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Behaviour of foam concrete under sulphate environments

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ABSTRACT

This paper reports the effects of variation in density, concentration and type of cation associated with sulphate on the expansion, mass and strength loss of foam concrete produced with two synthetic surfactants. Comparisons are made between behaviour of foam concrete of different densities and that of corresponding base mixes of mortar without foam. The investigations indicated that the expansion in sodium sulphate environment was up to 28% higher than that of magnesium sulphate environment which can be attributed to greater quantum of ettringite formation in sodium sulphate environment. The major deterioration mechanism in magnesium sulphate environment is disintegration of cementing material and this contributed to loss in mass of 1% and higher sulphate deterioration factor of 0.4 for specimens under very severe magnesium sulphate environment. Irrespective of the type of sulphate environment, the deterioration of foam concrete was lower than that of base mix.

1. Introduction

Mechanism of sulphate attack is complex as it depends on various factors like type of cement, presence of mineral admixtures, water–cement ratio, permeability, type of cation associated with sulphate anion, concentration of sulphate, time and duration of exposure and environment [1–4]. The commonly reported forms of sulphate attack involve viz., (i) removal of hydrated cement paste due to formation of gypsum, (ii) formation of ettringite resulting in failure by expansion and (iii) decomposition of C–S–H gel into non-cementitious magnesium silicate hydrate affecting the strength [1,5–7]. Several test methods are necessary to assess the damage due to the above mentioned mechanisms. In a study by Tian and Cohen [8], the effect of gypsum formation on the resulting expansion of C_3S paste and mortar prisms was investigated. A review of the models proposed by various researchers for sulphate attack based on statistical analysis of expansion data have been presented by Santhanam et al. [9]. It was observed that the pH, concentration of sulphate solution [10], and temperature [11] played an important role in the rate of expansion. Prasad et al. [1] and Al-Amoudi et al. [12] observed that the specimens in magnesium sulphate solution showed a different tendency in linear expansion than those under sodium sulphate environment. Jones and McCarthy [13] studied the performance of foam concrete exposed to Design sulphate Class 2 (DS2) and Class 4 (DS4) chemical solutions in terms of length change and chemical analysis for a period of 1 year. It was observed from their studies that the net expansion caused by chemical environment was lesser than 300 μ strain and in addition the lack of visual evidence due to chemical attack indicated good resistance of foam concrete.

Presently there are rising concerns about the changes in strength of concrete material under long-term exposure to sulphate environment. From the studies conducted by Justnes [14] on resistance of mortar specimens to 5% sodium sulphate solution, it was observed that there was significant increase in mass until 6 months (which was associated with expansion) and decrease in mass from 10 months as the material started degrading. A steady rate of mass gain was also observed by Santhanam et al. [15] for Portland cement and C_3S mortars when exposed to 4.44 mass% sodium sulphate solution for a period of 41 weeks. The gain in mass was reported to be associated with deposition of sulphate attack products in the pores [16]. Park et al. [17] assessed the variation in mass and strength of high strength concrete under 10% sulphate solution for a period of 270 days and reported that the compressive strength and mass showed a greater tendency for decrease in magnesium sulphate solution than that in sodium sulphate solution. A mass loss of nearly 6% and drop in strength of 40% under 10% magnesium sulphate solution was reported by the authors based on their results [17]. Mirza and Al-Noury [18] observed a drop in strength of nearly 40% when autoclaved aerated concrete was subjected to 5% magnesium sulphate solution for a period of 90 days and concluded that the resistance to sulphate environment could be improved by surface treatment. There have been several investigations on deterioration of normal weight concrete in sulphate environment. But only limited information is available on the behaviour of foam concrete in sulphate environment.

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The present work examines the behaviour of foam concrete produced with two synthetic surfactants under sodium and magnesium sulphate environment. The performance was evaluated by measurement of linear expansion, mass, strength and through chemical analysis. The parameters identified for this study were density, type of cation associated with sulphate anion, concentration of sulphate and time of exposure. The behaviour of foam concrete of densities ranging from 1000 to 1500 kg/m^3 in solutions of 0.5% and 5% sodium sulphate and 0.424% and 4.24% by mass of magnesium sulphate was evaluated for a period of 1 year. A comparison of behaviour of foam concrete of different densities and the corresponding base mixes of mortar without foam has also been reported.

2. Experimental investigations

2.1. Constituent materials and mix proportioning

Ordinary Portland cement conforming to IS 12269-1987 [19] and pulverised river sand finer than 300 μm (specific gravity = 2.52) was used. Foam was produced using surfactants sodium lauryl sulphate (SLS) and sodium lauryl ether sulphate (SLES) in an indigenously fabricated foam generator to a density of around 25 kg/m^3 and 38 kg/m^3 respectively. The optimum values of foam production parameters viz., surfactant concentration and foam generation pressure arrived at as 118 kPa and 2% respectively through earlier optimisation studies [20] have been adopted. Foam concrete (FC) mixes of different densities were made by varying the foam volume from 18% to 46% and by keeping the basic cement-sand ratio constant at 1:1 by weight. The water-solids ratios of these mixes were arrived at to provide the desired fresh foam concrete design density and consistency. The mix proportioning relationship between cement content, water content and foam volume of ASTM C 796-97 [21] is applicable for cement paste. Hence these equations were appropriately modified by including the fine aggregate (sand) component and the foam volume required to achieve foam concrete design densities of 1000, 1250 and 1500 kg/m^3 was computed (Table 1). A homogenous mortar mix of cement–sand slurry was first prepared by hand mixing followed by the addition of calculated weight of foam to the mortar mix and the mixing was continued till the foam is uniformly blended with slurry.

2.2. Test method

Table 2 summarizes the different test solutions adopted for the study. The mass percentages of magnesium sulphate ($MgSO_4$) and sodium sulphate (Na_2SO_4) chosen were different with the objective of maintaining the same SO_4^{2-} concentration in both sodium and magnesium sulphate solutions. The solutions were changed at regular intervals to maintain the concentration level throughout the test period. The experiments were carried out under ambient conditions and the measured temperature and relative humidity were in the range of 30–35° C and 70–75% respectively.

Table 2
Test solution concentrations.

Exposure [25]	Type of cation associated with sulphate	Mass% of corresponding sulphate solution	Equivalent SO_4^{2-} (ppm)
Severe	Sodium	0.5%	3380
Severe	Magnesium	0.424%	3380
Very severe	Sodium	5%	33,800
Very severe	Magnesium	4.24	33,800

For each mix, six prismatic specimens of size 40 mm × 40 mm × 160 mm were cast for exposure to each type of chemical and concentration of exposure. After 28-day water curing, steel balls were fixed at top and bottom of the specimen, initial length measurement was made using a length comparator and then the specimens were kept immersed in solutions of different sulphate environment. Periodical length measurement was done up to a period of one year. Along with length measurement the mass of the prismatic specimens were also determined to assess any mass loss due to disintegration. To evaluate the variation of strength with period of immersion in sulphate solution, 180 cubes of 50 mm size were cast for each mix for testing 6 cubes at different ages for a period of one year. Out of 180 cubes, 150 cubes were immersed in different sulphate solutions and 30 cubes were water cured to serve as reference specimen for comparison. The strength loss was measured by sulphate deterioration factor (SDF) which is the percentage difference in strength of cubes after immersion in sulphate solution and in water at age "*t*" [22,23].

For better understanding of the damage, the deteriorated parts, namely, the edges and corners of the mortar specimens were examined by X-ray Diffraction (XRD) analysis on an X-ray diffractometer using Cu Kα radiation with a wavelength of 1.54 Å at a voltage of 30 kV, scanning speed of 1°/min and current of 30 mA. The samples, which had been washed in acetone, were finely ground by hand and sieved through a 75 μm sieve. The powdered samples were then stored in airtight plastic containers. The samples used for investigation were fractured sections taken from the edge of foam concrete specimens.

Table 1
Mix proportions for cement–sand foam concrete mixes.

	Foam concrete			Mortar		
				Base mix-1	Base mix-2	Base mix-3
Fresh density (kg/m^3)	1000	1250	1500	1813	1832	1884
Cement (kg/m^3)	344.8	438.6	545.4	632.4	646.9	687.4
Fine aggregate (pulverised sand) (kg/m^3)	344.8	438.6	545.4	632.4	646.9	687.4
Air volume equation V_a	$(0.683\ W_c + 0.6032\ W_s)/1000$	$(0.603\ W_c + 0.504\ W_s - 0.25\ W_{tw})/1250$	$(0.524\ W_c + 0.405\ W_s - 0.5\ W_{tw})/1500$	NA	NA	NA
w/s						
SLS	0.45	0.425	0.375	0.434	0.416	0.37
SLES	0.45	0.425	0.4			
Foam volume (%)						
SLS	45.49	32.19	20.66	NA	NA	NA
SLES	46.1	32.62	20.94			

Where V_f = volume of foam; V_a = volume of air; W_{tw} = total weight of water; W_c = weight of cement; W_s = weight of sand.

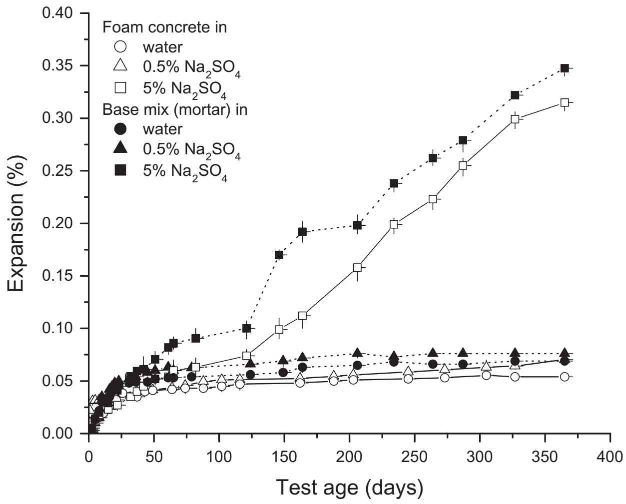


Fig. 1. Variation of expansion of FC (1000 kg/m^3) in sodium sulphate environment (SLS).

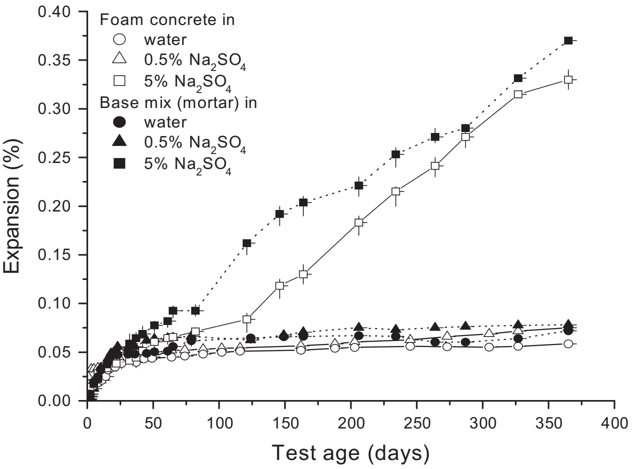


Fig. 2. Variation of expansion of FC (1500 kg/m^3) in sodium sulphate environment (SLS).

3. Results and discussion

3.1. Expansion in sodium sulphate environment

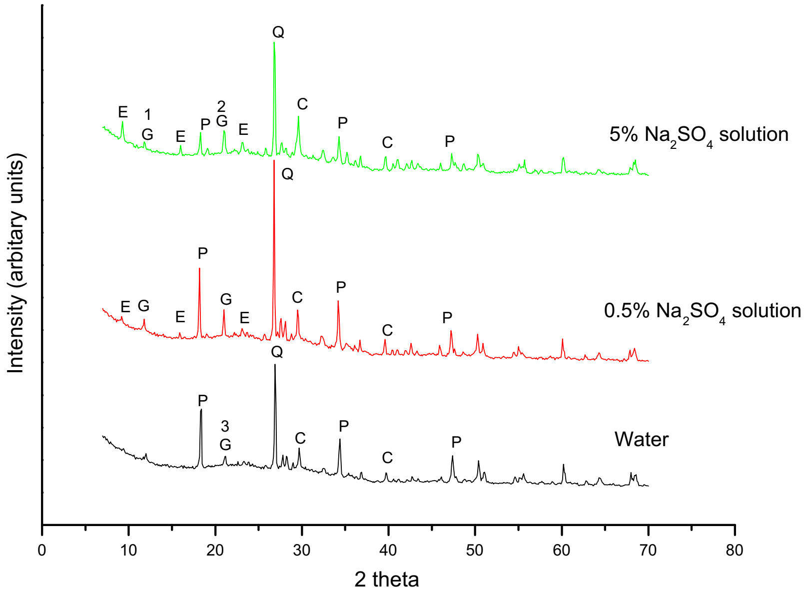
Figs. 1 and 2 shows the expansion of foam concrete under water and sodium sulphate environment for a period of 1 year. Expansion of order of 0.035% was observed for foam concrete under water during initial 28 days and there was no significant increase in expansion after 50 days. This confirms that the initial expansion observed in water was only from swelling due to absorption. For foam concrete in severe exposure sodium sulphate environment, the greatest expansion (up to 55% of expansion reported at the end of test period) occurred during initial 28 days. The specimens in very severe sodium sulphate showed a gradual expansion until 28 days (up to 11% of expansion reported at the end of test period). The expansion of foam concrete in sodium sulphate environment was marginally higher than that in water. For foam concrete under severe exposure conditions, the net expansion (excluding the absorption due to water) was less than 0.02% and also lack of visual evidence of chemical attack indicated that the length change due to sulphate exposure was not significant [13]. Under very severe sodium sulphate environment, beyond 75 days, the specimens expanded steeply till the end of 1 year. The expansion under very severe sodium sulphate environment was 4–4.5 times higher than those under severe exposure environment. Figs. 3 and 4 shows the comparison of XRD patterns of foam concrete subjected to different concentrations of sodium sulphate and water at the end of 1 year. The comparison of XRD patterns of foam concrete exposed to severe and very severe concentration of sodium sulphate indicated that the intensity of Portlandite (P–Ca $(OH)_2$, marked as 15 and 18 in Fig. 4) peak was higher in severe concentration exposed specimens for foam concrete with both the surfactants. This is because when subjected to lesser sulphate concentration, sulphate available was not sufficient to convert all portlandite into gypsum and ettringite. However in very severe exposure most of the calcium hydroxide is converted into gypsum and ettringite. Hence the intensity of ettringite (E-$6CaO\cdot Al_2O_3\cdot 3SO_3\cdot 32H_2O$, marked as 4 in Fig. 4) and gypsum (G-$CaSO_4\cdot 2H_2O$, marked as 5 and 8 in Fig. 4) was relatively higher in very severe exposure than the ettringite (marked as 12 in Fig. 4) and gypsum peaks (marked as 13 and 16 in Fig. 4) in concrete under severe sulphate exposure conditions. The above observation was more evident in foam concrete with design density 1500 kg/m^3 (Fig. 4). Also the calcite (C-$CaCO_3$, marked as 9 in Fig. 4) peaks are predominant in specimens exposed to very severe exposure conditions indicating that these specimens are subjected to high degree of leaching.

The variation of expansion with density under very severe exposure conditions is presented in Table 3. For a given exposure, up to 5% increase in expansion was observed when the fresh density of foam concrete varied from 1000 to 1500 kg/m^3. The larger variation in density of concrete with paste content variation of 40% did not resulted in significant variation in expansion because it was complex to differentiate the mechanism of expansive sulphate reactions with respect to density. For a given volume of foam concrete with reduction in density the foam volume increases and hence the paste content reduces and this can be attributed to the marginal reduction in expansion observed. The comparison of XRD patterns of foam concrete of two densities indicated that the intensity of gypsum peaks (marked as 22 and 23 in Fig. 5) in foam concrete with density 1500 kg/m^3 was higher than gypsum peaks (marked as 20 and 21 in Fig. 5) in concrete with density 1000 kg/m^3.

Irrespective of the density of foam concrete, the expansion of foam concrete was marginally lower than that of base mix (mortar) under severe exposure conditions. But for concrete exposed to very severe exposure conditions, the foam concrete with SLS and SLES was 10% and 29% respectively lower than that of the base mix (mortar). This is reflected in the XRD patterns of base mix specimens (mortar without foam) immersed in very severe sodium sulphate environment in which the intensity of peak of gypsum (marked as 24 in Fig. 5) was higher than the gypsum peak (marked as 20 in Fig. 5) for foam concrete with SLS.

3.2. Expansion in magnesium sulphate environment

Figs. 6 and 7 shows the expansion of foam concrete under water and magnesium sulphate environment for a period of 1 year. The expansion of foam concrete in magnesium sulphate environment was higher than that in water and lower than that of base mix. For foam concrete under severe exposure magnesium sulphate environment, the greatest expansion (up to 60% of expansion reported at the end of test period) occurred during the initial 28 days. Under very severe exposure conditions the early age development of expansion was gradual similar to that observed under sodium sulphate environment. For foam concrete under severe exposure conditions, the increase in expansion beyond 75 days was not significant. Under very severe magnesium sulphate environment, beyond 75 days the specimens expanded steeply. For a given density of foam concrete, the expansion under very severe environment



E- Ettringite ($6CaO.Al_2O_3.3SO_3.32H_2O$), G-Gypsum ($CaSO_4.2H_2O$), P-Portlandite ($Ca(OH)_2$), Q-Quartz ($SiO_2$), C-Calcite ($CaCO_3$)

Fig. 3. XRD patterns of FC (1000 kg/m^3) exposed to different concentrations of sodium sulphate environment (SLS).

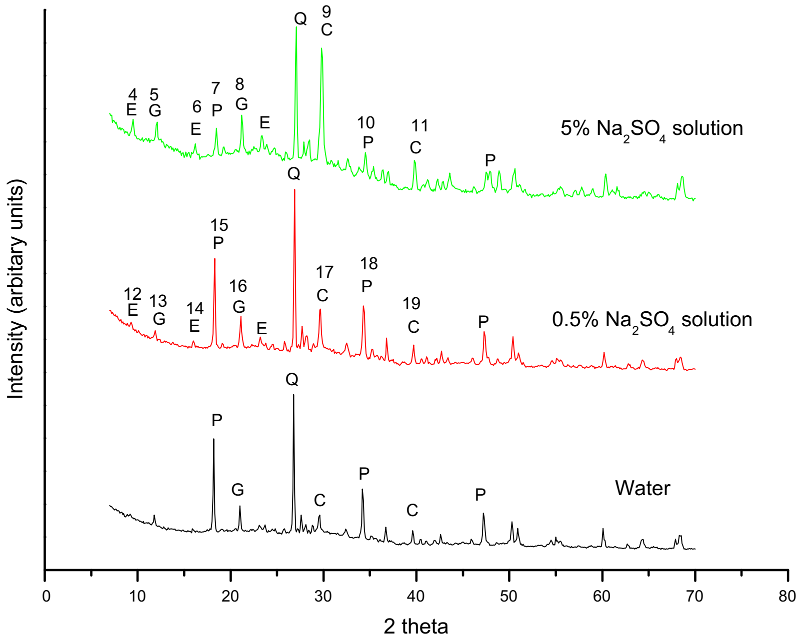


Fig. 4. XRD patterns of FC (1500 kg/m^3) exposed to different concentrations of sodium sulphate environment (SLS).

was up to 3.75 times higher than that in severe exposure environment. The comparison of XRD patterns of foam concrete exposed to different concentrations of magnesium sulphate and water at the end of 1 year are presented in Figs. 8 and 9. The XRD patterns show that the intensity of Calcium hydroxide (marked as 37 in Fig. 9) was relatively higher in foam concrete specimens subjected to severe exposure condition. In very severe exposure most of the calcium hydroxide (marked as 32 in Fig. 9) was converted into gypsum and ettringite indicating that the dominant sulphate chemical reactions involved the conversion of portlandite into gypsum and etringite. Hence the intensity of ettringite (marked as 30 in Fig. 9) and gypsum (marked as 31 and 33 in Fig. 9) were relatively higher under very severe exposure than ettringite (marked as 35 in Fig. 9) and gypsum (marked as 36 and 38 in Fig. 9) in foam concrete subjected to severe exposure sulphate environment (Fig. 9). Also the calcite peaks (marked as 34 in Fig. 9) were predominant in specimens exposed to very severe exposure condition.

The effect of density on expansion under very severe exposure conditions is presented in Table 3. For a given exposure, the difference in expansion observed in foam concrete with different densities (1000–1500 kg/m^3) was only 5%. The expansion of foam concrete was 30% and 47% lower than that of base mix (mortar) respectively under severe and very severe exposure conditions. For a constant density of foam concrete the mixes with surfactant Sodium lauryl ether sulphate has relatively higher expansion than that of sodium lauryl sulphate.

Table 3
Behaviour of foam concrete exposed to very severe Na_2SO_4 and $MgSO_4$ environments.

Fresh density (kg/m^3)	Expansion (%)				Mass change (%)				SDF			
	5% Na_2SO_4		4.24% $MgSO_4$		5% Na_2SO_4		4.24% $MgSO_4$		5% Na_2SO_4		4.24% $MgSO_4$	
	SLS	SLES	SLS	SLES	SLS	SLES	SLS	SLES	SLS	SLES	SLS	SLES
1000 (FC)	0.315	0.27	0.228	0.258	6.9	9.1	−1.05	−1.2	0.15	0.16	0.4	0.435
1500 (FC)	0.33	0.28	0.24	0.27	7.71	10.46	−1.15	−1.25	0.16	0.21	0.41	0.44
1813 (BM-1)	0.348	0.348	0.335	0.335	9.3	9.3	−1.3	−1.3	0.17	0.17	0.5	0.5
1884 (BM-2)	0.37	0.37	0.35	0.35	10.6	10.6	−1.5	−1.5	0.21	0.21	0.52	0.52

FC – Foam concrete, BM – Base mix (mortar).

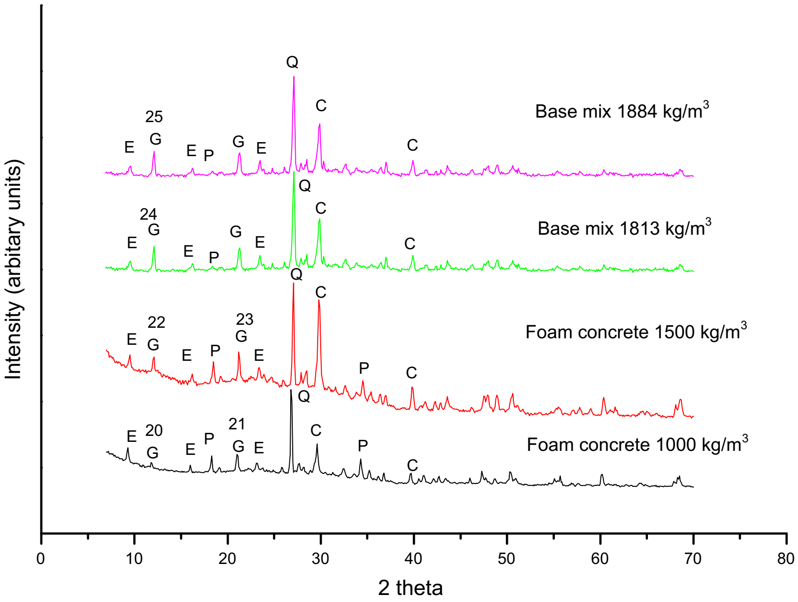


Fig. 5. XRD patterns of FC with different densities exposed to very severe sodium sulphate environment (SLS).

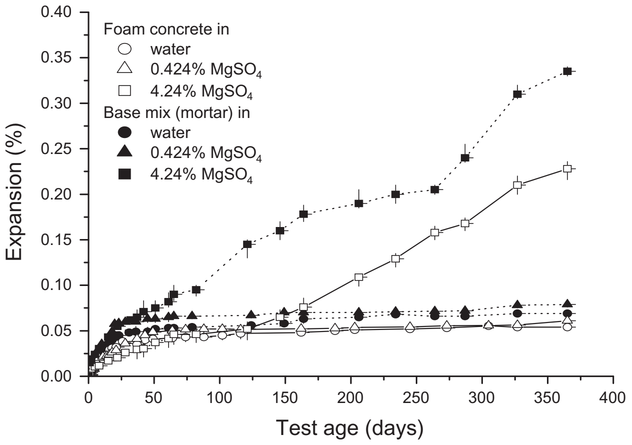


Fig. 6. Variation of expansion of FC (1000 kg/m^3) in magnesium sulphate environment (SLS).

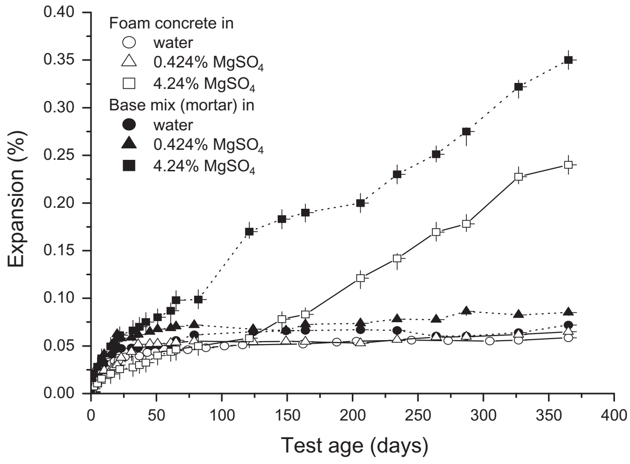


Fig. 7. Variation of expansion of FC (1500 kg/m^3) in magnesium sulphate environment (SLS).

3.3. Comparison of expansion under sodium and magnesium sulphate environment

The comparison between expansion of foam concrete under very severe sodium and magnesium sulphate environments is presented in Table 3. For a constant density, the expansion of foam concrete under sodium sulphate environment was higher than that exposed to magnesium sulphate environment. The above difference in expansion was noted to be 28% and 4% for foam concrete with SLS and SLES respectively under very severe exposure conditions. The chemical analysis showed that the sodium sulphate specimens had a higher amount of ettringite (marked as 40 in Fig. 10) as compared to specimens subjected to magnesium

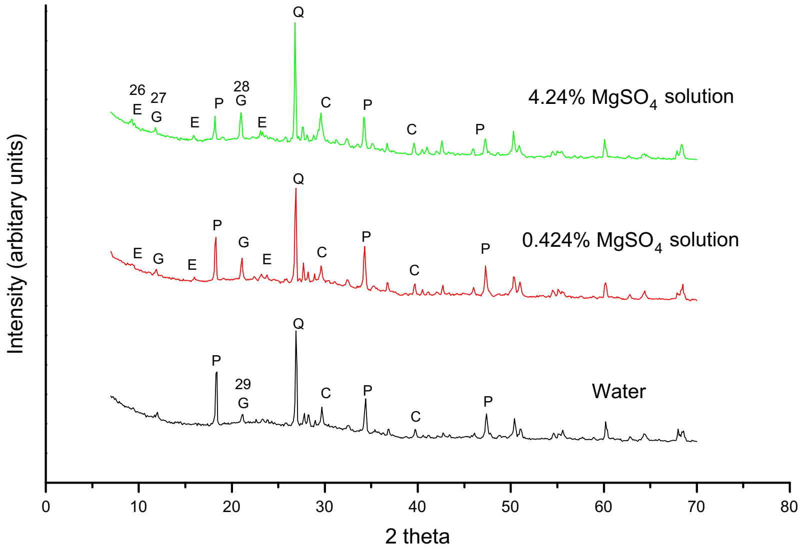


Fig. 8. XRD patterns of FC (1000 kg/m^3) exposed to different concentrations of magnesium sulphate environment (SLS).

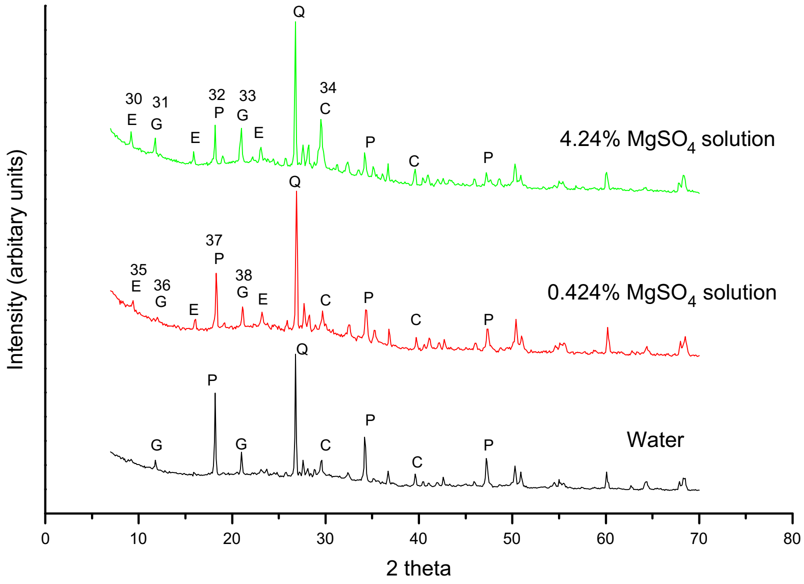


Fig. 9. XRD patterns of FC (1500 kg/m^3) exposed to different concentrations of magnesium sulphate environment (SLS).

sulphate wherein the gypsum peak (marked as 39 in Fig. 10) was high in particular for foam concrete with SLS. Hence the relatively higher expansion in sodium sulphate environment can be attributed to the dominant chemical reaction between gypsum and hydrated calcium aluminate resulting in the formation of ettringite which was characterised by expansion and cracking [12,13]. Also the formation of brucite in magnesium sulphate specimens obstruct the pores providing barrier to free passage of sulphate solution into the interior of mortar and this could be attributed to lesser expansion observed for specimens in magnesium sulphate environment [7,24].

3.4. Variation in mass under sodium sulphate environment

Figs. 11 and 12 shows the variation in mass with time under water and sodium sulphate environment for a period of 1 year. A continuous increase in mass was observed up to a period of 1 year when compared to the expansion which got leveled off beyond 28 days of exposure [20]. This shows that variation in mass could be associated with expansion only during the initial period [14]. Hence the measurement of linear expansion is not reliable measure for foam concrete. An increase in mass of up to 4.5% was observed under water for foam concrete with surfactant SLS. This gain in mass is due to swelling from absorption of solution. The increase in mass of foam concrete subjected to sulphate environment was 8% and 42% higher than that under water under severe and very severe exposure conditions respectively. For foam concrete in severe exposure sodium sulphate environment, the greatest increase in mass (up to 35% of final mass reported at the end of test period) was observed during initial 28 days. The specimens under very severe sodium sulphate showed a gradual increase in mass until 28 days (up to 24% of change in mass reported at the end of test period). Under very severe sodium sulphate environment, beyond 50 days the mass increased steeply till the end of 1 year. The

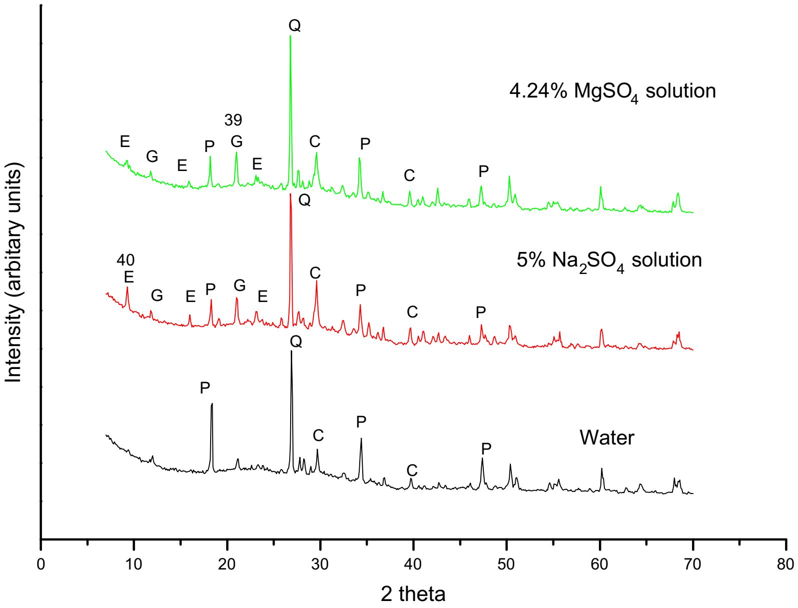


Fig. 10. XRD patterns of FC (1000 kg/m^3) exposed to two sulphate environments (SLS).

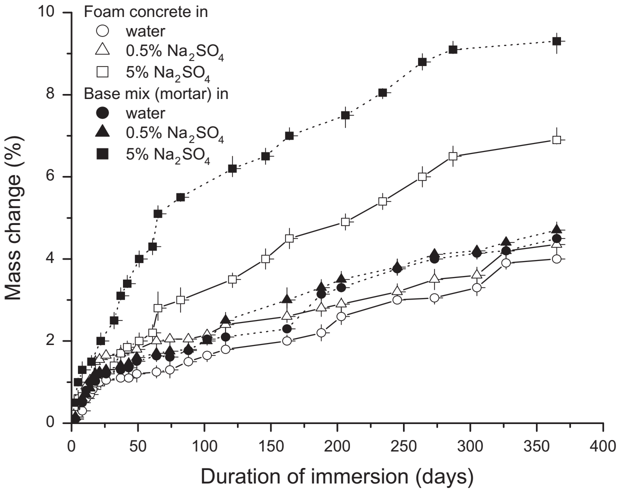


Fig. 11. Variation of mass of FC (1000 kg/m^3) in sodium sulphate environment (SLS).

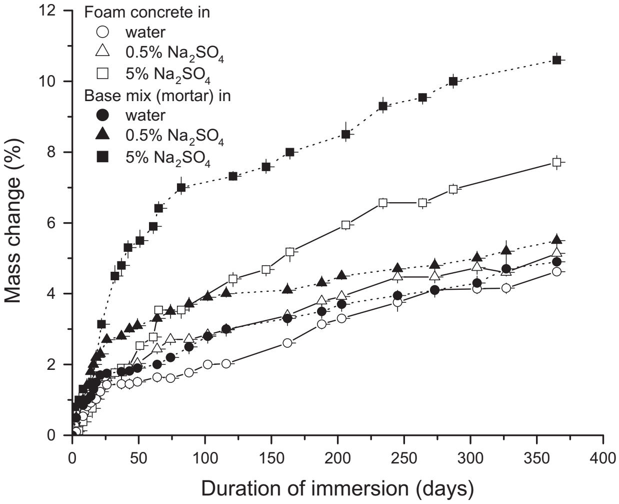


Fig. 12. Variation of mass of FC (1500 kg/m^3) in sodium sulphate environment (SLS).

final gain in mass was as high as 5% and 10% under severe and very severe exposure conditions respectively. The initial gain in mass was only from swelling due to absorption. But at later stages, the probable reason could be associated with the deposition of sulphate attack products namely gypsum and ettringite in the pores [16]. The increase in mass under very severe sodium sulphate environment was 1.5 times higher than those under severe exposure environment. The greater mass gain in very severe exposure environment can be attributed to formation of more quantum of gypsum and ettringite under very severe exposure environment as indicated in XRD analysis in earlier discussion on expansion.

The variation of mass with density under very severe exposure conditions is presented in Table 3. Under very severe exposure conditions, 12% and 15% increase in mass was observed for the variation in density studied for surfactants SLS and SLES respectively. The increase in volume of paste content for foam concrete with higher density could be attributed to higher mass gain. Irrespective of density of foam concrete, the gain in mass of base mix (mortar) was marginally higher than that of foam concrete under severe exposure conditions. The base mix was 26 and 2% higher than the foam concrete with SLS and SLES respectively under very severe exposure conditions.

3.5. Variation in mass under magnesium sulphate environment

Figs. 13 and 14 show the variation in mass with time under water and magnesium sulphate environment for a period of 1 year. The variation in mass under severe sulphate exposure conditions was up to 20% higher than that under water. The variation in mass in severe and very severe exposure conditions followed different trend. For specimens exposed to severe exposure conditions increase in mass with time was observed till the end of 1 year. Specimens immersed in 4.24% magnesium sulphate environment exhibited gain in mass up to 150 days. Beyond this period, the

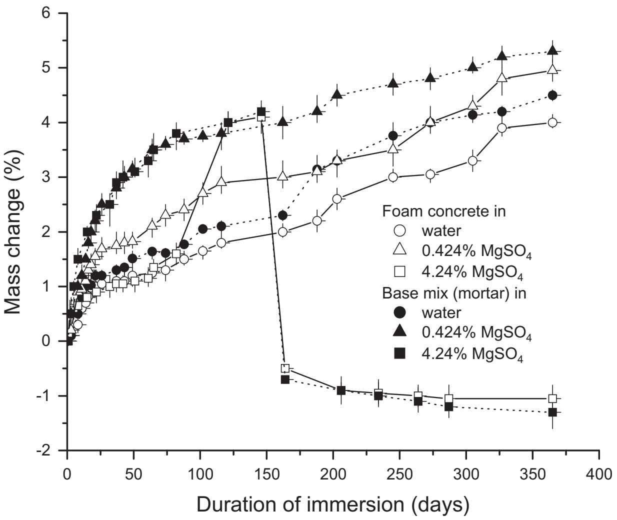


Fig. 13. Variation of mass of FC (1000 kg/m^3) in magnesium sulphate environment (SLS).

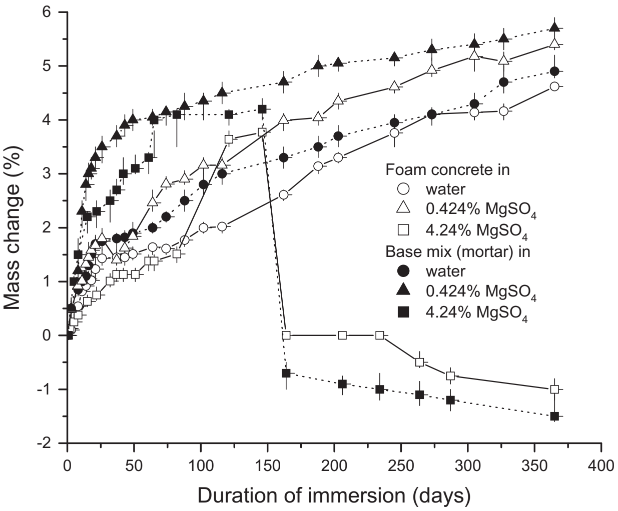


Fig. 14. Variation of mass of FC (1500 kg/m^3) in magnesium sulphate environment (SLS).

deterioration was so rapid which resulted in the spalling of edges and corners and thus the mass started reducing with time. The reason for loss in mass could be attributed to formation of more quantum of gypsum and decalcification of CSH gel in concrete under very severe exposure conditions which resulted in softening, loss of cementitious structure and thus led to disintegration of specimens [5,7]. Comparison of XRD patterns indicate that the intensity of gypsum peak (marked as 33 in Fig. 9) was high in very severe exposure when compared to concrete under severe exposure conditions. The variation in mass loss with variation in density was 10% and 4% for foam concrete with surfactants SLS and SLES respectively. The mass loss of base mix was 20% higher than that of foam concrete under very severe exposure conditions.

3.6. Comparison of mass variation under sodium and magnesium sulphate environment

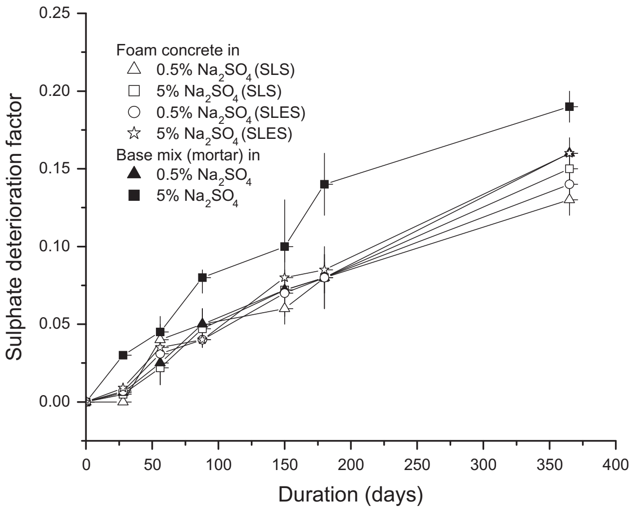


Fig. 15a. Variation of SDF of FC (1000 kg/m^3) in sodium sulphate environment.

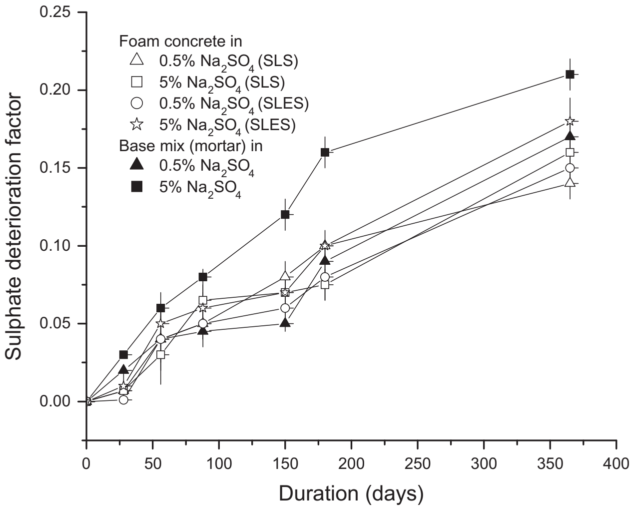


Fig. 15b. Variation of SDF of FC (1500 kg/m^3) in sodium sulphate environment.

Table 3 shows the comparison between variation in mass of foam concrete under very severe sodium and magnesium sulphate environment. Under very severe exposure condition loss in mass was observed in magnesium sulphate environment (due to disintegration of specimens) against the gain in mass observed for sodium sulphate environment. This observation was consistent with results of earlier researchers in normal weight concrete [5,17].

3.7. Variation of sulphate deterioration factor (SDF) under sodium sulphate environment

Fig. 15 shows the variation in SDF with time under sodium sulphate environment. For a given density, SDF of foam concrete under very severe exposure sodium sulphate environment was 25% and 12% higher than that under severe exposure conditions for surfactants sodium lauryl sulphate and sodium lauryl ether sulphate respectively. The difference in strength deterioration observed in foam concrete with different densities (1000–1500 kg/m^3) was 8% and 13% under severe and very severe exposure conditions respectively. The increase in strength deterioration with increase in density could be attributed to more volume of paste for mixes with higher density. The greater volume of sorbing paste at the higher densities leads to higher sorptivity [13] and thus resulted

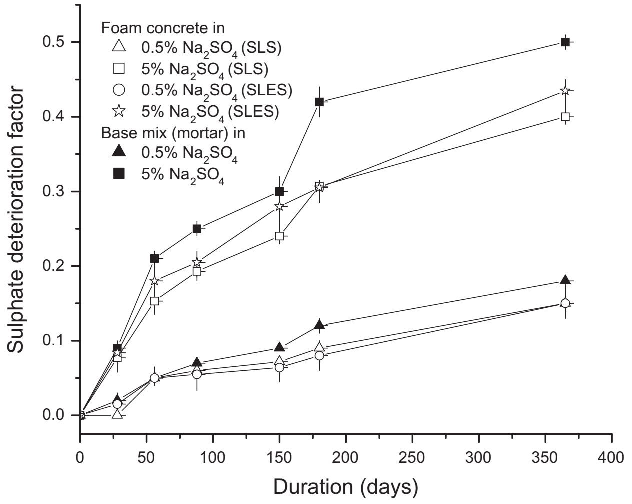


Fig. 16a. Variation of SDF of FC (1000 kg/m^3) in magnesium sulphate environment.

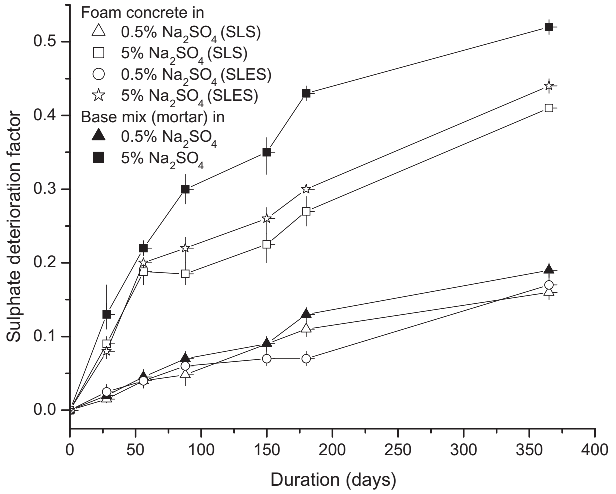


Fig. 16b. Variation of SDF of FC (1500 kg/m^3) in magnesium sulphate environment.

in rapid permeation of water containing sulphate ions. The SDF of base mix was up to 19% and 25% higher than the foam concrete under severe and very severe exposure conditions respectively.

3.8. Variation of sulphate deterioration factor under magnesium sulphate environment

The variation of SDF with time under magnesium sulphate environment is presented in Fig. 16. The SDF of concrete under very severe exposure magnesium sulphate environment was up to 70% higher than that under severe exposure conditions. For a given exposure, an increase in strength deterioration of up to 13% and 3% under severe and very severe exposure conditions respectively were observed for the variation in density studied. The SDF of base mix was 17% and 20% higher than the foam concrete under severe and very severe exposure conditions respectively.

3.9. Comparison of SDF under sodium and magnesium sulphate environment

Table 3 shows the comparison between SDF of foam concrete under sodium and magnesium sulphate environment of very severe exposure conditions. For a constant density, it was observed that the SDF of foam concrete under magnesium sulphate environment was 63% higher than that under sodium sulphate environment when subjected to very severe exposure conditions. This is because the major deterioration mechanism in magnesium sulphate environment is softening and disintegration of cementing material as the magnesium sulphate can react with cementitious C–S–H gel and form the non cementitious M–S–H [7]. This reaction produces more gypsum which renders the cementitious structure soft and thus resulted in reduction in strength [5,12]. This observation is supported by the XRD analysis as discussed in earlier sections.

4. Conclusions

The conclusions drawn from this study and discussed below are applicable to characteristics of materials used and the ranges of parameters investigated.

- Irrespective of the density of foam concrete, the expansion was 8% and 30% lower than that of base mix (mortar without foam) under severe sodium sulphate (0.5% by mass) and magnesium sulphate (0.424% by mass) exposure conditions respectively. But for foam concrete exposed to very severe exposure conditions (5% by mass of sodium sulphate and 4.24% by mass of magnesium sulphate), the above difference was 10% and 47%. The higher expansion of base mix can be attributed to higher paste content (with more volume of capillary pores) which is more susceptible to attack by sulphate ions.
- For a given exposure the difference in expansion observed in foam concrete with different densities (1000–1500 kg/m^3) was only 5%.
- The expansion of foam concrete under very severe sulphate environment was 3.75–4.5 times higher than that under severe exposure environment due to availability of more sulphate for the expansive sulphate reactions. The XRD analysis showed that the most of the portlandite was converted into ettringite which resulted in significant expansion and hence the intensity of ettringite peak was relatively higher and portlandite peak was lower for foam concrete subjected to very severe sulphate exposure conditions.
- The nature of sulphate attack depends on the type of cation present. The expansion of foam concrete under very severe sodium sulphate environment was up to 28% and 4% higher than that under magnesium sulphate for foam concrete with sodium lauryl sulphate (SLS) and sodium lauryl ether sulphate (SLES) respectively. Similar difference in expansion values was reported for the base mixes also. This can be attributed to greater quantum of ettringite formation in sodium sulphate environment as observed in chemical analysis.
- An increase of up to 15% of mass and SDF (sulphate deterioration factor) was observed as the density varied from 1000 to 1500 kg/m^3. The mass change and SDF of base mix was up to 26% higher than the foam concrete under very severe exposure conditions. The higher variation in mass and strength loss observed at higher density of foam concrete and base mix could be attributed to more volume of sorbing paste in mixes with higher density.
- Higher concentration of sulphate ion resulted in rapid deterioration. For a given density, SDF of foam concrete under very severe exposure sodium sulphate environment was 25% and 12% higher than that under severe exposure conditions for surfactants SLS and SLES respectively. The SDF under very severe exposure magnesium sulphate environment was up to 70% higher than under severe exposure condition. Such higher loss in strength was associated with mass loss of 1% observed due to spalling of edges and corners due to deterioration.

- The SDF observed under magnesium sulphate environment was up to 63% higher than that under sodium sulphate environment. This is because the major deterioration mechanism in magnesium sulphate environment was softening and disintegration of cementing material and this contributed to higher sulphate deterioration factor and its associated loss in mass.
- Irrespective of the concentration and type of sulphate environment, the expansion, SDF and loss in mass of foam concrete was lower than that of base mix (mortar without foam). Hence it can be concluded that the cell like structure of foamed concrete and possible porosity of the cell walls do not necessarily make the foam concrete less resistant to attack by sulphate ions. These results still need to be correlated with full scale, long term durability tests.

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