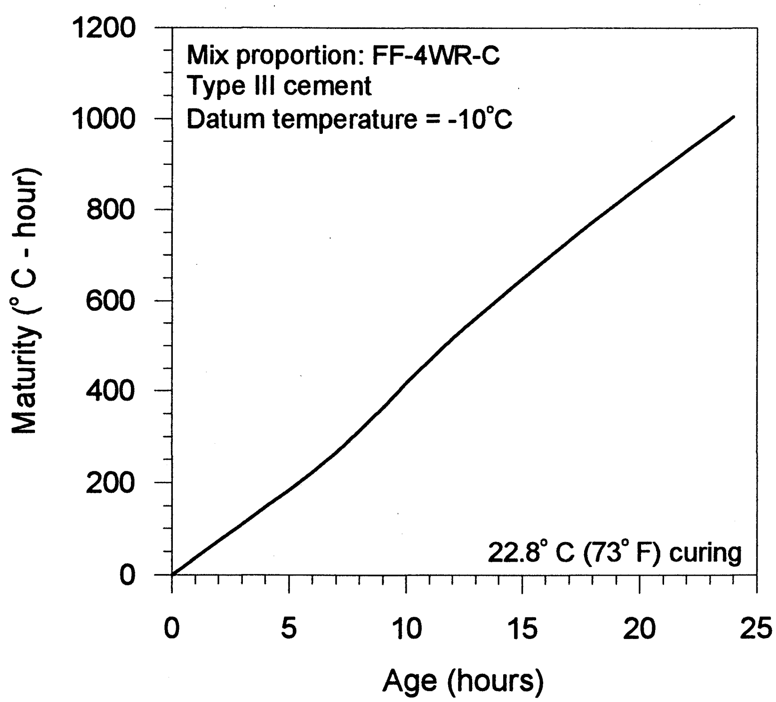


(b) Specimen maturity versus age

Fig. 3 Determination of specimen maturity based on measturements of specimen temperature for Mix No. 8 (Type I cement with the addition of calcium chloride)

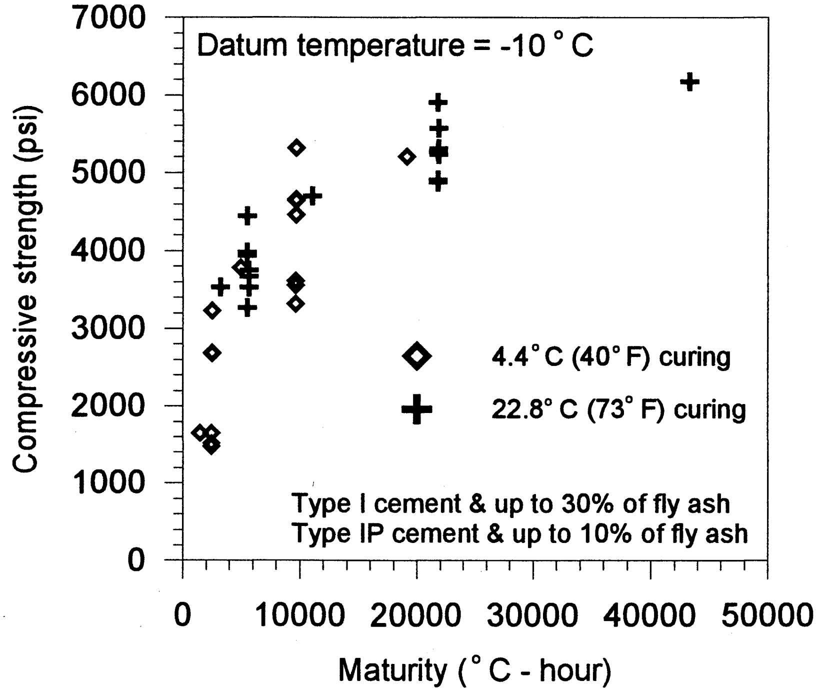


(a) Specimen temperature versus age

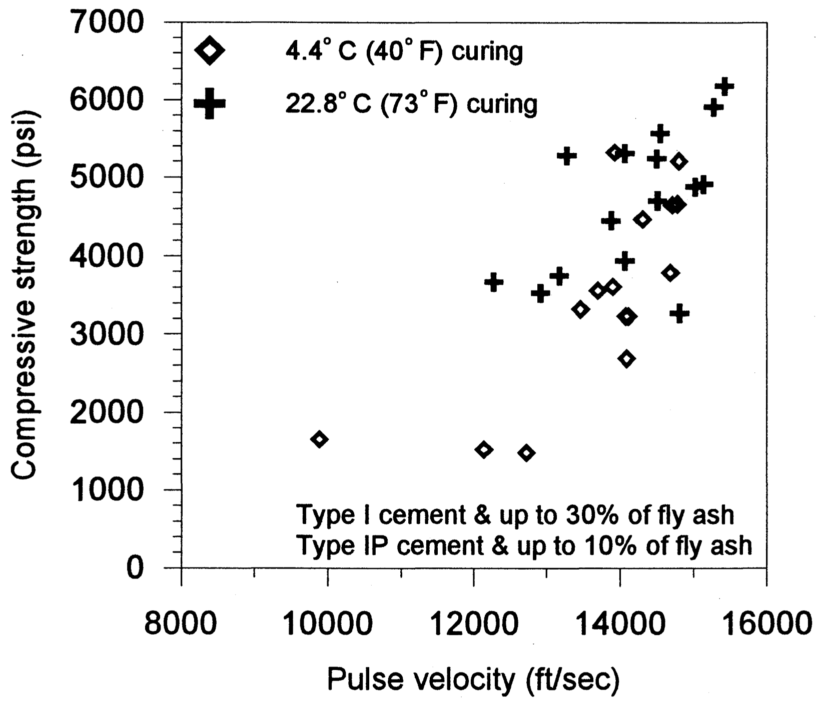


(b) Specimen maturity versus age

Fig. 4 Determination of specimen maturity based on measurements of specimen temperature for Mix No. 9 (Type III cement)

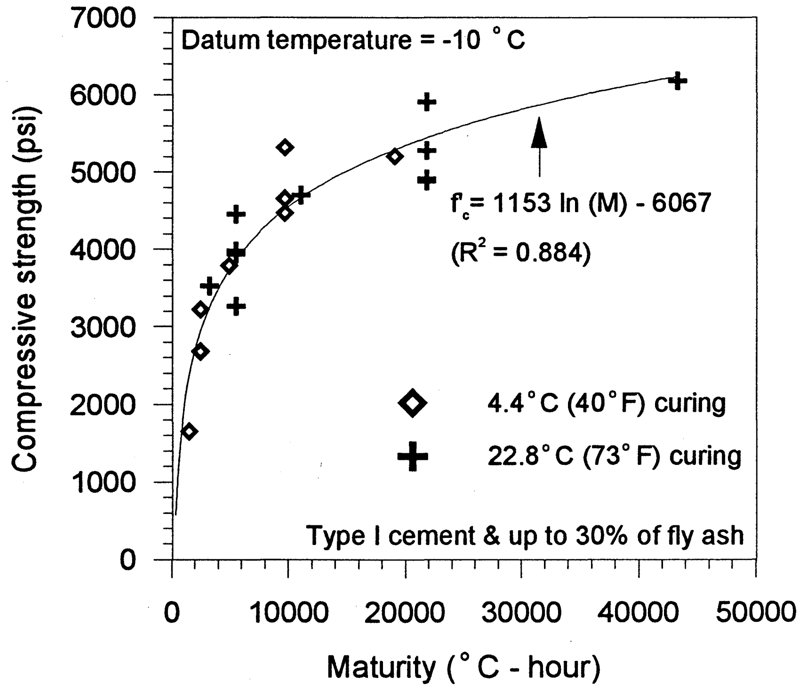


(a) Strength versus maturity

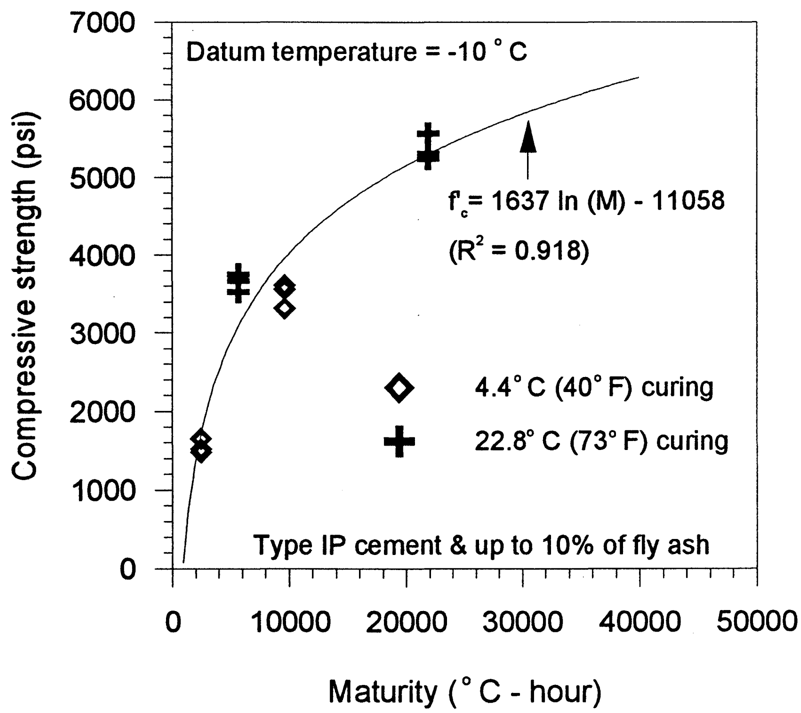


(b) Strength versus pulse velocity

Fig. 5 Relationships among strength, maturity and pulse velocity for Type I and Type IP cement mixes



(a) Type I cement mixes



(b) Type IP cement mixes

Fig. 6 Relationships between maturity and strength development

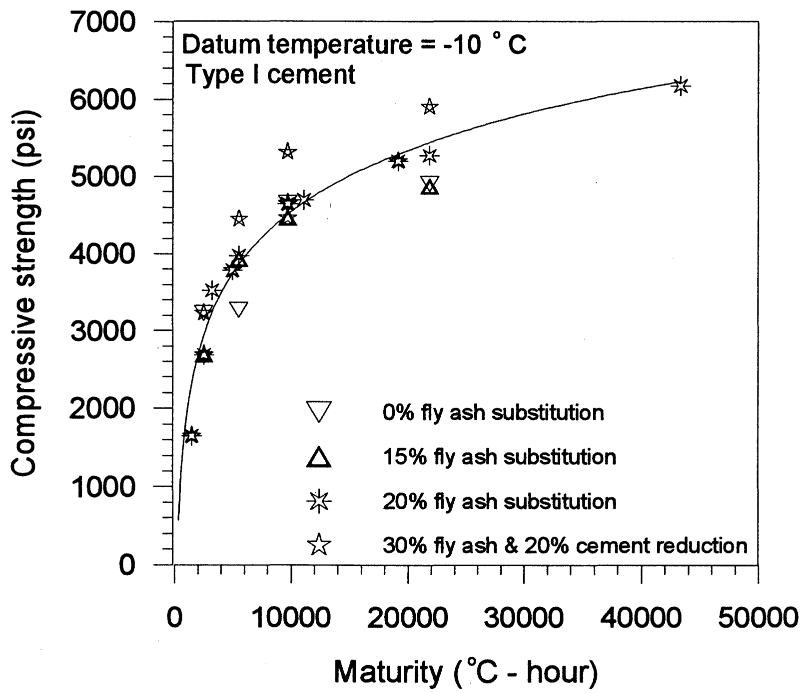
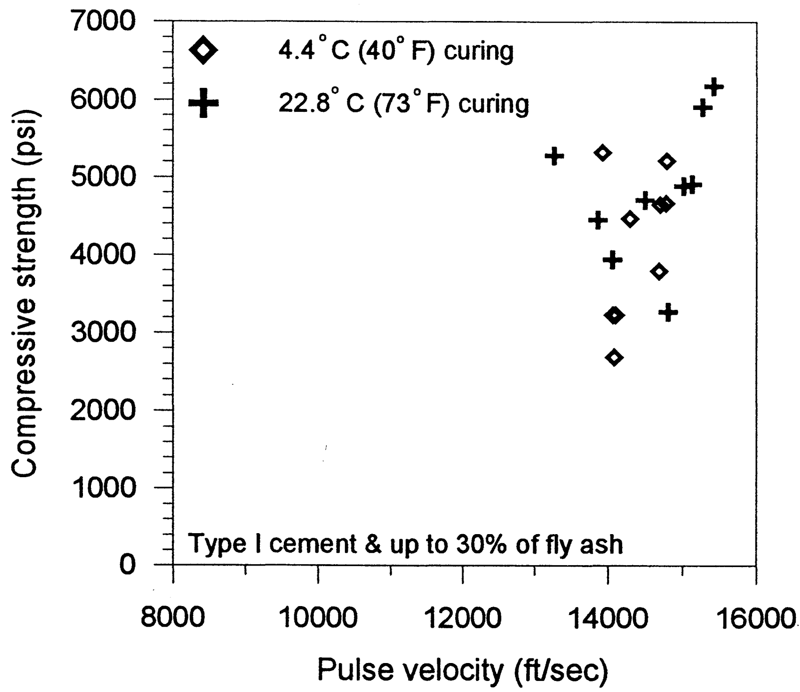
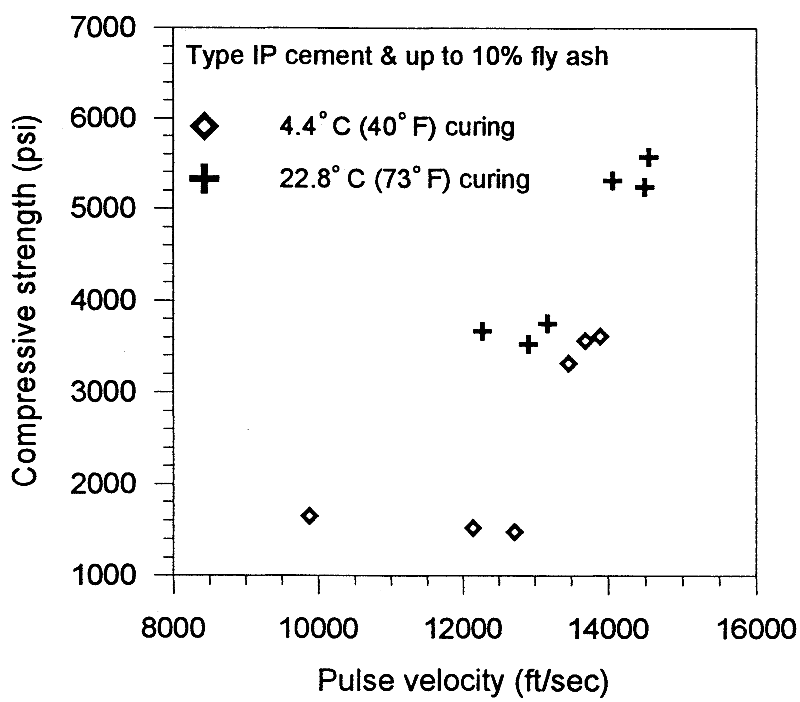


Fig. 7 The effect of fly ash substitution on strength-maturity curve



(a) Type I cement mixes



(b) Type IP cement mixes

Fig. 8 Relationships between strength and pulse velocity

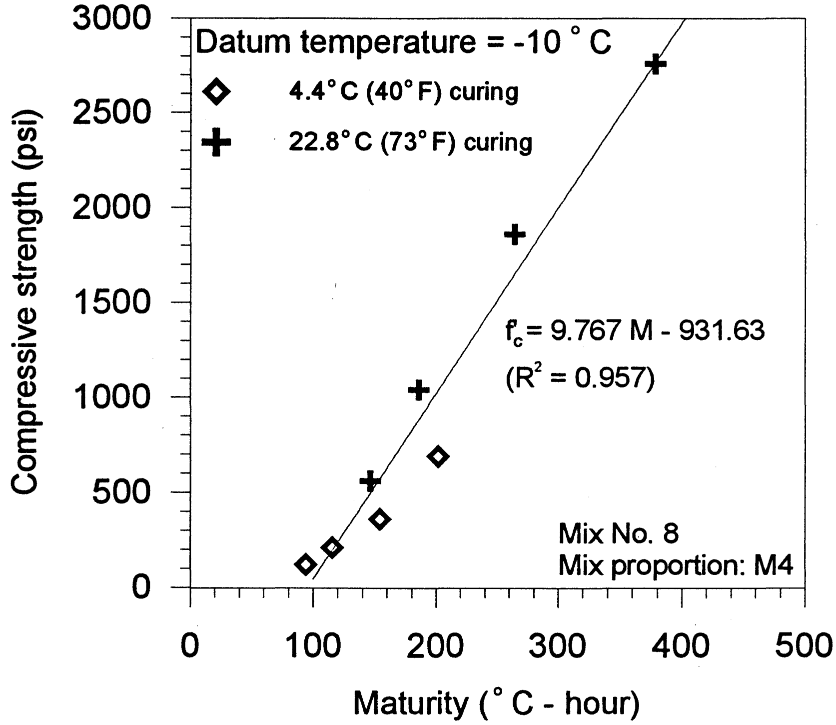


Fig. 9 Relationships between strength and maturity for Type I cement mix with the addition of calcium chloride

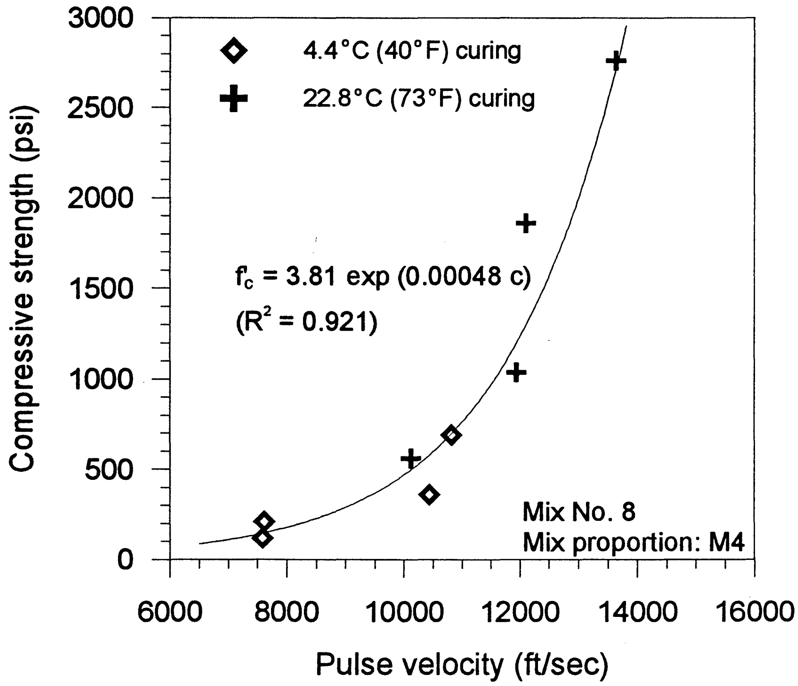
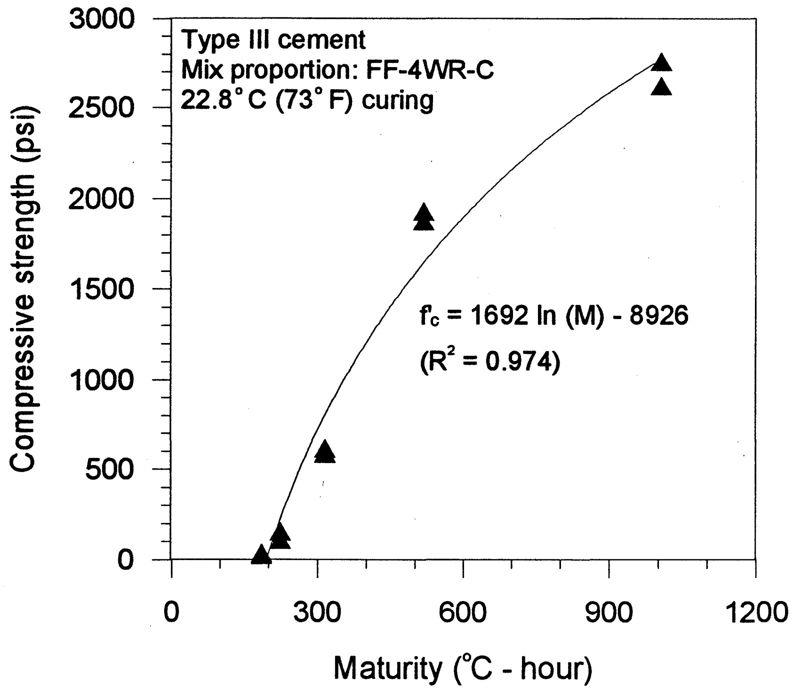
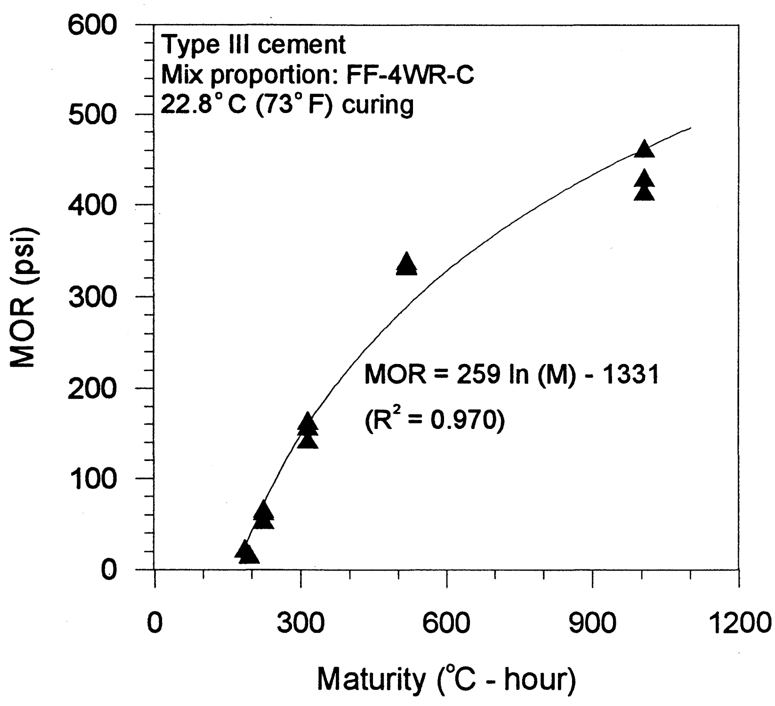


Fig. 10 Relationships between strength and pulse velocity for Type I cement mix with the addition of calcium chloride

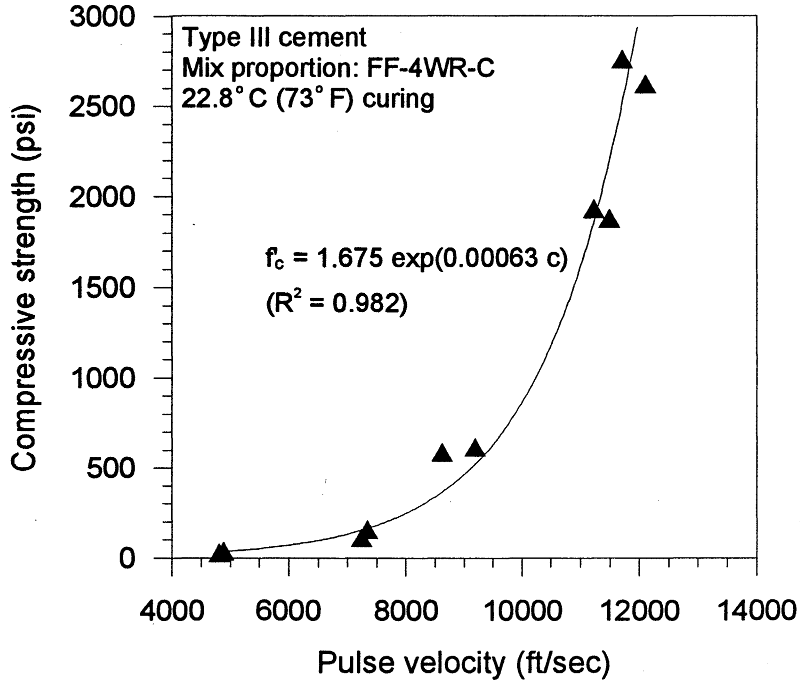


(a) Maturity versus compressive strength

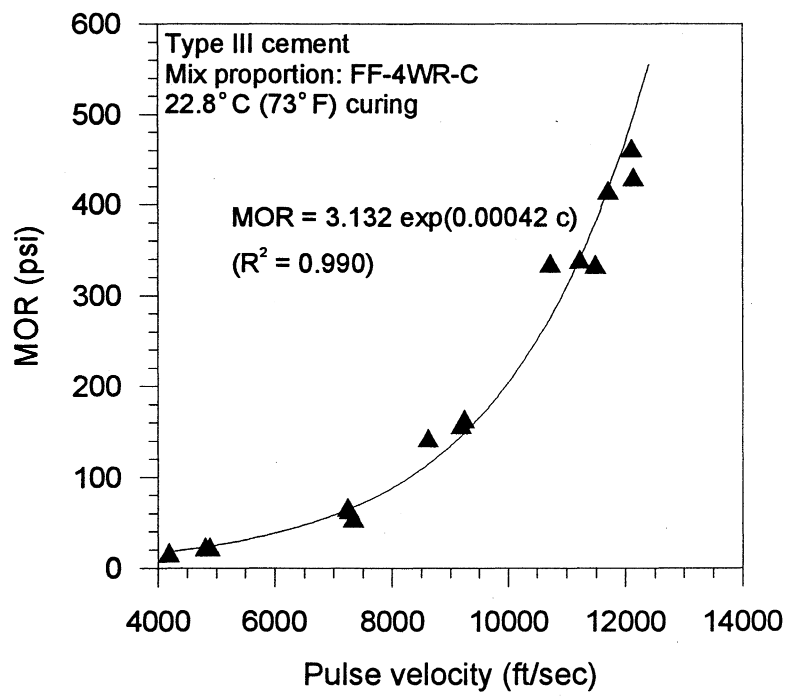


(b) Maturity versus MOR

Fig. 11 Relationships among compressive strength, MOR and maturity



(a) Pulse velocity versus compressive strength



(b) Pulse velocity versus MOR

Fig. 12 Relationships among compressive strength, MOR and pulse velocity