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Research Note

Effect of curing conditions on strength and durability of high-performance concrete

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Abstract. This paper describes the effects of variable curing temperatures on compressive strength and sulfate resistance of high-strength, high-performance concrete. Two different concrete mixtures were proportioned to attain the 56-day compressive strength of about 70 MPa upon moist-curing. One mixture contained more quantity of ASTM Class C fly ash than the other one. For each mixture, one set of specimens was cured in a standard moist-curing room at 23°C and 100% relative humidity; another set of specimens was sealed in plastic bags and cured in an elevated, Variable-Temperature Curing Environment (VTCE). The average temperature of the VTCE oscillated between about 30°C and 41°C once per day. This study revealed that the VTCE-cured concrete did not significantly exhibit different compressive strength or ability to resist sulfates attack compared to the standard moist-cured specimens. Thus, it was concluded, based on the results of this research, that additional effort to stabilize higher curing-temperatures would be necessary for field-cured concrete.

1. Introduction

Concrete is a porous solid that is created by combining four basic materials: cementitious binder, aggregates, admixtures, and water. The ability of concrete to perform in the desired manner is primarily dependent upon the proportions of these four materials along with the temperature and time during curing.

This research project was directed towards concrete strength and the ability of the concrete to resist undesirable sulfate expansion. Many studies were conducted regarding this issue. However, most of these reported studies were conducted in a controlled environment (room temperature, 23°C, and 100% relative humidity). Therefore, they may not accurately reflect the performance of concrete placed and cured in a variable curing temperature of an outdoor environment during summer months.

Of all the factors having a direct influence on the performance of concrete, curing temperature is probably the most uncontrollable. Concrete cured at a higher summer temperature will gain strength initially at a faster rate than identical concrete cured at a lower temperature.

Though strength is gained faster at higher temperatures at an early age, such concretes will exhibit lower long-term strength than concrete cured at lower temperatures at an early age under controlled conditions (23±1°C) [1]. For normal-strength concrete with the 28-day compressive strength of 40 MPa or less, high curing temperatures accelerate the cement hydration

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reaction, while lower curing temperatures will retard the hydration reaction. In fact, when the temperature was increased by about 7°C, the hydration reaction rate was reported to increase by 100% [2]. Elevated curing temperatures affect hardened concrete in two ways. First, at the microscopic level, Calcium-Silicate-Hydrate (C-S-H) crystals grow quickly, although they are thin, long, and wide. These long, wide crystals are comparatively large, but do not occupy all the available pore space within the concrete matrix. Second, the elevated curing temperatures usually prompt a greater water loss due to evaporation, leaving unhydrated cementitious particles in the concrete matrix, as well as the voids which are created by the evaporated water and are not yet filled with C-S-H crystals. Therefore, the concrete cured at higher temperatures tends to exhibit a more porous microstructure. This leads to lower long-term concrete strength and decreases the ability of the concrete to resist penetration of harmful substances such as sulfate-bearing water, for example in the marine environment. So, even if desired strength levels are achieved, porosity alone may prove to be a source of a serious challenge to durability issue in concrete structures constructed under a hot-weather curing condition.

High-Performance Concrete (HPC) has become an attractive option compared to normal-strength concrete. HPC is a specialized concrete designed to provide several benefits in the construction of concrete structures. HPC offers high strength, better durability properties, and good construction. High strength is one of the important attributes of HPC [3].

The advancement of High-Strength Concrete (HSC) has affected nearly every area of concrete construction. Since high-strength concrete (higher than 40 MPa at the 28-day age [4]) is now generally readily obtainable, the application of HSC as a viable construction material is now well accepted. However, if HSC is to be the construction material for use in any condition, then other properties must also be achieved in addition to the strength [5]. Some of these properties include, but are not limited to, the following: resistance to expansion caused by sulfate and alkali-silica reaction, low permeability to air and water, resistance to cycles of freezing and thawing, as well as chloride-ion penetration.

HSC, with high durability, is sometimes referred to as High-Performance Concrete (HPC). Unlike normal-strength concretes, high-strength concretes must almost always employ supplementary cementitious materials, chemical admixtures, and improved mixture proportioning, and handling/placement techniques. HSC is believed to be a more "sensitive" material than traditional normal-strength concrete [6]. Therefore, additional care must be exercised for such concretes in mixture proportioning and construction, often leading to increased costs. Despite these costs, HSC has proved to be a very economical option for certain structural elements such as columns for high-rise buildings [7-9].

The first uses of HPC in the 1970s were indoor applications, mainly in columns in high-rise buildings, which are not subjected to a particularly severe environment. Outdoor applications of HPC date back to the late 1980s and early 1990s, which means that not enough time has passed to fully assess the real service life of HPC structures under outdoor conditions. But, based on the experience with ordinary concrete, one can assume that HPC is more durable than ordinary concrete. Indeed, the experience gained with ordinary concrete has shown that concrete durability is governed by concrete permeability and the harshness of the environment [5,10].

Permeability dictates the rate at which aggressive agents penetrate into the concrete, leading to various types of undesirable physical and/or chemical reactions. The aggressive agents include gases (CO_2, SO_x, and NO_x) and liquids (acid rain, salt-bearing water, sea water, sulfate-bearing water, snow and ice water, and river or lake flowing water). The primary variables influencing concrete permeability are water to cementitious materials ratio, quantities of supplementary cementitious materials, grading and size of aggregates, compaction of concrete, and curing [5,11].

Seawater is not a particularly harsh environment for plain concrete, but such a marine environment can be very harmful to reinforced concrete due to the multiplicity of aggression that it can face. Marine concrete structure is widely concerned about long-term serviceability. It is well known that the destruction of concrete structure in marine environment is mainly due to sulfate attack and the corrosion of steel under chloride attack [12]. In a marine environment, a concrete structure is mainly subjected to four types of aggressive factors [13]. They are as follows:

1. Chemical factors related to the presence of various ions dissolved in the seawater or transported in the wet air;
2. Geometrical factors related to the fluctuation of the sea level, waves, tides, storms, and other similar factors;
3. Physical forces such as freezing and thawing, scaling, wetting and drying, abrasion, and other similar factors;
4. Mechanical factors such as the kinetic action of the waves and the erosion caused by sand [11].

Most sea waters are more or less the same in composition, containing about 3.5% soluble salts (chlorides and sulfates) by mass. The pH of seawater varies from 7.5 to 8.4, averaging about 8.2 [11].

Concrete exposed to seawater may deteriorate from the combined effects of the following chemical and physical processes [14]: sulfate attack; leaching of lime (primarily and easily dissolvable calcium hydroxide) from the concrete; alkali-aggregate expansion; scaling and/or salt crystallization from alternate wetting and drying; freezing and thawing; corrosion of embedded reinforcing or pre-stressing steel; and erosion and abrasion from waves. Attack by most of these processes can be slowed by reducing the permeability of concrete. Low permeability helps keep aggressive chemicals out of the concrete, slows leaching of soluble materials such as lime, and limits the depth of carbonation, thereby protecting the reinforcing steel better from corrosion [14].

Marine concrete can be classified according to their exposure zones: submerged, splash, and atmospheric. The submerged zone is continuously covered by seawater, the splash zone is subject to continuous wetting and drying, and the atmospheric zone is above the splash zone and subject to occasional seawater spray [14]. Concrete in the submerged zone is not as vulnerable as concrete in the other two zones. Deterioration in any of these zones tends to make the concrete more porous and weak, making the concrete susceptible to more deterioration. Cracks, spalls, mortar erosion, and corrosion stains are the early visible signs of deterioration [14].

Seawater can be very harmful to reinforced concrete, because once the chloride ions reach reinforcing steel and steel corrosion occurs, it can result in a rapid spalling of the cover concrete. Consequently, it becomes easier for the chloride ions to reach the second level of reinforcing steel, etc. By specifying a very dense, impervious concrete and placing it correctly, and by increasing the thickness of the concrete cover, the corrosion of the steel can be either inhibited or delayed [13].

The compressive strength of high-strength high-performance concrete depends upon an efficient and judicious use of Other Cementitious Materials (OCM). These materials augment the chemical reactions produced by the portland cement and water. The result from OCM reactions is a tight, densely packed concrete matrix, which produces a strong bond between the aggregates and the cementitious binder. The most effective OCM, capable of producing significantly improved microstructure and compressive strength of the concrete, is silica fume. Experiments have shown that silica fume used as a replacement for portland cement at a level of about 10% seems to give optimum strength [15,16]. Unfortunately, silica fume is expensive and presents difficulties in traditional mixing and finishing techniques exacting added costs [17,18]. While the benefits of silica fume are fairly well known, they are often misunderstood. With regard to the usual porosity-strength relationship for plain concrete, a reduction in porosity cannot be directly correlated with the silica fume use. This is because porosity is a stronger function of the water-cementitious materials ratio [19]. Other sources [17,20] specifically indicate that water needed to achieve adequate workability may be the single most significant trouble area in high-strength concrete production. Therefore, the amount of water added to a concrete mixture is critical and must be carefully determined if one is to make use of the important benefits of the silica fume.

One of the more common methods of attaining improved strength concrete economically is to add fly ash to concrete mixtures. Fly ash is favorable for use in high-strength concrete, with or without silica fume, for reasons other than economics. As fly ash is added to the concrete mixture, slump increases [21,22]. Therefore, fly ash in silica-fume concrete also enhances workability while contributing to improved compressive strength development. High-calcium fly ash (ASTM C 618 designation Class C) is cementitious as well as pozzolanic. Therefore, it is able to supplement the performance of portland cement and combine it with calcium hydroxide, an important ingredient contributing to the hydration reaction. Studies have indicated that compressive strength values increase in mixtures containing Class C fly ash [5,23-26]. At cement replacement levels exceeding 45%, Class C fly ash may be responsible for reductions in very early-age compressive strength value. While fly ash increases workability of high-strength concrete with or without silica fume, the use of a High-Range Water-Reducing Admixture (HRWRA) is still indispensable for such concretes with silica fume. Fly ash was used to improve strength and durability of such concrete mixtures.

Sulfate attack on concrete can manifest itself through two distinct forms [10]. First, sulfate ingress may prompt concrete to undergo deleterious expansions, causing cracking or spalling. Second, sulfates can cause a progressive loss of mass and loss of strength of concrete. Whichever of these two deterioration processes is prevalent under a given set of circumstances depends upon the concentration and source of the sulfate ions. Calcium hydroxide and alumina-bearing phases of hydrated portland cement are particularly vulnerable to attack by sulfate ions. If the tricalcium aluminate content of the portland cement is greater than 8%, the hydration reaction may cause the development of an expansive form of sulfate [11]. This substance is known as ettringite $\{C3A + 3\ CaSO_4 \rightarrow \text{ettringite}\}$. Ettringite is a crystalline structure capable of swelling with the absorption of water.

It is well known and accepted that inclusion of Class F fly ash in concrete would increase the resistance of concrete to sulfate attack [27]. Based on extensive microscopic investigation of blended cement pastes containing several fly ashes, Mehta [28] reported that irrespective of the calcium content, it is the amount of reactive alumina contributed by a fly ash (from the dissolution of the aluminosilicate glass and hydration of crystalline compounds, such as C3A and C4A3S), which controls the presence of the minerals highly vulnerable to sulfate attack. Mehta [29] also found that some high-calcium fly ashes formed ettringite as a product of hydration. As a result, such fly ash may experience the expansion and strength loss due to sulfate exposure. Similar results, with regard to sulfate resistance of Class C fly ash in concrete, were obtained by Manz and McCarthy [30]. The increase of fly ash replacement in concrete clearly reduces the chloride penetration, chloride penetration coefficient, and steel corrosion in concrete [12].

2. Experimental program

The scope of this study involves two types of HPC mixtures: “production-grade (P)” and “experimental-grade (E)” HPC mixtures. A concrete mixture with proven capability to achieve strengths in excess of 70 MPa (10000 psi) was used as the control mixture, the production-grade mixture (Mixture 10P). In addition, a more cost-effective, experimental-grade concrete mixture (Mixture 10E) was also produced and tested.

2.1. Materials

ASTM C 150 Type I portland cement was used in this investigation. The fine aggregate used was natural sand. A crushed limestone with nominal maximum size of 19 mm was used as the coarse aggregate. ASTM C 618 Class C fly ash and ASTM C 1240 silica fume were used as mineral admixtures. ASTM C 494 High-Range Water-Reducing Admixture (HRWRA) was used. ASTM C 494 retarding admixture was used to permit placement and finishing of the concrete mixtures.

2.2. Mixture proportions

The proportions and fresh properties of the HPC mixtures used for this study are presented in Table 1. The concrete mixtures were proportioned to have the 56-day compressive strength of 69 MPa. Mixture 10P contained approximately 15% fly ash by mass of cementitious materials (cement + fly ash), and Mixture 10E contained 40% fly ash. Slump values of the concrete mixtures exceeded 200 mm.

2.3. Preparation of test specimens

From each concrete mixture, 100 mm × 200 mm cylindrical specimens were cast for compressive strength measurement. The specimens for sulfate-resistance test were 100 mm × 75 mm × 400 mm prisms. All specimens were cast in accordance with ASTM C 192 [31].

Table 1. Mixture proportions and fresh properties of concrete.

Mixture number	10P	10E
Cement (kg/m^3)	387	298
Fly ash, class C (kg/m^3)	71	201
Water (kg/m^3)	142	154
Sand, SSD (kg/m^3)	737	715
Crushed stone, 19 mm max., SSD (kg/m^3)	1010	1029
HRWRA (L/m^3)	2.79	2.83
Retarding admixture (L/m^3)	0.89	0.93
w/c	0.37	0.52
w/cm	0.31	0.31
Slump (mm)	216	241
Air content (%)	5.0	2.4
Density (kg/m^3)	2350	2400

2.4. Curing of specimens

After casting, all the molded specimens were covered with plastic sheets to minimize moisture loss due to evaporation. After 24 ± 8 hours, the specimens were demolded and transferred to a standard moist-curing room or a specially-designed curing unit.

Two types of curing environments were used to provide the necessary insight into the development of hardened HPC properties as a function of curing temperature. The first environment was the standard moist-curing in a moist room maintained at 23 ± 1°C temperature and 100% relative humidity. The second curing environment was an elevated Variable-Temperature Curing Environment (VTCE) to simulate hot-weather curing conditions. The average temperature of the VTCE was raised from about 30°C to 41°C in 8 hours and lowered from 41°C to 30°C in 16 hours, completing one cycle each day (Figure 1). The concrete specimens were wrapped and sealed in a plastic bag before placing them in the VTCE chamber in order to minimize moisture loss due to evaporation. The relative humidity of the VTCE chamber was found to vary between 35 and 85%.

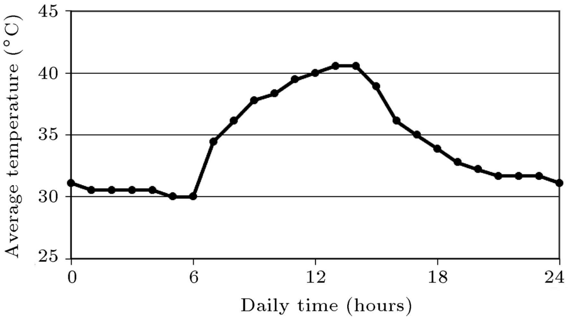

Figure 1. Recorded temperature for VTCE.

2.5. Testing of specimens

For each concrete mixture and curing environment, the compressive strength was determined for three cylinders (total 21 cylinders) at 3, 7, 28, 56, 91, 182, and 365 days of age in accordance with ASTM C 39. Upon obtaining the desired compressive-strength level of 69 MPa, prism specimens were immersed in a 10% sodium sulfate solution. The sulfate-resistance test specimens were tested for the change in dynamic modulus of elasticity to determine the soundness of concrete (ASTM C88). The sulfate-resistance test continued for a period of 420 days.

3. Test results and discussion

3.1. Compressive Strength

Compression test results of Mixtures 10P and 10E are presented in Figure 2 and Table 2. Mixture 10P exceeded the target 56-day compressive strength of 70 MPa. Both the normal moist-curing environment and VTCE did not produce significant differences in strength gains for Mixture 10P over the early curing period of 91 days. Beyond the 91-day age, the moist-cured 10P specimens showed almost constant strength with age, and the VTCE-cured 10P specimens showed a reduction in strength with age possibly due to desiccation of concrete. Accordingly, the coefficient of variation for 10P mixes was 3%, and the maximum coefficient of variations for 10E mixes was 5%. According to ACI 214 (Standards of Concrete Control) [32], a 5% maximum coefficient of variation is considered “fair” for laboratory trial batches. Values in excess of 5% are considered “poor”.

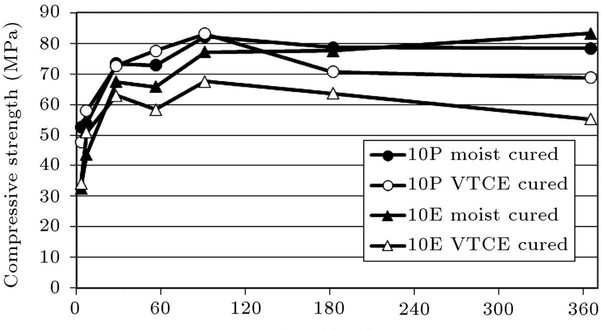

Figure 2. Compressive strength of concrete mixtures.

Table 2. Compressive strength of concrete mixtures (MPa).

Age (days)	10P moist cured	10P VTCE cured	10E moist cured	10E VTCE cured
3	52.5	47.8	32.6	34.1
7	53.7	58.0	43.7	50.9
28	73.3	72.7	67.4	63.0
56	72.8	77.6	65.8	58.4
91	82.1	83.1	77.2	67.6
182	78.6	70.7	77.6	63.7
365	78.3	68.7	83.3	55.2

Mixture 10E reached the 56-day strength of 66 MPa after moist curing and 58 MPa after curing in the VTCE. Moist-cured 10E specimens continued to gain strength with age, while the VTCE-cured 10E specimens showed a reduction in strength beyond the 91-day age.

If the relative humidity of the air surrounding the specimens in the VTCE had been 100%, the long-term strength of VTCE-cured 10P and 10E specimens might have been higher. Based on the strength results of the moist-cured specimens and the VTCE-cured specimens at the early age of up to about three months, it may be said that the elevated, variable curing temperature did not affect the compressive strength of concrete noticeably.

3.2. Sulfate resistance

Fundamental longitudinal frequencies of each concrete specimen were recorded at predetermined intervals per ASTM C215 [33]. These data were used to compute any change in dynamic modulus of the concrete occurring over the test period. Fundamental longitudinal frequencies of each concrete in Figure 3 and Table 3 present test results pertaining to the change in dynamic modulus versus the time of sulfate exposure. An increase in dynamic modulus implies an improvement in microstructure of the concrete. After storage in the sodium sulfate solution, both the moist-cured specimens and the VTCE-cured specimens showed considerable increase in the dynamic modulus. Study of Shah et al. [34] showed that nanoindentation along with imaging is a powerful technique to determine the mechanical properties of different phases of micro- and nano-structure of cement paste. Young's modulus of unhydrated cement particles and C-S-H gel was determined by Shah et al. Using the imaging capability of the nanoindenter tip made it possible to position

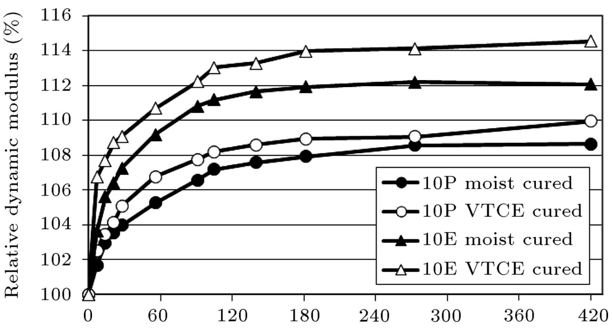

Figure 3. Change in dynamic modulus of concrete due to exposure to sulfate solution.

Table 3. Change in dynamic modulus of concrete due to exposure to sulfate solution.

Age (days)	10P moist cured (%)	10P VTCE cured (%)	10E moist cured (%)	10E VTCE cured (%)
7	101.68	102.52	103.63	106.73
14	102.94	103.44	105.59	107.7
21	103.54	104.13	106.41	108.71
28	103.97	105.08	107.26	109.07
56	105.25	106.77	109.17	110.69
91	106.56	107.74	110.8	112.22
105	107.17	108.19	111.18	113.04
140	107.57	108.58	111.64	113.29
182	107.92	108.93	111.92	113.97
273	108.56	109.06	112.2	114.12
420	108.63	109.94	112.06	114.55

the indenter exactly in the narrow region of Interfacial Transition Zone (ITZ) and perform nanoindentation to determine the local mechanical properties directly. It was found that the paste in the ITZ has, in general, a lower Young's modulus [34].

Moist-cured specimens of both 10P and 10E mixtures recorded somewhat lower values of the increase in the dynamic modulus than their VTCE-cured counterparts. The behavior of these specimens indicates that exposure to severe sulfate solutions would not result in the internal deterioration of this class of concrete, at least over the 420-day test period. It is, therefore, likely that the 70 MPa concrete tested was not susceptible to the formation of expansive ettringite as a result of the exposure to the sulfate solution.

4. Conclusions

Substantial differences in strength-gain behavior and long-term strengths between moist-cured specimens and VTCE-cured specimens were expected in the evaluation of curing temperature effects. The absence of these differences in this research indicates that efforts to stabilize curing temperatures may not be necessary to attain approximate moist-cured specimen strengths for concrete cured under summer-weather variable temperatures.

Specimen measurements involving changes in dynamic modulus were analyzed to illustrate the effects of sulfate attack and for differences in behavior between moist-cured specimens and VTCE-cured specimens. The effect of curing was insignificant on the sulfate resistance of the HPC mixtures tested in this investigation. The absence of any considerable differential behavior between identical concretes cured in different environments substantiates the conclusion that efforts to maintain normal curing temperatures are probably necessary to attain moist-cured levels of sulfate resistance for concrete cured under variable temperatures as long as moisture loss is minimized.

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Biographies

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Tarun R Naik, FACI, is an Emeritus Professor of Structural Engineering at the University of Wisconsin-Milwaukee and Former Research Professor and Academic Program Director of the UWM Center for By-Products Utilization. He was a member of ACI's Board Advisory Committee on Sustainable Development; and ACI Committees 123, Research and Current Developments; 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete; 229, Controlled Low-Strength Materials; 232, Fly Ash and Natural Pozzolans in Concrete; and 555, Concrete with Recycled Materials.