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Strength and Durability of High-Performance Concrete Subjected to Simulated Summer Weather Construction

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Synopsis: High-performance concrete (HPC) offers several benefits over normal-strength concrete. A greater understanding of HPC behavior under different weather conditions should improve the confidence in its uses. Mechanical properties of concrete are adversely affected by hot weather. Hot weather affects internal structure of the concrete such as pore structure and microcracking due to thermal incompatibility of the ingredients of the concrete. Durability of concrete is affected more than its strength due to hot weather. There is limited information about summer weather use of high-performance concrete. Therefore, this research was directed towards evaluating the effects of laboratory simulated hot weather conditions on strength and durability of HPC for placement during summer construction. Properties such as strength, permeability, resistance to chloride-ion penetration, sulfate attack, alkali-silica reaction, etc. for high-performance concrete having 28-day strength of 80 to 100 MPa are reported in this paper. This paper consists of current state-of-the-knowledge along with recent research conducted at the University of Wisconsin-Milwaukee Center for By-Products Utilization (UWM-CBU).

Keywords: Alkali silica reaction, chloride-ion penetration, compressive strength, concrete testing, fly ash, high-performance concrete, hot weather, permeability, silica fume, sulfate resistance.

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INTRODUCTION

In recent years, high-performance concrete (HPC) has become an option for structures varying from pavements to skyscrapers where reliability of performance and long-service life are sought. Various definitions exist for high-performance concrete (HPC) according to its uses. For example, Strategic Highway Research Program (1) (SHRP) has defined HPC depending on the performance requirements of a highway. The ACI Committee on High-Performance Concrete (2) defines HPC as, "Concrete meeting special performance requirements which cannot always be achieved routinely using any conventional constituents and normal mixing, placing, and curing practices. These requirements may involve enhancements of the following: ease of placement without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, and life in severe environments." According to Neville (3) "High-performance concrete is concrete selected so as to fit for the purpose for which it is required. There is no mystery about it, no unusual ingredients are needed and no special equipment has to be used. All we use is an understanding of the behavior of concrete and will to produce a concrete mix within closely controlled tolerances". The basic fact that properties of material originate from its internal structure is also valid for high-performance concrete. This principle of modifying internal structure suitably has been used in developing a number of metals, composite, etc. (4). From material point of view, high-performance concrete is a densely packed, less permeable, concrete obtained by using low water/cementitious ratio (5-19).

In normal strength concrete, water in excess of the quantity required for hydration reaction of cement particles is used. This excess water is used for achieving workability and self-desiccation (20). At a simplified form, concrete can

be treated as a three-phased material, consisting of aggregate phase, hydrated cement paste phase (hcp), and the transition zone (21). The transition zone is the interfacial region between the particles of aggregate and hydrated cement paste. The thickness of it varies from 10 to 50 micron. It is the weakest phase in the concrete but has greater influence on mechanical behavior of the concrete than other phases. Both the bulk hydrated cement paste and transition zone of concrete contains a heterogeneous distribution of solid phase, pores, and microcracks. These two components of the structure of concrete, i.e., hcp and transition zone, are affected by environment, time, humidity, and temperature (21). The pore structure of fully compacted cement-based composites, such as mortar and concrete, mainly consists of two types of pores: gel pores and capillary pores (20-22). Gel pores, are of colloid size particles and too small to be filled up by the hydration products, which are likely to form during further hydration of the cement. The average size of such pores is 15-20 Angstrom (23-25). On the other hand, capillary pores are much bigger than gel pores having size of the order about one micrometer (23-25). As the hydration of cement progress, the hydration products fills up the capillary pores and make them discontinuous. However, the hydration product does not fill up all the capillary pores. These pores were originally water-filled spaces, which remained unoccupied by the C-S-H gel after the hydration reaction. The formation of capillary pores is depended on the water-to-cementitious materials ratio of the mixture and the degree of the hydration of the cementitious particles. Practically all the important properties, such as strength and durability, of concrete are dependent on the capillary porosity and its distribution (21, 23, 24, 26-28).

Improved properties of high-performance concrete are due to modification of the microstructure of the HPC. The modification in microstructure of high-performance concrete is mainly dependent on the reaction mechanism among the ingredients of concrete, physical process, and curing. Chemical and mineral admixtures augment the reaction mechanism. In high-performance concrete, commonly used admixtures are silica fume (10, 21, 29-30), fly ash (8, 21, 30-32), metakaolin (30), and rice husk ash (33). These materials improve the microstructure of concrete by pozzolanic action as well as a filler effect. Better performance of high-performance concrete is primarily due to refinement of the pore structure of concrete particularly at the transition zone (21).

High-performance concrete is more sensitive to curing environment than conventional concrete since it has high-cement content and low-water to cementitious materials ratio. For the same level of workability, HPC has less water to cementitious materials ratio than the conventional normal strength concrete. When concrete is mixed, transported, and placed in an environment of hot weather, low-humidity, solar radiation, or wind, then it is called as hot weather concreting. Hot weather adversely affects the internal structure such as the pore structure and microcracking due to thermal incompatibility of the ingredients of the concrete. High-temperature reduces degree of hydration. The reduced degree of hydration occurs because of rapid water loss due to evaporation, leaving unhydrated cement

particles within the concrete matrix. Poor microstructure results in increased microcracks, high permeation quality, and reduced durability of the concrete. Generally, the C-S-H crystals grow long and thin/narrow and occupy less space in the matrix at high temperatures, resulting in decreased density of the microstructure. Thus, homogeneity and density of the concrete microstructure are adversely affected because of the aforementioned factors. Consequently, long-term strength and durability-related properties are adversely affected for concrete subjected to summer construction. A greater understanding of HPC behavior in this type of weather conditions should improve the confidence in its uses. There is a limited information about summer weather use of high-performance concrete. Therefore, in the study reported herein, the effects of laboratory simulated hot weather conditions on the strength and durability of HPC for placement during summer construction are reported.

PREVIOUS STUDIES

It is beyond dispute that hot weather causes problems in mixing, placing, and curing of conventional concrete. It ultimately affects the long-term strength and durability of the concrete also. Most of the problems are related to the increased rate of cement hydration at higher temperature and the increased rate of moisture loss from the fresh concrete (34). In hardened state, hot weather affects long-term strength and durability of concrete by changing its pore structure and introducing cracks due to thermal incompatibility of the ingredients (34-35). Increase in curing temperature shows an increase in strength at an early age but a decrease is observed for later age concrete (21, 23, 34). Elevated curing temperature hinders the hydration of cement at later ages and form an open pore structure of cement paste and, therefore, affects the properties of hardened concrete (23). Such concrete is more prone to chemical attack by water or other aggressive agents. On the other hand, the use of supplementary cementitious materials such as fly ash, silica fume, etc. in concrete, including high-performance concrete, positively modifies its behavior. Fly ash concrete has been reported to show strength gain due to increase in the curing temperature (32, 36-37, 56-57). The pozzolanic reaction rate of fly ashes increases with temperature (38-39, 57) and the kinetics of this reaction is influenced by the curing temperature (40). Zain, et al. (41) investigated the effect of curing temperature in range of 20 to 75 °C on the water permeability of mortars containing silica fume. They reported decrease in the water permeability of the mortar with increase of curing temperature. This is due to high pozzolanic reactivity and microfiller effect of silica fume that might have led to much denser and discontinuous pore structure at medium temperature. Study conducted on the effect of curing temperature in the range of 20 °C to 50 °C on the strength and dynamic modulus of elasticity of high-performance concrete containing silica fume, fly ash, and ground granulated blast-furnace slag has shown greater strength development from the age of 7 days. This indicates that significant acceleration of pozzolanic reaction occurs with increase of curing temperature (42).

The microstructural study (43) of the cement pastes hydrated at temperature ranging from 10 °C to 60 °C has showed greater apparent porosity for paste cured at 60 °C compared to those cured at 10 °C. Studies by Beeldens and Vandewalle (44) have shown the difference in compressive strength between the specimens cured at 7 °C and 20 °C until the age of 3 days. Afterwards, the effect of curing temperature on the strength of high-strength concrete containing silica fume was negligible. The results on high-strength concrete with and without polypropylene fibers exposed up to 200 °C has shown small changes in compressive strength, modulus of elasticity, and splitting tensile strength. This could be due to fiber melting. Scanning electron microscopy analysis has shown existence of supplementary pores and small channels created in concrete with fibers, due to melting of fibers (45). Gjorv and Martisen (46) reported “The maximum curing temperature up to 90 °C did not adversely affect the mechanical properties such as compressive strength and modulus of elasticity. Neither was the capillary absorption, porosity, and the resistance to water penetration affected, indicating that the capillary pore system was not affected. However, maximum curing temperatures above 50 °C did adversely affect the chloride-ion permeability. Thus, at 90 °C the permeability was increased by a factor of approximately four compared to that of 20 °C, indicating a more open and porous microstructure”.

Reports (47-49) show that the use of Class F fly ash and silica fume improves concrete resistance to sulfate attack. Some publications (47-50) reported that inclusion of Class C fly ash reduces ability of concrete to resist sulfate attack. However, Mehta (48-51) indicated that irrespective of the amount of calcium content, it is the amount of reactive alumina content contributed by a fly ash that controls the presence of mineral highly vulnerable to sulfate attack. ACI Committees 201 (52) and 318 (53) offer recommendations to stem the effects of sulfate attack.

The alkali hydroxides liberated during cement hydration can react with aggregates containing amorphous silica, resulting in formation of expansive products. Uses of supplementary cementing materials such as Class F fly ash, ground granulated blast-furnace cement, and silica fume, either individually or combined in concrete, suppress alkali-silica reactions (30).

EXPERIMENTAL PROGRAM

Materials

ASTM C 150 Type I, normal portland cement was used throughout this investigation. Its physical and chemical properties are presented in Table 1. A Class C fly ash conforming to ASTM C 618 requirements was used, the physical properties of which are presented in Table 2. The fly ash met the general requirement of ASTM. A silica fume conforming to ASTM C 1240 was also used.

The fine aggregate used consisted of natural sand. A crushed limestone with maximum nominal size of 19 mm was used as the coarse aggregates. Both aggregates met the ASTM C 33 requirements. Further, a commercially available superplasticizer was used to obtain the desired consistency of the concrete at low-water to cementitious materials ratio. A commercially available retarder was also used to control the rate of hydration reaction to avoid damaging effects of accelerated hydration due to evolution of heat of hydration and to permit placement and finishing of the concrete mixtures.

Mixture Proportions

The proportions of the HPC concrete mixtures used for this study are summarized in Table 3. The concrete mixtures were proportioned to have strength in the range of 80 to 100 MPa at the age of 28 days. The first mixture contained 15% Class C fly ash but no silica fume. The second and third mixtures contained 19% Class C fly ash and 5% silica fume, and 9% Class C fly ash and 14% silica fume by weight of total cementitious materials, respectively. These mixtures were designated as M-1, M-2, and M-3, respectively. The details of mixture proportions along with their fresh properties are given in Table 3.

Preparation of Test Specimens

Weighed quantity of coarse and fine aggregates were fed into a 0.16 m³ mixing capacity revolving drum concrete mixer and allowed to dry mix the ingredient for two minutes. The cement and fly ash were then added to the mixer and allowed to dry mix with the aggregates for two more minutes. After the dry mixing, one half of the required amount of superplasticizer and all of the retarder were mixed in a bucket with the required amount of water for the mixture. Then this water was added to the mixer. For Mixture M-2 and M-3, the required amount of silica fume slurry was added at the time of addition of the water. The wet concrete was then allowed to mix for minimum three minutes and rest for two minutes. During the two-minute rest period, wet concrete that adhered to the surface of the drum was manually scraped off. At the end of the two-minute rest period, the remaining amount of superplasticizer was added to the mixture and the resulting concrete was mixed again for minimum three minutes. Soon after mixing, tests were conducted to determine the properties of fresh concrete such as slump (ASTM C143), air content (ASTM C 231), and temperature (ASTM C1064). Ambient air temperature was also recorded.

From each concrete mixture, 100 mm x 200 mm cylindrical specimens were cast for compressive strength and resistance to chloride-ion penetration measurements. These cylinders were cast in two layers and compacted on a vibrating table. Slab specimens of dimensions 100 mm thick x 300 mm x 300 mm

were cast for air and water permeability measurements. For conducting sulfate resistance and alkali-silica reaction (ASR), test specimens of 100 mm x 75 mm x 400 mm were cast and compacted by using a 35-mm diameter needle vibrator. All specimens were cast in accordance with ASTM C 192.

Curing of Specimens

After casting, all the molded specimens were covered with plastic sheets to minimize moisture loss due to evaporation. After 24 hours, the demolded samples were transferred to a standard moist curing room at 23°C (73°F) and 100% relative humidity or a specially-designed curing unit. Specially-designed curing unit maintained a Variable Temperature Curing Environment (VTCE) with temperature varying from $29 \pm 3^\circ\text{C}$ for 12 hours each day to $41 \pm 3^\circ\text{C}$ for the remaining 12 hours each day, simulating hot weather curing conditions in USA. All concrete specimens were wrapped and sealed in a plastic bag to minimize moisture loss due to evaporation before placing them in the VTCE unit. The relative humidity of the VTCE chamber was found to vary between 35 and 85%.

Testing of Specimens

For each concrete mixture, the compressive strength was determined for three cylinders at 3, 7, 28, 56, 91, 182, and 365 days of age in accordance with ASTM C 39. Chloride-ion penetration resistance test was performed in accordance with ASTM C 1202. Figg's method (54-55) was used to determine the air and water permeability of the concrete specimens. Prism specimens, after initial length measurements, were immersed in a 10% sulfate solution for evaluation of sulfate resistance of the HPC. Each specimen was tested for length change (ASTM C 157), longitudinal frequency (ASTM C 215), and pulse velocity (ASTM C 597). The sulfate solution in each container was replaced with a new solution after each measurement.

Prism specimens were also used for tests related to alkali-silica reaction (ASR) evaluations. The effects of ASR were evaluated by measuring length change (ASTM C 157) as a function of age of the concrete. It is believed that the expansions resulting from alkali-silica reaction would be translated into increases in length.

RESULTS AND DISCUSSIONS

Compressive Strength

The compressive strength for the different concretes is given in Table 4 and depicted in Fig. 1. In general, all standard moist cured concrete mixtures gained

strength in excess of 50 MPa at the age of three days. With increase in silica fume content in the concrete, the early strength at three days was further increased for Mixtures M-2 and M-3. Maximum compressive strength of 64 MPa at the age of three days was achieved by moist-cured Mixture M-3. A similar range of strength was achieved by concrete mixtures cured in Variable Temperature Curing Environment (VTCE). At three days, the maximum compressive strength (66 MPa) was achieved by VTCE Mixture M-3. Similar trends were observed for all concrete cured in both types of curing environments up to age of 91 days. Generally, all VTCE-cured specimens exhibited higher strengths than corresponding moist-cured specimens at the ages up to 91 days.

All mixtures attained strengths in excess of 73 MPa (10,600 psi) at 28 days. Moist-cured concrete Mixture M-3 exhibited strength of 99 MPa (14,380 psi) while the VTCE cured attained 100 MPa (14,530 psi). At 91 days, all the concrete mixtures irrespective of curing type attained strength more than 82 MPa (11,900 psi). In general, VTCE cured concrete mixtures showed slightly more strength than standard moist cured concrete. This may be due to higher rate of hydration in VTCE environment.

After 91 days, there was a noticeable decrease in strength of VTCE cured concrete for all the mixtures. This may be due to the desiccating effect of the high-curing temperature on the microstructure of the concrete. The decrease in strength was less than 20%. A detailed study of microstructure of concrete either by scanning microscope or by mercury intrusion porosimetry would have given some insight and explanation for the cause of decrease in strength.

Resistance to Chloride-Ion Penetration

The resistance to chloride-ion penetration for each concrete mixture was determined in accordance with ASTM C 1202. The chloride-ion penetration resistance data are presented Table 5. The table indicates that with the increase of the age, concrete resistance to chloride-ion penetration increased for both curing environments. VTCE cured concrete achieved more resistance to chloride ion penetration than the standard moist cured concrete. Maximum resistance to chloride ion penetration was observed in the case of concrete of Mixture M-3. With increase in silica fume content, quantitative values of resistance to chloride-ion penetration increased (i.e., Coulomb's values decreased) but according to ASTM C 1202 requirements, given in Table 6, all data are in the range of the same category of chloride-ion penetration. According to relevant ASTM standard for chloride-ion penetration, at 28 days, moist cured concrete Mixture M-1 is in the category of high- chloride permeability, which attained a moderate permeability value at ages after that. On the other side, VTCE concrete Mixture M-1 is in the category of moderate permeability for all the ages. However, concrete Mixture M-2 and Mixture M-3 are in the category of very low chloride permeability irrespective

of ages and curing type. This shows that a simulated summer weather condition has no noticeable effect on the resistance to chloride ion penetration of high-performance concrete.

Air and Water Permeability

Each high-performance concrete mixture was evaluated for air and water permeability in accordance with the Figg's method (54-55). The test data are reported elsewhere (12). The analysis of the test results did not exhibit any particular trend with respect to air and water permeability for these HPC mixtures. It was concluded that this test procedure might not be applicable when used to test high-performance concrete. Similar conclusion has been reported by other researchers (56).

Sulfate Resistance

The effects of sulfate attack on HPC were studied by determining changes in length of specimens, dynamic modulus, and pulse velocity for the specimen under consideration. Fig. 2 through Fig. 9 present the effect of sulfate attack on the specimens from all mixtures of HPC. The specimens were immersed in 10% sulfate solution for the study of sulfate attack on HPC.

The length change data are depicted in Fig. 2 for Mixture M-1, Fig. 3 for Mixture M-2, and Fig. 4 for Mixture M-3, respectively. Generally, VTCE-cured specimens exhibited higher length change than moist-cured specimens. However, the length change for all the concrete mixtures revealed insignificant effect of sulfate attack on all HPC mixtures cured in both curing environments.

Fig. 5 and Fig. 6 depict changes in the dynamic modulus for HPC Mixtures M-1 and M-2, respectively. The results indicate the increase in dynamic modulus of concrete with age when exposed to sulfate solution. The difference in dynamic modulus values of VTCE-cured and moist-cured concrete specimens for concrete Mixture M-1 is insignificant. However, it is significant for Mixture M-2. Addition of silica fume probably is responsible for this improvement.

The changes in pulse velocity values for Mixture M-1 through M-3 are given in Fig. 7 to 9, respectively. Fig. 7 shows that up to 15 weeks of age the changes in pulse velocity for both VTCE and moist-cured concrete Mixture M-1 was significant which reduced at the later age. For Mixture M-1, moist-cured specimens had higher change in pulse velocity than VTCE-cured concrete. A reverse trend is visible in Fig. 8 and Fig. 9 for concrete Mixture M-2 and M-3. However, the differences in change in pulse velocity for concrete cured by both modes of curing seldom exceeded 10%. This indicates that simulated summer

weather concreting does not have significant effect on the resistance to sulfate attack of the HPC mixtures under study.

Alkali-Silica Reaction

The expansion resulting from possible alkali-silica reaction (ASR) was evaluated by measuring change in density and length. The data are given elsewhere (12). The changes in density and length values from the initial values were insignificant for all the three HPC mixtures under both the curing environments. The results indicated no significant ASR activities in HPC mixtures.

CONCLUSIONS

Based on the experimental investigation carried out on three HPC mixtures the following main conclusions could be drawn:

1. Simulated summer weather construction, i.e. VTCE-cured specimens, achieved higher strength compared to moist-cured specimens for all HPC mixtures up to the age of 91 days. At the age of 28 days, all the concrete achieved strength ranging from 73 MPa to 100 MPa.
2. Simulated summer weather construction had no detrimental effect on strength development of HPC mixture.
3. Simulated summer weather concreting had insignificant effect on resistance to chloride-ion penetration of HPC mixtures. All HPC mixtures may be rated to have a very high resistance to chloride-ion penetration ("very low" chloride-ion penetration in accordance with ASTM C 1202 criteria).
4. Figg's method for evaluating air and water permeability of concrete was inadequate to determine the effect on air and water permeability of HPC mixtures.
5. The simulated summer weather construction had no noticeable influence on sulfate resistance of the HPC mixtures.
6. HPC can be used for the summer weather construction without adversely affecting the properties of concrete. However, further research on the effect on microstructure of HPC mixtures due to simulated hot weather should be conducted.

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Table 1 - Physical and chemical properties of cement

Physical Properties of Cement		
Air content (%)	9.5	12 max.
Fineness (m ² /kg)	351	280 min.
Autoclave expansion (%)	-0.02	0.8 max.
Specific gravity	3.16	-
Compressive strength (MPa)		
1-day	13.7	-
3-day	24.1	12.3 min.
7-day	29.2	19.2 min.
28-day	37.4	-
Vicat's time of initial Set (min)	145	45 min. 375 max.
Chemical Properties of Cement		
Chemical Composition (%)	Cement Type I	ASTM C 150, Type I
Silicon dioxide, SiO ₂	20.0	-
Aluminum oxide, Al ₂ O ₃	4.3	-
Ferric oxide, Fe ₂ O ₃	2.5	-
Total, SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	26.8	-
Sulfur trioxide, SO ₃	2.3	3.0 max.
Calcium oxide, CaO	65.0	-
Magnesium oxide, MgO	2.0	6.0 max.
Titanium dioxide, TiO ₂	0.0	-
Potassium oxide, K ₂ O	0.6	-
Sodium oxide, Na ₂ O	0.3	-
Moisture content	-	-
Loss on ignition	2.0	3.0 max.

Table 2 - Physical properties of fly ash

Test Parameter	Fly Ash	ASTM C 618		
		Class C	Class F	Class N
Retained on No. 325 sieve (%)	14.0	34 max	34 max	34 max
Pozzolanic activity index with cement, 28-day (% of control)	119	75 min	75 min	75 min
Water requirement (% of control)	92	105 max	105 max	115 max
Autoclave expansion (%)	0.11	±0.8	±0.8	±0.8
Specific gravity	2.5	-	-	-

Table 3 - Mixture proportions and fresh properties of concrete

Mixture Number	M-1	M-2	M-3
Cement, lb/yd ³ (kg/m ³)	645 (383)	746 (443)	797 (473)
Class C Fly Ash, lb/yd ³ (kg/m ³)	118 (70)	187 (111)	99 (59)
Silica Fume, lb/yd ³ (kg/m ³)	0 (0)	47 (28)	149 (88)
Water, lb/yd ³ (kg/m ³)	236 (140)	281 (167)	229 (136)
Sand (SSD), lb/yd ³ (kg/m ³)	1225 (728)	1070 (635)	1165 (692)
19 mm Aggregates (SSD), lb/yd ³ (kg/m ³)	1680 (998)	1675 (995)	1590 (944)
Superplasticizer, oz/yd ³ (L/m ³)	71 (2.8)	127 (4.9)	260 (10.1)
Retarder, oz/yd ³ (L/m ³)	23 (0.9)	28 (1.1)	44 (1.7)
Slump, in (mm)	8-1/4 (210)	7 (175)	2 (51)
W/Cm	0.31	0.29	0.22
Air Content, %	N.A.	2.3	2.8
Air Temperature, °F (°C)	70 (22)	68 (21)	74 (23.3)
Concrete Temperature, °F (°C)	72 (22.3)	63 (20)	73 (23)
Concrete Density, lb/yd ³ (kg/m ³)	147.5 (2363)	150 (2403)	150.7 (2414)

Table 4 - Compressive strength of concrete mixtures

Age, days	Compressive Strength, MPa					
	M-1		M-2		M-3	
	Moist cured	VTCE	Moist cured	VTCE	Moist cured	VTCE
3	53	48	57	58	64	66
7	54	58	69	75	73	86
28	73	73	87	88	99	100
56	73	78	93	92	105	101
91	82	83	99	100	104	130
182	79	71	94	88	81	73
365	78	69	91	77	94	81

* Average of three readings

Table 5 – Chloride-ion permeability of concrete mixtures

Age, days	Average Charged Passed, Coulombs					
	M-1		M-2		M-3	
	Moist cured	VTCE	Moist cured	VTCE	Moist cured	VTCE
28	4360	3170	690	190	240	105
60	2060	1740	330	170	180	65
91	1895	1830	300	215	150	200

* Average of three readings

Table 6 – Chloride-ion permeability of concrete (ASTM C 1202)

Charged Passed, Coulombs	Chloride Permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

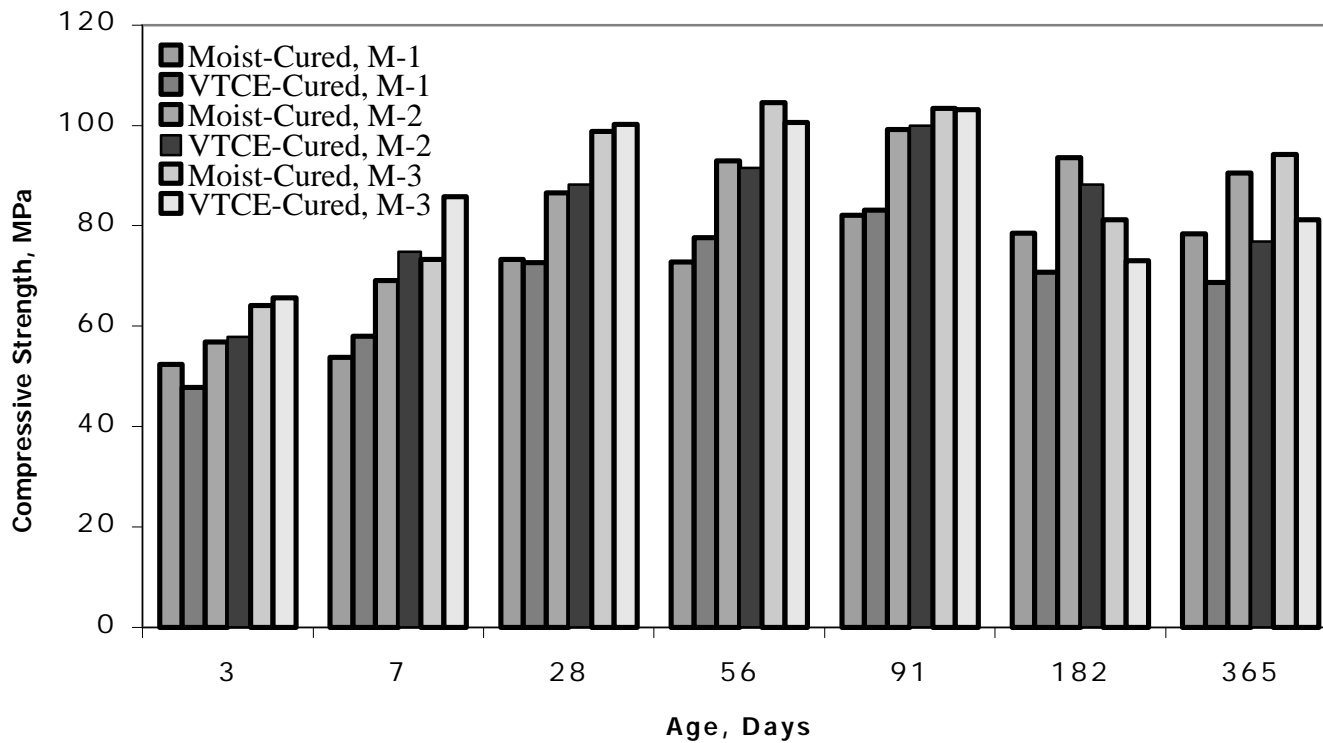


Fig. 1 - Compressive strength versus age of concrete

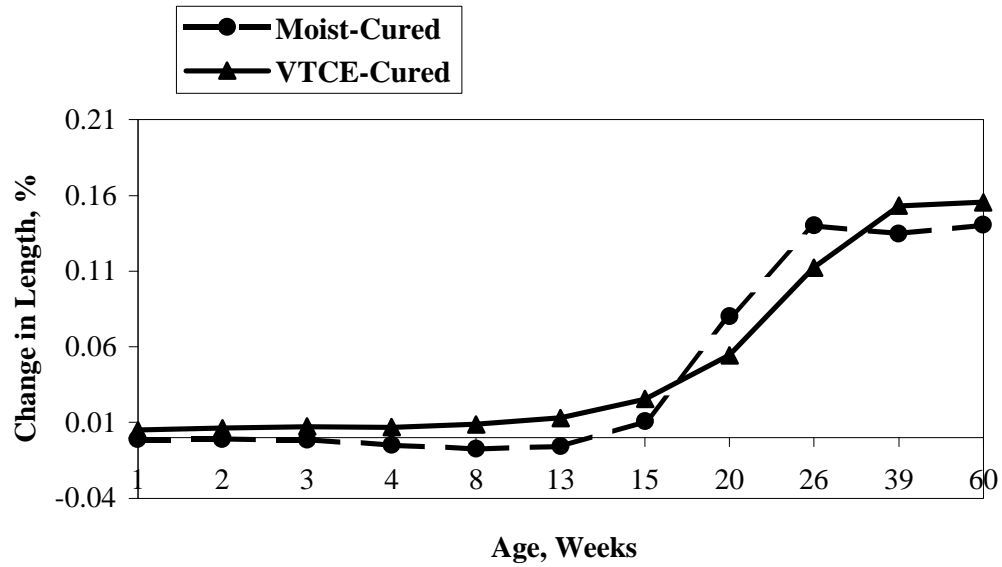


Fig. 2 - Change in length under sulfate test versus age for concrete Mixture M-1

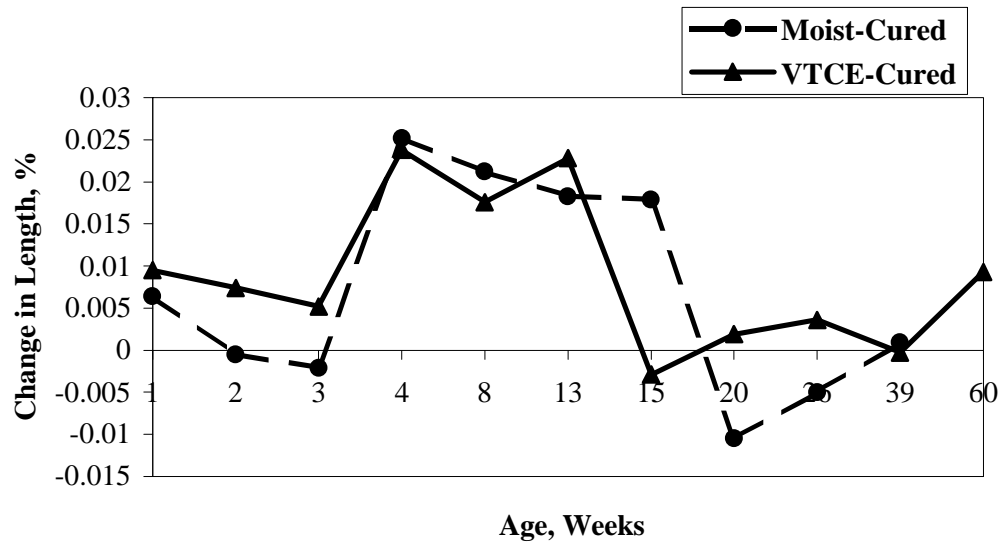


Fig. 3 - Change in length under sulfate test versus age for concrete Mixture M-2

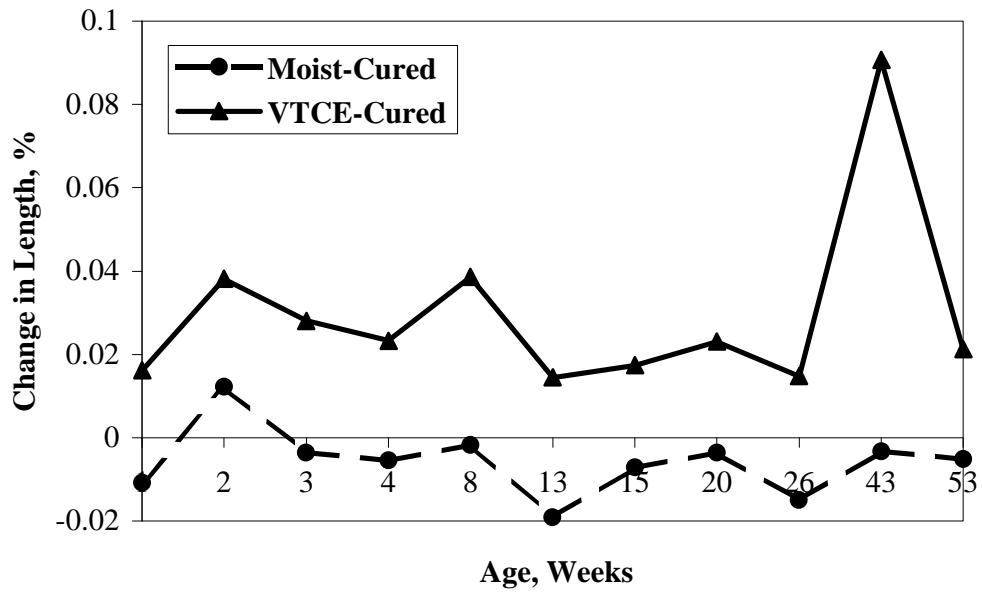


Fig. 4 - Change in length under sulfate test versus age for concrete Mixture M-3

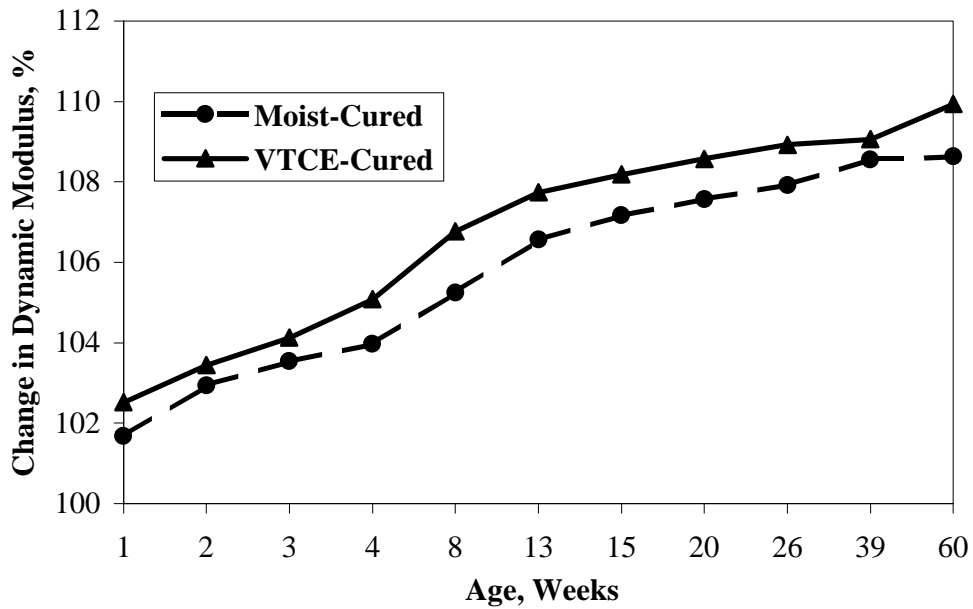


Fig. 5 - Change in dynamic modulus for Mixture M-1 concrete under sulfate test versus age

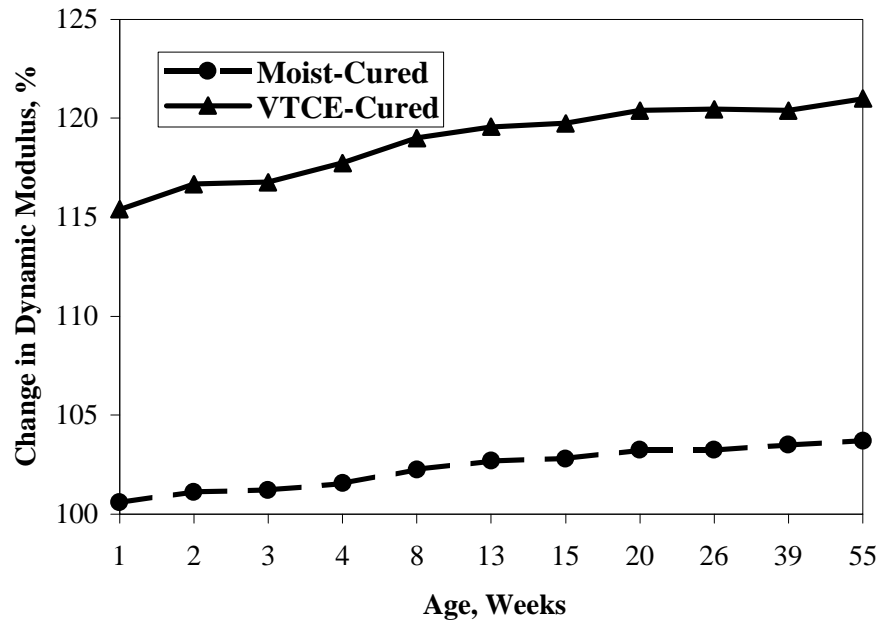


Fig. 6 - Change in dynamic modulus for Mixture M-2 concrete under sulfate test versus age

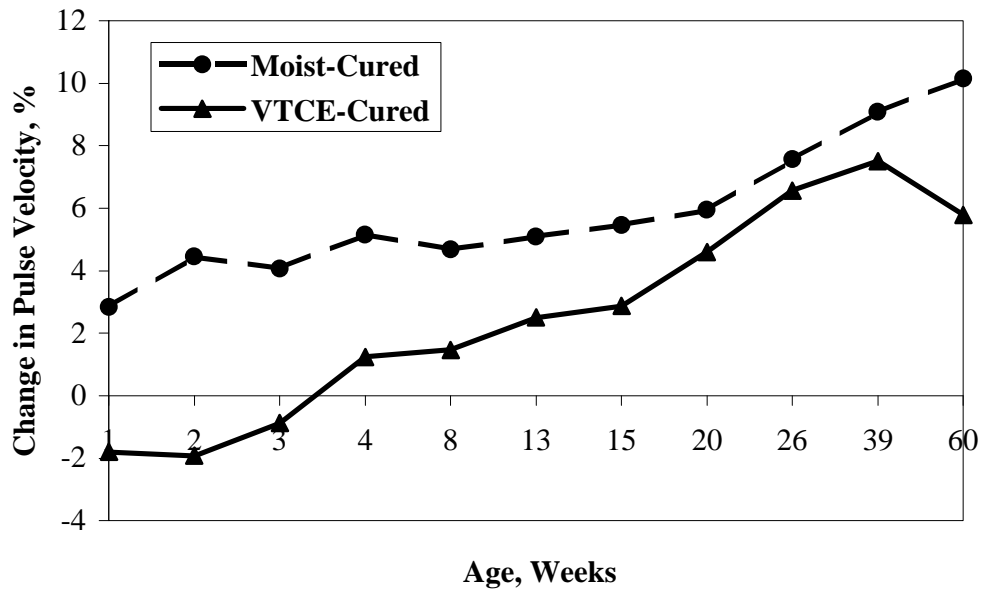


Fig. 7 - Change in pulse velocity of concrete Mixture M-1 under sulfate test versus age

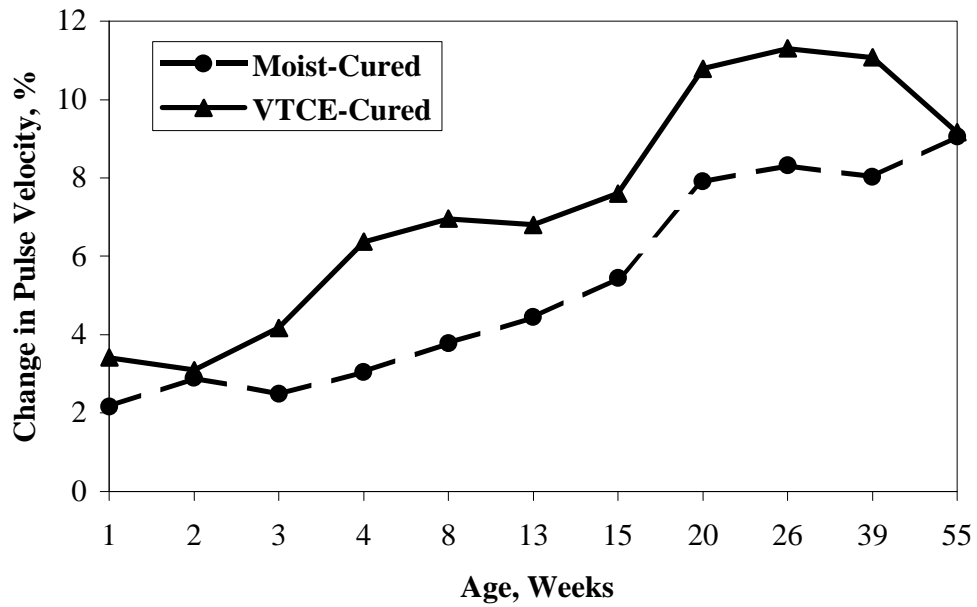


Fig. 8 - Change in pulse velocity of concrete Mixture M-2 under sulfate test versus age

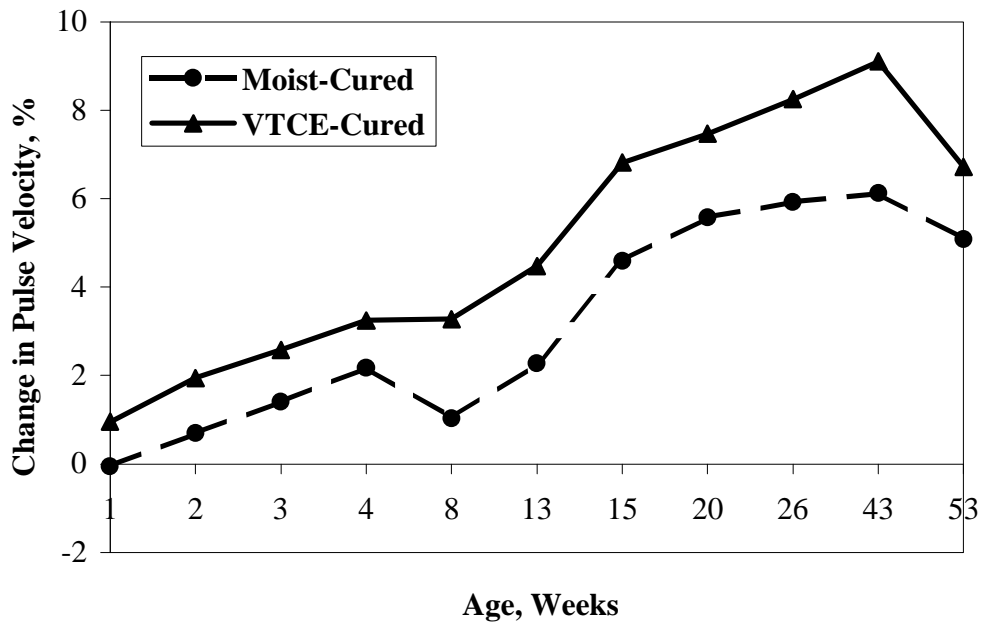


Fig. 9 - Change in pulse velocity of concrete Mixture M-3 under sulfate test versus age