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Resistance to external sodium sulfate attack for early-opening-to-traffic Portland cement concrete

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Abstract

The results of a study on sulfate resistance of early opening-to-traffic concretes with accelerating admixture, also known as fast-track concretes (FTC), are presented. A total of 11 concretes made with four different cement factors and three different cement types were investigated at both opening and maturity (28 days) ages. Upon curing, the test samples were immersed in a 5% sodium sulfate solution. Length change, mass loss, and compressive strength were monitored for a period of 270 days to evaluate the performance of the test specimens exposed to severe sulfate attack. The influence of immersion period, curing age and cement type and factor on bulk characteristics and sulfate resistance were evaluated.

The study produced FTC with excellent sulfate resistance. Length change of FTC incorporating accelerating admixture increased with increasing immersion age and stabilized within 3 months from initial contact. No mass of concrete residues nor notable strength loss were found in any opening time fast track concretes used in the investigation.

Keywords: Fast track concrete; Accelerating admixture; Sulfate resistance; Gypsum; Ettringite; Strength; Curing; Opening time; Maturity

1. Introduction

Sulfate attack occurs when components of cement paste come into contact with sulfate ions introduced from external sources into the matrix. The result is a chemical reaction that can have detrimental effects on the concrete. Sulfates are found in a variety of sources. Groundwater, high clay-content soils, seawater, organic materials in marshes, mining pits, and sewer pipes all have potential to contain sulfates. Common sulfates include calcium, magnesium, sodium, potassium, and ammonium [1].

There are two ways in which sulfate attack can compromise the integrity of concrete: expansion of the cement matrix, and progressive loss of strength and mass [2]. Expansion due to sulfate attack is a three-step process. First, ettringite forms in the cement matrix from the result of reactions between the tricalcium aluminate in the Portland cement and sulfate ions from internal or external sources or both. More specifically, calcium sulfate dihydrate (gypsum) combines with C_3A to form 6-calcium aluminate trisulfate hydrate (ettringite) [1]. The reaction is shown below:

$$\underset{C_3A}{\underset{\uparrow}{3CaO * Al_2O_3}} + 3(\underset{\text{Gypsum}}{\underset{\uparrow}{CaSO_4 * 2H_2O}}) + 26H_2O$$
$$\rightarrow 3CaO * Al_2O_3 * \underset{\text{Ettringite }(C_6AS_3H_{32})}{\underset{\uparrow}{3CaSO_4}} * 32H_2O$$

Next, monosulfoaluminate is formed. Specifically, sulfate ions from the ettringite react with the remaining C_3A to form tetracalcium aluminate monosulfate-12-hydrate

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(monosulfoaluminate) [4]. The chemical reaction is given below:

$$2(3CaO * Al_2O_3) + 3CaO * Al_2O_3 * 3CaSO_4 * 32H_2O + 4H_2O \rightarrow 3(\underset{\substack{\uparrow \\ \text{Monosulfoaluminate}}}{4CaO * Al_2O_3 * SO_3} * 12H_2O)$$

In the third step, ettringite is formed again when the monosulfoaluminate is brought into contact with a new source of sulfate ions [1]. This reaction is shown below:

$$4CaO * Al_2O_3 * SO_3 * 12H_2O + 2(CaSO_4 * H_2O) + 16H_2O \rightarrow \underset{\substack{\uparrow \\ \text{Ettringite}}}{3CaO * Al_2O_3 * 3CaSO_4} * 32H_2O$$

The continued formation of ettringite within confined solids causes significant internal pressure leading to expansion and cracking [1].

Progressive loss of strength and mass occurs when concrete is exposed to external sources of highly concentrated sodium sulfate (Na_2SO_4) or magnesium sulfate ($MgSO_4$). Calcium hydroxide from the cementitious material reacts with sulfate ions to form gypsum [1]. The two reactions with sodium sulfate and magnesium sulfate are shown below:

$$Na_2SO_4 + Ca(OH)_2 + 2H_2O \rightarrow \text{Gypsum} + 2NaOH$$
$$Mg_2SO_4 + Ca(OH)_2 + 2H_2O \rightarrow \text{Gypsum} + Mg(OH)_2$$

When magnesium sulfate attack occurs, the deterioration of the concrete is further enhanced by the decomposition of calcium silicate hydrate to hydrated magnesium silicate, which has no binding properties [1]. This reaction is shown below:

$$3MgSO_4 + 3CaO * 2SiO_2 * 3H_2O + 8H_2O \rightarrow 3Mg(OH)_2 + 2SiO_2 * H_2O$$

The extent of sulfate attack is also dependent on the quantity of the liberated hydrolyzed calcium-containing compounds of Portland cement. The continued hydrolysis of cement paste produces an environment in which most of the calcium hydroxide is leached away, thus exposing the other cementitious materials to chemical decomposition. The process eventually results in loss of strength of Portland cement paste [3].

Cement's constituents also play a major role in sulfate vulnerability. The amount of C_3A is an indicator as to how much ettringite can form. To limit potential expansion due to sulfate attack, the amount of C_3A should be restricted [1].

While concretes with air-entrainment perform much better against sulfate attack than concretes without air entrainment, perhaps the most important factor affecting expansion due to sulfate attack is permeability. Permeability controls the rate of diffusion of sulfate ions into the concrete. Reducing the amount of sulfate in the pore structure reduces reactions with C_3A and calcium hydroxide. Low permeability may be attained by using a low water-to-cementitious materials ratio and proper compaction [1].

The use of accelerating admixtures (i.e., calcium chloride, $CaCl_2$) can also influence the ability to resist sulfate attack [2]. The use of calcium chloride in Portland Cements has been shown to increase strength as far out as 28 days compared to concretes without $CaCl_2^4$. However, in situations where the durability of concrete may be compromised by external sources such as sulfate, the use of calcium chloride is cautioned [5].

Sulfate attack is difficult to measure. The main problem in assessing concrete's resistance to practical levels of sulfate is that deterioration may not occur in a reasonable amount of time. For this reason, the rate of sulfate attack is accelerated in the laboratory. Techniques used in short-term methods of testing include increasing the reactive surface, using highly concentrated solutions, percolating the attacking solution, and raising the temperature of the aggressive medium. Laboratory tests are not very accurate at predicting the service life of concrete in a sulfate-rich environment. Rather, the tests are more applicable in comparing the relative performances of different concrete mixtures [1].

There is no universally accepted criterion for measuring failure of laboratory specimens exposed to sulfate. Common methods of evaluation include strength loss, change in dynamic modulus of elasticity, expansion, loss of mass, and visual inspection. Miller and Manson proposed a 0.02% expansion limit to classify failure of specimens exposed to a 1% solution of sodium sulfate [6]. Stark devised a visual rating scale for evaluation of concrete. Ratings were based on a scale of 1.0–6.0, with the upper limits indicating failure [7]. Mehta based an evaluation on strength loss, a drop of more than 25% indicating failure [2]. Other failure criteria have been proposed, each based on different variables such as type of specimen and type of exposure.

2. Background on early-opening-to-traffic concrete

The development of fast-track concrete (FTC) grew out of the need for engineers and material scientists to devise a way to reduce congestion and public dissatisfaction as it pertained to roadway construction and repair. The result was a material capable of being placed and opened to the traveling public in the same day.

Fast-track concrete has been demonstrated to meet opening-time strength requirements in less than 24 h and occasionally in as little as 4 h. This requires a high rate of early strength gain obtained by using cements with high tricalcium silicate and tricalcium aluminate contents, high cement content, low water-to-cement ratio, and accelerating admixtures [8].

An important feature in FTC is the curing methods employed to aid in the development of early strength. The most commonly used curing method involves the application of curing compounds and placement of insulating blankets. Curing compounds, in conjunction with the use of curing blankets, enable the concrete to retain the heat of hydration and promote the rapid gain of strength [9].

The first major application of fast-track concrete occurred in Iowa in 1986 [10]. Since then, a variety of placement methods, mixture proportions, and curing methods have been used. Other states using FTC technology include Colorado, Kansas, Michigan, Montana, Nebraska, North Carolina, Pennsylvania, Virginia, Wyoming, and Wisconsin [11].

3. Scope of the work

The scope of the investigation was to determine the behavior of laboratory-made fast-track concretes incorporating accelerating admixture in a severe sulfate-rich environment. A large number of specimens were cast, cured in insulating boxes for the designated opening ages, immersed in a 5% sodium sulfate solution, and tested to generate and analyze specific data on the sulfate resistance of opening-time and mature (28-day moist cured) fast-track concretes. The influences of cement type and factor, immersion period, and curing age on resistance to sulfate attack were also examined. The fresh properties included slump, air content, bleeding, setting times, and adiabatic temperature. The bulk characteristics of interest included demolded unit weight and compressive strength. Sulfate durability was ascertained through linear expansion, mass loss, and reduction in strength.

4. Experimental program

4.1. Raw materials and proportions

The matrix constituents used in the investigation included cementitious binder of ASTM Types I, III, and V, siliceous fine aggregate, crushed limestone coarse aggregate, chemical admixtures, and tap water. The three cement types had an average specific gravity of 3.15. The chemical properties of the Portland cements are shown in Table 1. The fine aggregate (fineness modulus of 2.56, oven-dry specific gravity of 2.6, saturated surface-dry specific gravity of 2.63, and absorption of 1.10) had a well-graded size distribution with particles that were dense, smooth in texture, and rounded in shape. The crushed limestone coarse aggregate (nominal maximum size of 19 mm) had an oven dry specific gravity, saturated surface dry specific gravity, absorption, and unit weight of 2.64%, 2.67%, and 1.20%, and 1567 kg/m^3, respectively. Both fine and coarse aggregates satisfied ASTM C33 gradation requirements.

The mixing tap water used throughout the investigation was pre-heated to a temperature of 49 ± 1 °C. High range water-reducer and air-entraining admixtures were used to achieve the desired workability and air content, respectively. To enhance early opening-time strengths, an accelerator, namely calcium chloride ($CaCl_2$), was used in all trial mixtures.

Table 1
Chemical composition of Portland cements

Chemical compositions	Type I Portland cement (%)	Type III Portland cement (%)	Type V Portland cement (%)
Silicon dioxide (SiO_2)	21.88	20.61	22.02
Aluminum oxide (Al_2O_3)	4.37	5.67	3.90
Ferric oxide (Fe_2O_3)	2.84	2.33	4.58
Calcium oxide (CaO)	62.62	64.62	64.17
Magnesium oxide (MgO)	4.50	0.94	2.00
Sulfur trioxide (SO_3)	2.70	3.46	2.15
Loss on ignition	1.10	1.60	0.50
Tricalcium silicate (C_3S)	49.90	55.00	58.00
Dicalcium silicate (C_2S)	27.00	17.00	21.70
Tricalcium aluminate (C_3A)	6.90	11.00	2.90
Tetracalcium alumino-ferite (C_4AF)	8.64	7.00	13.90
Available alkalis as Na_2O	0.55	0.69	0.43

The dry quantities of the concrete constituents and water-to-binder ratio are shown in Table 2. Four cement factors, namely: 386, 446, 505, and 564 kg/m^3 were used. Based on the physical properties and gradations of the coarse and fine aggregates, a uniform coarse aggregate weight of 1059 kg/m^3 was found suitable for the selected concretes. Water-to-cement ratios raging from 0.325 to 0.4 were used. The quantity of the water-reducer used was determined by various trials until the desired slump of 127 ± 6 mm was attained. Similarly, various amounts of the air-entraining admixture were used to achieve $6 \pm 1\%$ by volume air content for the freshly mixed matrices. All concretes contained an accelerator by 2% weight of Portland cement.

4.2. Opening-to-traffic time

A minimum compressive strength of 20.7 MPa, corresponding to a flexural strength of 4.5 MPa at opening-time, was required for all fast track concretes used in the investigation.

4.3. Casting and curing

Two types of laboratory-made FTC specimens were used in the investigation, namely: $102 \times 102 \times 356$ mm prisms and 102×204 mm cylinders. A total of six beams

Table 2
Mixture constituents of fast-track concretes (kg/m^3)

Mixture type	Cement content (kg/m^3)	Actual water (kg/m^3)	Designed w/c	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Chemical admixtures	
						WRDA-19 (kg/m^3)	Daravair (kg/m^3)
I-386 AA	386	131	0.350	729	1059	7.62	0.11
I-446 AA	446	153	0.350	627	1059	4.21	0.62
I-505 AA	505	173	0.350	525	1059	3.99	1.76
I-564 AA	564	179	0.325	458	1059	4.46	1.96
III-386 AA	386	151	0.400	679	1059	5.18	0.81
III-446 AA	446	175	0.400	569	1059	4.57	1.55
III-505 AA	505	185	0.375	492	1059	5.58	1.76
V-386 AA	386	131	0.350	729	1059	13.42	0.14
V-446 AA	446	153	0.350	627	1059	8.44	0.62
V-505 AA	505	173	0.350	525	1059	8.80	1.76
V-564 AA	554	179	0.325	458	1059	11.63	2.74

and nine cylinders were cast for each mixture in accordance to ASTM C 31 and cured in insulating boxes for a pre-designated period of time sufficient to attain the above-noted minimum opening-time compressive strength. The insulation boxes were made of styrofoam with an internal insulation blanket having an "R" value of 2.45×10^{-5} h m^2 °C/J. The amount of curing time was dependent on the opening-time classification of the fast-track concretes. Upon removal from the insulation boxes, each cylinder was weighed, and each prism was measured to determine its initial length. Half the specimens were placed directly in a 5% sulfate solution, and the remainder were placed in a lime saturated water tank at a temperature of 23 ± 2 °C for a period of 28 days prior to being immersed in a 5% sulfate solution. The volumetric ratio of sulfate solution-to-concrete was kept constant at 3.0. When the sulfate content dropped to a level of roughly 32,000 ppm, the old solution was replaced with a fresh 5% sulfate solution. This occurred every 3–4 months. The immersion age of all test specimens was kept uniform for a period of 9 months.

4.4. Testing procedure

The slump, air content, and setting times of freshly mixed fast-track concretes were measured using ASTM C 143, ASTM C 231, and ASTM C 403, respectively. The unit weight and compressive strength of the cylindrical samples were obtained using ASTM C 138 and ASTM C 39, respectively. Length change at different immersion ages was calculated using ASTM C 1012.

5. Results and discussion

5.1. Fresh properties

Fresh properties of the trial fast-track concretes are shown in Table 3. A uniform slump of 127 ± 6 mm was achieved by using various dosages of the water-reducing admixture. Similarly, different dosage rates of the air-entrainer were used to attain the target air content of $6 \pm 1\%$. The maximum dosage rate of the air-entrainer was limited to 142 ml per 45 kg of Portland cement to avoid extreme dosages that were not practical.

In examination of the matrix constituents and proportions, no bleeding was observed in any of the selected fast rack concretes.

The setting times of the trial matrices were investigated and the results are shown in Table 3. For mixtures of the same cement type, Type III concretes had initial set times lower than Type I and Type V by 21% and 22%, respectively. Type III concretes also had final setting times shorter than Type I and Type V by 20% and 24%, respectively. This can be attributed to the chemical compositions of the different types of cement. Type III cements have a higher percentage of C_3A, the chemical responsible for early strength gain and subsequently faster setting times. For concretes of the same cement factor, those with higher cement contents had initial and final set times lower than those with lower cement contents. Increases in cement content of 60 kg/m^3 from 386–446 to 505–564 kg/m^3 reduced initial set times by 20%, 6%, and 15% respectively. For the same increases in cement content, final setting times were reduced by 19%, 10%, and 15%, respectively.

The results for the adiabatic temperature of the selected fast-track concretes are documented in Table 3. Freshly mixed temperatures had little variation, ranging from 28 to 32 °C. The peak temperatures reached during the insulated curing period ranged from 48 to 69 °C. On average, Type III cements reached higher peak temperatures than Type I and Type V by 20% and 27%, respectively. Moreover, Type III cements reached their peak temperatures faster than Type I and Type V by 28% and 29%, respectively. Additionally, concretes with a higher cement contents produced higher peak temperatures when compared to the mixtures of lower cement contents. On average, peak temperatures increased 3.6 °C for each 60 kg/m^3 increase in cement factor, whereas the time to reach the peak temperature reduced by an average of 0.9 h for each 60 kg/m^3 increase in cement content.

Table 3
Fresh characteristics of fast-track concretes

Mixture type	Opening time (h)	Slump (mm)	Measured air content (%)	Initial time of setting (h)	Final time of setting (h)	Freshly mixed temperature (°C)	Peak temperature (°C)	Time to peak (h)
I-386 AA	8	121	6.50	5.47	6.21	28	48	12.00
I-446 AA	8	127	5.50	3.03	3.82	29	52	9.38
I-505 AA	8	127	4.90	2.81	3.52	31	55	9.25
I-564 AA	8	121	4.90	2.58	3.13	32	59	9.00
III-386 AA	6	127	6.50	2.91	3.61	28	59	9.25
III-446 AA	6	133	4.40	2.73	3.28	29	64	8.38
III-505 AA	6	133	4.50	2.56	2.93	32	69	8.25
V-386 AA	8	114	5.40	4.38	5.75	29	46	13.00
V-446 AA	8	127	5.00	3.50	4.20	31	48	11.78
V-505 AA	8	127	4.60	3.15	3.85	32	53	10.50
V-564 AA	8	121	5.10	2.70	3.43	32	54	9.75

5.2. Ettringite-based expansion

Table 4 presents the sulfate expansion test results for all trial mixtures at various immersions and curing ages. The discussion of the ettringite-based expansion pertaining to the influence of immersion age, cement factor, and cement type is devoted to the results obtained for the opening-time specimens. The impact of curing age on sulfate expansion of the opening-time and 28-day cured samples is also discussed.

5.2.1. Influence of immersion age

A total of 21 length-comparator readings were taken on each specimen during the 9-month immersion in the sodium sulfate solution. A typical average linear expansion as a function of immersion age is shown in Fig. 1 for the opening-time fast-track concretes containing 505 kg/m^3 cement factor. The graph displayed is representative of the expansion behavior for the mixtures of all cement factors, i.e., the rate of expansion was highest during the first 12–15 weeks of submersion, and then slowly leveled off during the last two-thirds of the immersion period. For Type V, Type I, and Type III concretes displayed in Fig. 1, after just 12 weeks of immersion, each had reached 79%, 80%, and 77% of their ultimate 9-month expansion, respectively. While Fig. 1 exhibits, in detail, the expansion rates for opening-time mixtures of three distinct cement types all containing the same cement factor, Fig. 2 displays the rate of expansion for all trial opening-time FTC for the immersion period of 0.5, 1, 3, 6, and 9 months. As can be seen, the average expansion rate decreased steadily over time. After the first month of sulfate exposure, the rates of expansion (given as percentage of total expansion) for Type I, III, and V matrices were approximately 48%, 43%, and 47%, respectively. During the next 2 months of immersion, from 1 to 3 months, the Type I, III, and V mixtures expanded an additional length equal to 31%, 34%, and 33%, respectively, of their ultimate 9-month expansions. During the last 6 months of immersion, the additional lengths expanded were just 20%, 23%, and 21%, respectively, of the ultimate 9-month expansions for each cement type. The steady decrease in the rate of expansion may be explained by (1) continued conversion of the C_3A to ettringite compound and (2) the buildup of sulfate reaction by-products, which typically occupy a greater volume than the compounds they replace, within the pores of the test specimens. The latter process can effectively lower the permeability of the pore structures, thus restricting further permeation of the sulfate ions and limiting the potential expansion.

Table 4
Linear expansion of fast-track concretes (opening-time and 28-day curing)

Mixture type	Linear expansion (%)									
	Immersion age (months)									
	0.5		1		3		6		9	
	OT	28 days	OT	28 days	OT	28 days	OT	28 days	OT	28 days
I-386 AA	0.005758	0.005152	0.009394	0.007879	0.017273	0.013636	0.019697	0.015758	0.021212	0.016061
I-446 AA	0.005758	0.003939	0.008485	0.006364	0.013636	0.011212	0.015758	0.014545	0.017273	0.013939
I-505 AA	0.004848	0.004848	0.007576	0.007576	0.012424	0.011515	0.014545	0.010909	0.015455	0.012727
I-564 AA	0.004242	0.003636	0.006364	0.006061	0.009091	0.008788	0.010909	0.022727	0.011818	0.010000
III-386 AA	0.005758	0.005152	0.010000	0.009091	0.018485	0.016667	0.022727	0.020606	0.024545	0.019697
III-446 AA	0.005758	0.005152	0.009697	0.008788	0.017879	0.015455	0.020606	0.016364	0.022424	0.018485
III-505 AA	0.005152	0.004242	0.008182	0.006364	0.013333	0.011212	0.016364	0.015455	0.017879	0.014515
V-386 AA	0.003333	0.00303	0.005152	0.003939	0.009091	0.006970	0.011212	0.011212	0.011818	0.008788
V-446 AA	0.00303	0.00303	0.004545	0.004545	0.007879	0.006970	0.009394	0.009394	0.010000	0.008182
V-505 AA	0.002727	0.002424	0.003939	0.003333	0.006667	0.005455	0.007576	0.007576	0.008182	0.006667
V-564 AA	0.002424	0.002121	0.003636	0.002727	0.005758	0.004848	0.006970	0.006970	0.007273	0.005455

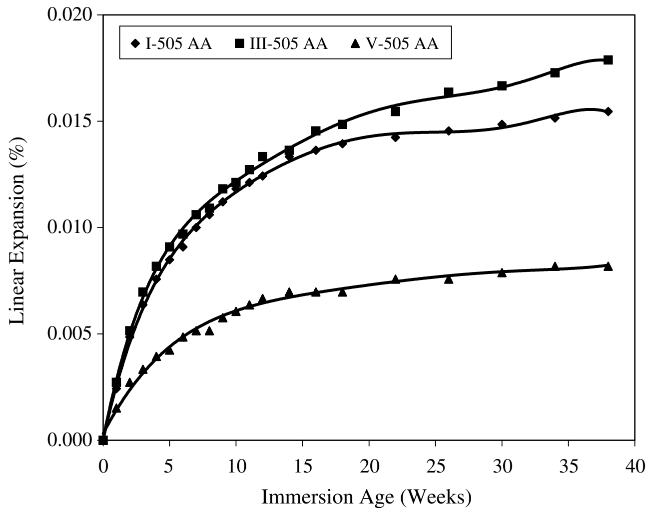

Fig. 1. Linear expansion of fast-track concretes (opening-time): effect of immersion age.

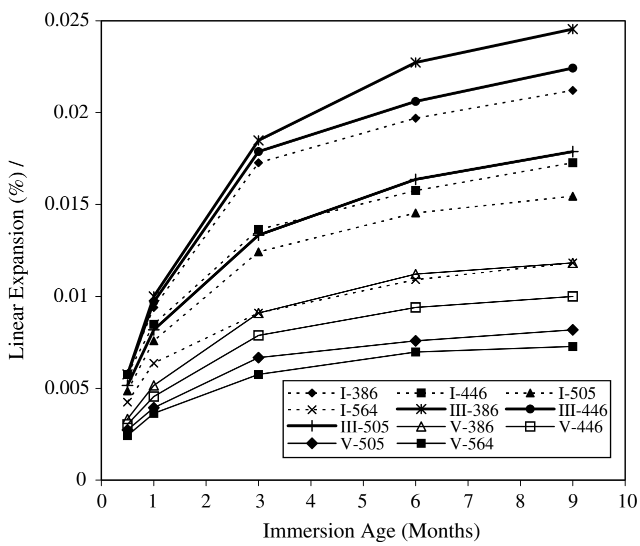

Fig. 2. Linear expansion (up to 9 months) of fast-track concretes.

A statistical program was used to determine the best-fit predictive equations for sodium sulfate expansion test results. Analyses were conducted at 95% confidence level. The predictive equations were tested for accuracy using R^2 (the coefficient of multiple determination) and S (average standard deviation). Correlations between the data predicted from the regression equations and the actual results obtained from expansion test results were evaluated using F and T tests.

The relationship between the sodium sulfate expansion and the immersion age is as follows:

$$\text{Type I cement:}\quad (\text{SExp})_{\text{OT}} = \frac{0.0186\text{IA}}{\text{IA}_{\text{w}} + 5.301} \tag{1}$$

$$\text{Type III cement:}\quad (\text{SExp})_{\text{OT}} = \frac{0.0253\text{IA}}{\text{IA}_{\text{w}} + 6.723} \tag{2}$$

$$\text{Type V cement:}\quad (\text{SExp})_{\text{OT}} = \frac{0.0109\text{IA}}{\text{IA}_{\text{w}} + 6.364} \tag{3}$$

where $(\text{SExp})_{\text{OT}}$ = sulfate expansion at opening-time (%); IA_{w} = immersion age (week).

The regression variables R^2, S, Prob(t) and Prob(F) are given in Table 6. The calculated values are indicative of a strong relationship between the dependent variable (beam expansion) and the independent variable (immersion age) for all three cement types.

5.2.2. *Influence of cement factor*

The influence of cement factor on sulfate-induced expansion of opening-time fast-track concretes was also examined and the results are documented in Fig. 3. As can be seen, for mixtures of the same type, average linear expansion decreases with increases in cement factor. Using the 386 kg/m^3 cement factor as the basis for comparison, on average, opening-time fast-track concretes with cement factors of 446, 505, and 564 kg/m^3 expanded 14%, 28%, and 41% less, respectively. For Type I mixtures, as the cement factor was increased from 386 to 446, 505, and 564 kg/m^3, the reduction in expansion was 19%, 27%, and 44%, respectively. For Type V concretes, the reductions in linear expansion were 15%, 31%, and 38%, respectively. For opening-time FTC containing Type III cement, an increase in cement factor from 386 to 446 and 505 kg/m^3 resulted in roughly 9% and 27% less expansion, respectively. The preceding trends suggest that the increase in cement content results in a decrease of expansion, although sufficient differences in expansion exist among different cement types. Based on the chemistry of the reactions, concretes with higher cement content, which also contain a greater amount of C_3A (by mass), are potentially more vulnerable to external sulfate attack by producing more ettringite. The fact that this did not occur suggests that the paste quality, and its effect on permeability and strength, is the main deterrent to expansion caused by

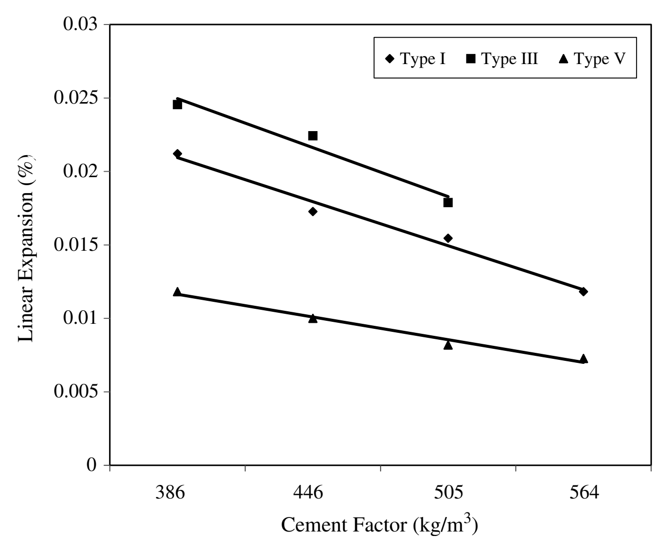

Fig. 3. 9-Month linear expansion of fast-track concretes (opening-time): effect of cement factor.

sulfate reactions. Fast-track concretes with higher cement contents contain a smaller void structure and are thus more effective in restricting the infiltration of the sulfate solution. Additionally, the improved paste quality also offers greater resistance to the internal pressure induced by the accumulation of reaction by-products, thereby limiting potential sulfate expansion.

The best-fit predictive equation defining the relationship between the sodium sulfate expansion and the cement content is as follows:

$$\text{Type I cement: } (\text{SExp}_u)_{OT} = 0.01486 - 3.77 \times 10^{-11}\text{CF}^3 + \frac{1247.69}{\text{CF}^2} \quad (4)$$

$$\text{Type III cement: } (\text{SExp}_u)_{OT} = 0.03027 - 9.44 \times 10^{-11}\text{CF}^3 \quad (5)$$

$$\text{Type V cement: } (\text{SExp}_u)_{OT} = 0.02066 - 8.90 \times 10^{-9}\text{CF}^{2.5} + 3.00 \times 10^{-10}\text{CF}^3 \quad (6)$$

where $(\text{SExp}_u)_{OT}$ = 9-month sulfate expansion at opening-time (%); CF = cement factor (kg/m^3), with 386 kg/m^3 $\leqslant$ CF $\leqslant$ 564 kg/m^3.

The regression variables R^2, S, Prob(t) and Prob(F) are given in Table 6. The calculated values are indicative of a strong relationship between the dependent variable (ultimate beam expansion) and the independent variable (cement factor) for all three cement types.

5.2.3. *Influence of cement type*

The influence of cement type on the linear expansion of opening age samples is shown in Fig. 4. For mixtures of the same cement factor, Type V mixtures performed the best in their ability to resist expansion due to ettringite formation, followed by Type I and Type III. Using Type I FTC as the basis for comparison, on average, Type III mixtures expanded 31% more, while Type V mixtures expanded 43% less. On average, Type III mixtures expanded 2.3 times that of Type V mixtures. This trend can be explained by the chemical composition of each cement type. Type V cements, designed specifically to resist ettringite-induced expansion, contain a smaller amount (less than 5%) of tricalcium aluminate which gives it the ability to resist expansion [3]. Type III groups, designed specifically for early strength gain; contain more tricalcium aluminate which increases its vulnerability to expansion. Type I FTC is chemically similar to Type III matrices, but is not ground as fine, thus reducing the rate of expansion by ettringite attack.

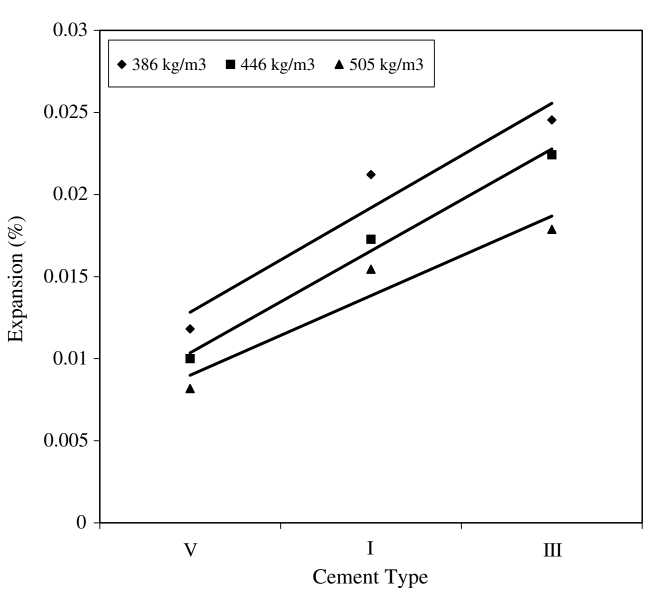

Fig. 4. 9-Month linear expansion of fast-track concretes (opening-time): effect of cement type.

The beams expansion due to 5% sodium sulfate attack was also evaluated under the combined action of immersion age and cement factor. The following expressions were found:

Type I cement

$$(\text{SExp})_{OT} = -0.311 - 2.351 \times 10^{-4}\text{IA}_w + \frac{453.830}{\text{CF}} - 3.912 \times 10^{-5}\text{IA}_w^2 - \frac{200,837.529}{\text{CF}^2} + 1.027\frac{\text{IA}}{\text{CF}} + 9.831 \times 10^{-7}\text{IA}_w^3 + \frac{30,596,154.498}{\text{CF}^3} - 52.078\frac{\text{IA}_w}{\text{CF}^2} - 1.528 \times 10^{-2}\frac{\text{IA}_w^2}{\text{CF}} \quad (7)$$

Type III cement

$$(\text{SExp})_{OT} = -0.050 + 3.045 \times 10^{-3}\text{IA}_w - 2.296 \times 10^{-4}\text{IA}_w^2 + 9.643 \times 10^{-6}\text{IA}_w^3 - 2.066 \times 10^{-7}\text{IA}_w^4 + 1.756 \times 10^{-9}\text{IA}_w^5 + 2.679 \times 10^{-4}\text{CF} - 3.414 \times 10^{-7}\text{CF}^2 \quad (8)$$

Type V cement

$$(\text{SExp})_{OT} = -0.071 + 2.226 \times 10^{-3}\text{IA}_w + 4.651 \times 10^{-4}\text{CF} - 4.667 \times 10^{-5}\text{IA}_w^2 - 9.849 \times 10^{-7}\text{CF}^2 - 4.035 \times 10^{-6}\text{IA}_w\text{CF} + 4.271 \times 10^{-7}\text{IA}_w^3 + 6.861 \times 10^{-10}\text{CF}^3 + 2.477 \times 10^{-9}\text{IA}_w\text{CF}^2 + 2.810 \times 10^{-8}\text{IA}_w^2\text{CF} \quad (9)$$

where $(\text{SExp})_{OT}$ = sulfate expansion at opening-time (%); IA_w = immersion age (week); CF = cement factor (kg/m^3), with 386 kg/m^3 $\leqslant$ CF $\leqslant$ 564 kg/m^3. The regression variables R^2, S, Prob(t) and Prob(F) are given in Table 6. The calculated values are indicative of a good relationship between the dependent variable (beam expansion) and the independent variables (immersion age and cement factor) for all three cement types.

5.2.4. Influence of curing age

To gauge the influence of the curing age on sulfate expansion, additional FTC prisms were allowed to be water-cured for 28 days, immediately after the designated blanket curing time, prior to the placement into a 5% sulfate solution. The results are shown in Table 4. On average, the expansion of opening-time fast-track concretes was roughly 1.3 times that of the 28-day mixtures. The above-mentioned behavior can be attributed to the improved paste quality, resulting in an enhanced impermeability and increased tensile strength for the trial fast-track concretes.

The relationship between expansion at 28 days and the expansion at opening-time for various immersion ages and cement factors is as follows:

Type I cement

$$(\mathrm{SExp})_{28} = 0.796(\mathrm{SExp})_{\mathrm{OT}} + 9.728 \times 10^{-5}\mathrm{IA_m} + 1.832 \times 10^{-5}\mathrm{CF} - 7.937 \times 10^{-3} \quad (10)$$

Type III cement

$$(\mathrm{SExp})_{28} = 0.911(\mathrm{SExp})_{\mathrm{OT}} - 1.922 \times 10^{-4}\mathrm{IA_m} - 1.099 \times 10^{-6}\mathrm{CF} + 4.271 \times 10^{-4} \quad (11)$$

Type V cement

$$(\mathrm{SExp})_{28} = 0.978(\mathrm{SExp})_{\mathrm{OT}} - 1.119 \times 10^{-4}\mathrm{IA_m} + 2.112 \times 10^{-6}\mathrm{CF} - 1.276 \times 10^{-3} \quad (12)$$

where $(\mathrm{SExp})_{28}$ = sulfate expansion at 28 day (%); $(\mathrm{SExp})_{\mathrm{OT}}$ = sulfate expansion at opening-time (%); CF = cement factor (kg/m^3), with $386\ \mathrm{kg/m^3} \leqslant \mathrm{CF} \leqslant 564\ \mathrm{kg/m^3}$; $\mathrm{IA_m}$ = immersion age (month). The regression variables R^2, S, Prob(t) and Prob(F) are given in Table 5. The calculated values are indicative of a good relationship between the dependent variable (beam expansion at 28 day) and the independent variables (beam expansion at opening-time, immersion age, and cement factor) for all three cement types.

5.3. Gypsum-based strength reduction and mass loss

In addition to expansion, loss of mass and reduction in strength resulting from gypsum formation were also monitored. After 9 months exposure to a sulfate-rich environment, no material residue was collected and the FTC samples were in the same condition as the beginning of the test, indicating little or no softening. Table 6 highlights the compressive strength data for the opening-time

Table 5
Statistical regressions variables

Equation	Description	Coefficient of multiple determination, R^2 (%)	Standard deviation, S (%)	Prob(t)	Prob(F)
(1)	Influence of immersion age on sulfate expansion, Type I cement	99.8	$1.8.1 \times 10^{-4}$	0.00	0.00
(2)	Influence of immersion age on sulfate expansion, Type III cement	99.9	1.9×10^{-4}	0.00	0.00
(3)	Influence of immersion age on sulfate expansion, Type V cement	99.7	1.4×10^{-5}	0.00	0.00
(4)	Influence of cement factor on sulfate expansion, Type I cement	98.6	7.9×10^{-4}	<0.45	0.12
(5)	Influence of cement factor on sulfate expansion, Type III cement	98.2	6.5×10^{-4}	<0.09	0.09
(6)	Influence of cement factor on sulfate expansion, Type V cement	99.8	1.6×10^{-4}	<0.13	0.05
(7)	Influence of immersion age and cement factor on sulfate expansion, Type I cement	98.2	7.2×10^{-4}	<0.02	0.00
(8)	Influence of immersion age and cement factor on sulfate expansion, Type III cement	97.6	1.04×10^{-4}	<0.16	0.00
(9)	Influence of immersion age and cement factor on sulfate expansion, Type V cement	98.7	3.3×10^{-4}	<0.01	0.00
(10)	$\mathrm{Expansion_{(28)}}$ vs. $\mathrm{expansion_{(OT)}}$, immersion age and cement factor, Type I cement	66.0	3.1×10^{-3}	<0.394	0.000
(11)	$\mathrm{Expansion_{(28)}}$ vs. $\mathrm{expansion_{(OT)}}$, immersion age and cement factor, Type III cement	98.3	8.4×10^{-4}	<0.879	0.000
(12)	$\mathrm{Expansion_{(28)}}$ vs. $\mathrm{expansion_{(OT)}}$, immersion age and cement factor, Type V cement	91.8	8.1×10^{-4}	<0.581	0.000
(13)	Expansion vs. compressive strength for OT	82.8	4.5×10^{-3}	<0.171	0.296
(14)	Influence of water-cured and sulfate immersed compressive strength on sulfate expansion for OT	99.9	7.6×10^{-5}	<0.041	0.009
(15)	Influence of compressive strength and cement factor on sulfate expansion for OT	99.1	1.8×10^{-3}	<0.153	0.225
(16)	Expansion vs. compressive strength for 28 days	79.5	3.9×10^{-3}	<0.000	0.365
(17)	Influence of water-cured and sulfate immersed compressive strength on sulfate expansion for 28 days	99.7	8.1×10^{-4}	<0.225	0.125
(18)	Influence of compressive strength and cement factor on sulfate expansion for 28 days	81.1	4.6×10^{-3}	<0.466	0.566

Table 6
Bulk properties of fast-track concretes

Mixture type	Opening time (h)	Demolded unit weight (kg/m^3)	Compressive strength (MPa)			Compressive strength of water-cured specimens (MPa)		9-Month sulfate-immersed compressive strength (MPa)	
			Curing age (h)			Curing age (days)		Sample type	
			6	8	12	28	270	Opening time	28 days
I-386 AA	8	2366	–	17.0	27.9	55.4	62.8	60.0	64.0
I-446 AA	8	2368	–	21.2	28.7	56.6	66.5	64.1	66.0
I-505 AA	8	2370	16.4	22.8	29.5	57.6	72.4	70.4	72.0
I-564 AA	8	2379	22.3	27.3	33.4	63.5	79.8	78.4	79.6
III-386 AA	6	2348	26.4	32.8	–	56.5	57.9	52.6	55.0
III-446 AA	6	2357	33.6	37.3	–	59.1	64.9	60.9	61.9
III-505 AA	6	2370	37.1	41.5	–	62.2	68.3	64.2	65.6
V-386 AA	8	2362	–	15.8	25.7	52.6	64.0	62.3	64.0
V-446 AA	8	2365	–	20.8	26.9	54.9	66.2	65.2	66.0
V-505 AA	8	2369	15.3	21.6	28.6	56.1	67.6	67.2	67.5
V-564 AA	8	2372	19.5	25.7	31.2	62.8	68.0	67.7	67.9

and 28-day specimens immersed in a 5% sulfate solution for different periods. As can be seen, mixtures with the same cement content, Type V fast-track concretes performed the best, followed by Types I and III. The average percent strength loss for Type I, III, and V matrices was 3.2%, 7.0%, and 1.3%, respectively. For concretes of the same cement type, those with higher cement factors performed better than the ones with lower cement contents. The average strength reductions of the FTC containing 386, 446, 505, and 564 kg/m^3 were 5.5%, 3.7%, 3.1%, and 1.1%, respectively. In the absence of any softening, as evident by the lack of noticeable material loss and strength reduction, it can be concluded that the bulk of the sulfate attack occurred in the form of expansion due to the formation of ettringite compounds.

5.4. Relationship between sulfate expansion and compressive strength

Table 6 gives the compressive strength of water-cured and sulfate-immersed specimens for different cement factors and cement types. It can be seen from that table that an increase in cement factor leads to an increase in compressive strength and reduction in expansion. The best-fit predictive equations of linear expansion as a function of compressive strength for the specimens exposed to 5% sodium sulfate during 9-month (270 days) period were determined at 95% confidence level. The relationship can be expressed as follows:

For opening-time specimens, cement types I, III and V

$$(\mathrm{SExp_u})_{\mathrm{OT}} = -8.605\times10^{-9}\mathrm{CS}^7 + 3.773\times10^{-6}\mathrm{CS}^6 - 7.063\times10^{-4}\mathrm{CS}^5 + 7.318\times10^{-2}\mathrm{CS}^4 - 4.531\mathrm{CS}^3 + 167.722\mathrm{CS}^2 - 3434.949\mathrm{CS} + 30,027.279 \quad (13)$$

$$(\mathrm{SExp_u})_{\mathrm{OT}} = 2818.468 - 67.644\mathrm{CS_w} - \frac{254,796.618}{\mathrm{CS_s}} + 0.536\mathrm{CS_w^2} + \frac{7,590,040.104}{\mathrm{CS_s^2}} + 4116.962\frac{\mathrm{CS_w}}{\mathrm{CS_s}} - 1.407\times10^{-3}\mathrm{CS_w^3} - \frac{74,334,349.388}{\mathrm{CS_s^3}} - 62,034.831\frac{\mathrm{CS_w}}{\mathrm{CS_s^2}} - 16.459\frac{\mathrm{CS_w^2}}{\mathrm{CS_s}} \quad (14)$$

$$(\mathrm{SExp_u})_{\mathrm{OT}} = -1392.555 - 37.071\mathrm{CS} + 1070.746\log(\mathrm{CF}) - 0.441\mathrm{CS}^2 - 286.508\log(\mathrm{CF})^2 + 21.332\mathrm{CS}\log(\mathrm{CF}) - 9.790\times10^{-4}\mathrm{CS}^3 + 25.417\log(\mathrm{CF})^3 - 2.816\mathrm{CS}\log(\mathrm{CF})^2 + 0.102\mathrm{CS}^2\log(\mathrm{CF}) \quad (15)$$

For 28-day specimens, cement types I, III and V

$$(\mathrm{SExp_u})_{28} = 1.346\times10^{-7}\mathrm{CS}^7 - 6.309\times10^{-5}\mathrm{CS}^6 + 1.264\times10^{-2}\mathrm{CS}^5 - 1.405\mathrm{CS}^4 + 93.518\mathrm{CS}^3 - 3726.803\mathrm{CS}^2 + 82,346.587\mathrm{CS} - 778,236.405 \quad (16)$$

$$(\mathrm{SExp_u})_{28} = 14,984.019 - 340.017\mathrm{CS_w} - \frac{1,468,394.160}{\mathrm{CS_s}} + 2.562\mathrm{CS_w^2} + \frac{47,742,212.644}{\mathrm{CS_s^2}} + 22,302.746\frac{\mathrm{CS_w}}{\mathrm{CS_s}} - 6.418\times10^{-3}\mathrm{CS_w^3} - \frac{514,565,724.455}{\mathrm{CS_s^3}} - 364,270.177\frac{\mathrm{CS_w}}{\mathrm{CS_s^2}} - 84.331\frac{\mathrm{CS_w^2}}{\mathrm{CS_s}} \quad (17)$$

$$(SExp_u)_{28} = 1077.700 - 82.173CS + 2.496CS^2 - 3.775 \times 10^{-2}CS^3 + 2.843 \times 10^{-4}CS^4 - 8.532 \times 10^{-7}CS^5 + 1.589 \times 10^{-3}CF - 2.892 \times 10^{-6}CF^2 + 1.753 \times 10^{-9}CF^3 \quad (18)$$

where $(SExp_u)_{OT}$ = 9-month sulfate expansion for the opening-time (%); $(SExp_u)_{28}$ = 9-month sulfate expansion for the 28-day curing (%); CS_w = 9-month water-cured compressive strength (MPa); CS_s = 9-month sulfate-immersed compressive strength (MPa); CF = cement factor (kg/m^3), with 386 kg/m^3 $\leqslant$ CF $\leqslant$ 564 kg/m^3.

The regression variables R^2, S, Prob(t) and Prob(F) are given in Table 6. The calculated values are indicative of a good relationship between the dependent variable (ultimate beam expansion) and the independent variable (ultimate compressive strength and cement factor) for both the OT and 28 days.

Finally, in order to ascertain the performance of the selected opening-time fast-track concretes, the results were compared to the applicable expansion limits as noted in the introductory segment of the manuscript. Based on the 6-month expansion limit recommended by ASTM C1012, all opening-time fast-track concretes displayed expansion below 0.05% and, thus, can by classified as having "high sulfate resistance". Moreover, Mehta's recommended 25% strength loss limit for sulfate-resistant concretes was also met by all selected opening-time fast-track matrices.

6. Conclusions

The following conclusions are drawn based on the experimental results presented in the manuscript.

1. During the 9-month immersion in a 5% sulfate solution, the opening-time test samples experienced continued length change, but did not exhibit any signs of softening. Moreover, the highest rate of expansion occurred within the first 3 months of exposure to sulfate.
2. An increase in cement content of 60 kg/m^3 resulted in reduced 9-month linear expansions of roughly 19%, 27%, and 44% for the opening-time Type I concretes with cement factors ranging from 386 to 564 kg/m^3. For the equivalent Type V groups, the corresponding reductions in expansion were 15%, 31%, and 38%. The opening-time fast-track concretes containing Type III Portland cement ranging from 386 to 505 kg/m^3 showed reductions in sulfate-induced expansion of 9% and 27% with an incremental increase of 60 kg/m^3 of cement.
3. The opening-time fast-track concrete specimens containing Type V Portland cement displayed the least amount of expansion followed by the mixtures made with Type I, and III cement. After 9 months exposure in a sulfate-rich environment, on average, the opening-time Type V fast-track concretes produced linear expansion results which were 45% and 54% less than the companion concretes containing Type I and Type III Portland cements, respectively.
4. Fast-track concretes allowed to mature prior to immersion in a sulfate solution resisted expansion and strength loss more effectively than those exposed to a sulfate-rich environment immediately at the opening-time. On average, the opening-time concretes displayed 9-month linear expansions that were roughly 1.3 times higher than those of the equivalent 28-day water-cured specimens.
5. When applying the failure criteria for expansion, the trial opening-time fast-track concretes performed remarkably well. With 9-month linear expansions well below the limit of 0.05%, the selected opening-time matrices are considered to have "high sulfate resistance".
6. The results of the statistical regression studies revealed the presence of strong relationships among the sodium sulfate expansion (dependant variable), immersion age, cement factor, and compressive strength (independent variables) for the fast-track concretes made with different cement types.

Conversion factors

1 mm = 0.0394 in.
1 MPa = 145 psi
1 kg/m^3 = 1.684 lb/yd^3
°C = (5/9)(°F − 32)
1 h m^2 °C/J = 20,408 h ft^2 °F/Btu

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