Original Research Paper

Effect of Sulfonated Acetone Formaldehyde (SAF) on the Firing Resistance and Aggressive Attach of SRC-SF Composite Cement Pastes

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Abstract: This work aimed to study the effect of the dosage of laboratory synthesized Sulfonated Acetone Formaldehyde (SAF) on the physic-mechanical characteristics and durability of SF-SRC cement pastes immersed in 4% $MgCl_2$ or 4% $MgSO_4$ solutions or at elevated temperatures up to 800°C. The compressive strength of thermally treatment cement pastes with 1.5% SAF increases up to 600°C, then decreases up to 800°C. Presence of 2.0% SAF works to produce a compact cementing structure, which decreases the accessibility of the penetration of chloride as well as sulphate ion penetration and enhances the durability, hence the total chloride and sulphate contents diminished.

Keywords: Accelerator, Firing Resistance, Aggressive Attack, SAF

Introduction

The durability of cementing materials has been a major concern of civil engineering professionals over the last few decades (Chen and Wu, 2013; Sánchez *et al.*, 2011). Cements with low C_3A as well $Ca(OH)_2$ contents generally, exhibit good performance in sulphate environment. It is possible to produce, durable concrete with long-term strength by partial replacement of cement with Supplementary Cementitious Materials (SCMs), such as Fly Ash (FA), Silica Fume (SF) and Granulated Blast-Furnace Slag (GBFS) (Irassar *et al.*, 2000; Shanahan and Zayed, 2007; Montes *et al.*, 2012).

The superior performance of pozzolanic cements containing SCMs over plain cements in minimizing sulphate and chloride attack is mainly due to the following: (i) The pozzolanic reaction of SCMs, which reduces gypsum formation; (ii) low C_3A content, dilution effect; (iii) the reduction of pH value therefore, the ettringite becomes less expansive; (iv) the formation of additional amounts of CSH, which produces a coating film on the alumina-rich and other reactive phases, thereby hindering the formation of secondary and lastly ettringite; and (v) the formation of secondary CSH also results in pore size refinement, which reduces the permeability as well as the ingress of aggressive ions (Wong and Poole, 1988; Al-Dulaijan, 2007; Aye and Oguchi, 2011; Thomas *et al.*, 2012).

The aggressive attack of sulphate and chloride ions is one of the factors responsible for damage to concrete.

The corrosive action of chlorides is due to the formation of chloroaluminate hydrate, $C_3A.CaCl_2.10H_2O$, commonly known as Friedel's salt, which causes softening of concrete. The formed $CaCl_2$ from the reaction of $MgCl_2$ with the liberated lime increases the solubility of $Ca(OH)_2$ that permits leaching. Thus, brucite $(Mg(OH)_2)$ dissociates C-S-H and produces $Ca(OH)_2$ and silica gel. The later may react with $Mg(OH)_2$ to form Magnesium Silicate Hydrates (M-S-H), which has no binding properties. Also, sulphate ions can enter into chemical reactions with certain constituents of concrete, producing sulphoaluminate hydrates, $C_4A.S_3.H_{32}$ (ettringite), gypsum and M-S-H which has little binding properties (Page and Page, 2007). All of these reactions are accompanied by decrease in strength.

The production of Sulphate Resisting Cement (SRC) is expected to increase, due to its high durability against the aggressive attack of sulphates in soils and ground water. Therefore, it could be argued that, it is theoretically ideal cement for massive structures exposed to seawater or ground water (Hewlett, 2004).

Durability of concrete with Sulfonated-Acetone Formaldehyde (SAF) condensate superplasticizer was studied using sulfuric acid at pH = 4.0 and magnesium sulphate at pH = 6.5 after 6 months of immersion. The use of SAF improved the resistance of concrete to the solutions which is a direct result of reducing the water absorption and the permeable pores of concrete. It was concluded that, the aggressive solutions did not have

significant damage effect on the concrete mixtures incorporating SAF resin compared to the control mix (Pei *et al*., 2004). It was found that, the effectiveness of superplasticizers on concrete was strongly related to the adsorption behavior of the admixtures on cement particles, as well as the degree of hydration (Hsu *et al*., 1999).

The effect of temperature on the properties of cement pastes can be studied up to 800°C. The change in the phase composition of the thermally treated cement pastes can be investigated by the XRD and SEM techniques. The elevated temperature reduces the cement paste-aggregate bonds, progressive breakdown of cement gel structure, loss in concrete load-bearing capacity, reduces durability and increases tendency of structural cracking. This deterioration can often reach a level at which the structure may have to be thoroughly renovated or completely replaced, depending on various factors such as: Humidity, rate of heating, temperature level, heating time, cooling mode after heating, applied load, type of mineral admixture and inclusion levels (Yazıcı *et al*., 2012; Handoo *et al*., 2002; Aydın and Baradan, 2007; Lau and Anson, 2006).

The evaporable water is lost at 100-110°C, whereas the interlayer CSH water and some of combined water from the CSH and sulfoaluminate hydrates lost at about 300°C. Further decomposition of CH begins at about 400-550°C. On cooling, the CaO is rehydrated to $Ca(OH)_2$ with a volume expansion of 97% and formation of cracks. Tobermorite gel (CSH) is decomposed at 900°C (El-Didamony *et al*., 2012).

Use of SCMs can reduce the thermal deterioration of cement paste, mortar and concrete which can react with the liberated CH forming excess CSH, whiych more powerful and thermally stable than CH. Therefore, pozzolanic cement blends are less affected to high temperature (Yazıcı *et al*., 2012; Handoo *et al*., 2002; Aydın and Baradan, 2007; Lau and Anson, 2006; El-Didamony *et al*., 2012; Shui *et al*., 2010).

The aim of the present investigation is to evaluate the effectiveness of laboratory synthesized SAF condensate on the durability of SRC pastes incorporating 10% SF immersed in 4% $MgSO_4$ or 4% $MgCl_2$ corrosive solutions up to one year as well as subjected to elevated temperatures up to 800°C.

Materials and Methods

Starting Materials

The materials used in this investigation were Sulphate Resisting Cement (SRC) provided from El-masria Cement Company and condensed Silica Fume (SF) from Ferrosilicon Alloys Company, (Edfo and Aswan, Egypt). The chemical composition of starting materials is shown in Table 1. The surface area of SRC determined by the Blaine air permeability method, was found to be 3488 cm^2/g whereas that of silica fume is about 20 m^2/g.

The mineralogical composition of silica fume and preparation of Sulfonated Acetone-Formaldehyde (SAF) Resin are found in previous study by Osman and Al-Masry (2014).

Preparation of Cement Pastes

Preparation of Dry Mixes

The ingredients of each mix of Sulphate Resisting Cement (SRC) and 10 wt% silica fume were mixed for one hour with four balls using a mechanical roller to assure complete homogeneity. The samples were kept in airtight container.

Mixing of Cement Paste

The required amount of each dry mix was placed on a smooth, non-absorbent surface and a crater was formed in the center. The required amounts of mixing water as water of consistency containing the admixture with different dosages (0.0, 0.5, 1.0, 1.5 and 2.0% of the water-admixture) were poured into the crater and the cement on the outer edges was turned into the crater by the aid of a trowel. The dry cement around the outside of the crater was slightly toweled over the mixture to absorb the water for about one minute. The mixing operation was then completed by continuous vigorous mixing for about three minutes by means of gauging trowel.

Moulding

Stainless steel ½ inch cubic moulds were used to prepare the cement pastes. Freshly prepared cement paste was placed in the moulds into two approximately equal layers. Each layer was compacted and manually pressed until homogeneous specimen was obtained. After the top of the layer was compacted, the moulds were then vibrated for a few minutes to remove any air bubbles to get a better compaction of the prepared pastes. The surface of the paste was smoothed by the aid of thin edged trowel.

Curing

Immediately after moulding, the moulds were cured in humidity chamber at about 100% relative humidity at room temperature 23±1°C for 24 h then demoulded and cured under tap water up to the time of testing. In the present study, all mixes were moulded and divided into three sets which used in the following curing modes:

Curing Under Tap Water

One set of all cement pastes was cured under tap water immediately after demoulding to study the hydration characteristics after one, 3, 7, 28, 90 days (Osman and Al-Masry, 2014).

Table 1. Chemical analysis of starting materials, (wt%)

Oxides Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	I.L	Total
SRC	21.40	3.67	5.05	64.73	1.50	2.05	0.30	0.22	2.60	99.70
Silica fume	94.81	0.16	0.84	0.89	0.49	0.08	0.20	0.05	2.43	99.95

Curing Under 4% $MgSO_4.7H_2O$ or $MgCl_2.6H_2O$ Solution

Another set of all cement pastes was cured under tap water for 28 days (zero time) then cured under 4% $MgSO_4.7H_2O$ or 4% $MgCl_2.6H_2O$ to investigate their resistance to these aggressive media at the desired testing times 1, 3, 6, 9 and 12 months respectively. The aggressive solution was renewed monthly to maintain constant concentration.

Firing at 200-800°C

Last set of cement pastes was cured under tap water for 28 days, dried at 105°C for 24 h and fired at 200-800°C in intervals of 100°C to investigate their firing resistance. The firing program is carried out in a muffle furnace with a rate of l0°C/min for 2 h at each temperature and cooled to room temperature in the furnace.

Methods of Investigation

Fire Resistance Determination

The fire resistance of cement pastes was studied at 250, 450, 600 and 800°C in a muffle furnace with soaking time for 2 h. The cement pastes were kept to cool in the furnace then, the fire resistance was measured (ignition loss), bulk density, total porosity and compressive strength of each cement paste at a definite temperature.

A set of three cubes for each mix fired at an appropriate temperature were immersed in kerosene for 24 h. Specimens were then weighed (weight of saturated sample) and reweighed suspended in kerosene (weight of suspended sample). Specimens were dried at 105°C for 24 h and weighed in air (dried weight).

The bulk density and total porosity were calculated as in case of water but using the density of kerosene (0.8 g/cm³).

The Ignition loss illustrates the behavior of cement pastes after fire exposure and was assessed as the difference between the weights before and after ignition divided by ignited weight:

$$\text{lgnition loss},\% \frac{\text{Weight before ignition} - \text{Weight after ignition}}{\text{Weight after iginition}} \times 100$$

The compressive strength measurements were done on a compressive strength machine of SEIDNER, Riedinger, Germany, with maximum capacity of 600 KN forces (ASTM, 2007).

Determination of Total Sulphate

The total sulphate content was gravimetrically estimated by using one g of powdered sample dissolved in 5 mL of concentrated HCl, 100 mL of distilled water was added, then boiled for 5 min, then filtered and washed several times with distilled water. Ten milliliters of 10% $BaCl_2$ was added to the filtrate, which was digested, filtered and ignited at 1000°C for 30 min. The total sulphate content was calculated as:

$$SO_3\% = \frac{\text{Weight of ppt}}{M} \times 34.3$$

where, M is the weight of sample in grams.

Determination of Total Chloride

Total chloride content was determined in the hardened pastes by weighing 2 g sample into a stopper conical flask. The specimen was dispersed with 25 mL water and then added with 10 mL of nitric acid (sp. gr. 1.42). Fifty milliliters of hot water was added, heated to near boiling and kept warm for 10 to 15 min. If the supernatant liquid is turbid, it was filtered through a rapid paper (41 filter paper) and washed with hot water and then cooled to room temperature. An excess of standard 0.1 N AgNO3 (16.98 g pure dry $AgNO_3$, in liter) was added and 2-3 mL of nitrobenzene to stopple the flask, then vigorously shaken to coagulate the precipitate, then 1 mL ammounium ferric alum as indicator and titrate against standard 0.1 N ammonium thiocyanate.

Results and Discussion

Effect of Treatment Temperature

The effect of temperature on the properties of cement pastes admixed with various dosages of SAF can be studied by the determination of the weight loss, bulk density, total porosity and compressive strength of hardened cement pastes treated up to 800°C.

Weight Loss

The weight loss of cement pastes admixed with various dosages of SAF as a function of treatment temperature up to 800°C is represented in Fig. 1. The weight loss increases with treatment temperature. This is mainly due to the decomposition of some hydration products (Cook and Hover, 1999). The free water is removed at 105°C, a partial decomposition of calcium silicate hydrate and sulphoaluminate hydrates occurred around 200°C. Moreover, the decomposition of

gehlenite hydrate (C_2ASH_8) is occurred above 200°C and dehydration of calcium hydroxide at 400-500°C (Cook and Hover, 1999). Also, the decomposition of calcium carbonate at temperature 750-800°C is occurred.

On the other side, as the amount of SAF increases up to 1.5 wt% the weight loss increases due to the acceleration of hydration. This leads to increase the hydration products. The weight loss decreases at 2.0 wt% SAF due to the retardation effect which leads to decrease the hydration products as well as the decrease of mixing water. The increase of the weight loss of cement pastes at all treatment temperature may be due to the absence of accelerator which accelerates the hydration and the decrease of free water.

Bulk Density

The bulk density of cement pastes admixed with various dosages of SAF as a function of treatment temperature is graphically plotted in Fig. 2. The results indicate that the bulk density of cement pastes decreases with the treatment temperature up to 250°C. This is related to the removal of the free as well as some of bound water leaving pores that leads to decrease the density.

Generally, the bulk density for all cement pastes increases up to 600°C due to the reaction of silica fume with the decomposed lime forming more cementitious materials that fill some of the open pores. As the temperature increases up to 800°C the bulk density sharply increases due to the activation of hydration with the treatment temperature forming extra cementitious materials. On the other side, as the amount of SAF increases up to 1.5 wt% the bulk density increases due to the acceleration of hydration. The bulk density decreases at 2.0 wt% SAF due to the retardation effect that decreases the hydration products and then the bulk density.

Total Porosity

The Total porosity of cement pastes admixed with various dosages of SAF as a function of treatment temperature is plotted in Fig. 3.

The total porosity decreases with the treatment temperature up to 250°C. This is attributed to that the treatment temperature enhances the hydration of cement clinker phases as well as the reaction of silica fume with CH liberated from the hydration of Portland cement to form additional hydration products that fill more pores (Radwan *et al*., 2011; Komonen and Penttala, 2003). Therefore, the total porosity decreases.

Obviously, the total porosity increases sharply from 250°C up to 800°C for all cement pastes as a result of the formation of microcracks which result from the dehydration of CH crystals, the decomposition of calcium carbonate, increase vapor pressure of steam and crystal transformation of pozzolana as well as increase of crystallinity of the formed hydrates leading to a sort of opening of the pore system of cement paste (Komonen and Penttala, 2003). On the other hand, as the amount of SAF increases up to 2.0 wt% the total porosity increases due to the retardation effect.

Compressive Strength

Figure 4 shows the compressive strength of thermally treated cement pastes admixed with SAF up to 2.0 mass% cured up to 28 days, then subjected to elevated temperature up to 800°C.

The compressive strength of cement pastes increases as a result of enhancing the hydration of unhydrated cement clinker (Walters and Jones, 1991) as well as the improvement of pozzolanic reaction of silica fume with free lime to form extra CSH that has low Ca/Si ratio with high strength (Walters and Jones, 1991).
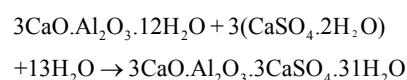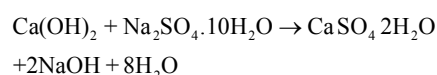
This is also occurred by the internal autoclaving effect that builds up as a result of flow of steam produced from elimination of capillary, physically adsorbed and combined water at high temperature that increases the pressure which accelerates the hydration (Chan and Anson, 1999; Mohammed *et al*., 2014a; Piasta *et al*., 1984).

The compressive strength increases with the treatment temperature up to 600°C due to the pozzolanic reaction of silica fume with the decomposed CaO to produce more C-S-H which deposits in the pore system and forms more dense structure. However, the decrease of the compressive strength at 800°C may be ascribed to the decomposition of cementitious materials as well as the $CaCO_3$.

On the other side, as the amount of SAF increases up to 1.5 wt% the compressive strength increases due to the acceleration of hydration. This leads to increase the hydration products. The compressive strength decreases at 2.0 wt% SAF due to the retardation effect which leads to decrease the hydration products.

Aggressive Attack on Cement Pastes

The presence of sulphate or chloride ions in water leads to an aggressive behavior towards concrete because some constituents of the cement can enter into deleterious chemical reactions with these ions. Sulphates of various bases attack hardened cements very markedly. Magnesium, sodium, potassium, ammonium and various other sulphates react with both free calcium hydroxide in set cement to form calcium sulphate and with its hydrated calcium aluminates to form the more insoluble calcium sulphoaluminate hydrates. The reactions with sodium sulphate, for example, can be formulated as:

$$Ca(OH)_2 + Na_2SO_4.10H_2O \rightarrow CaSO_4 2H_2O$$
$$+2NaOH + 8H_2O$$

$$3CaO.Al_2O_3.12H_2O + 3(CaSO_4.2H_2O)$$
$$+13H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O$$

The alkali sulphates do not attack hydrated calcium silicates to any appreciable extent, they are more insoluble than the calcium sulphate and alkali silicates which would result.
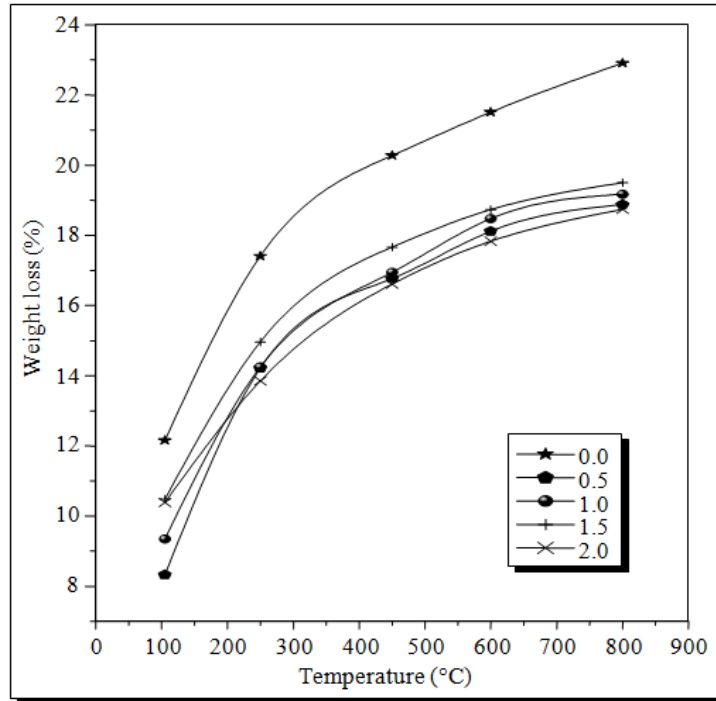

Fig. 1. The weight loss of cement pastes in presence of different dosages of SAF as a function of treatment temperature
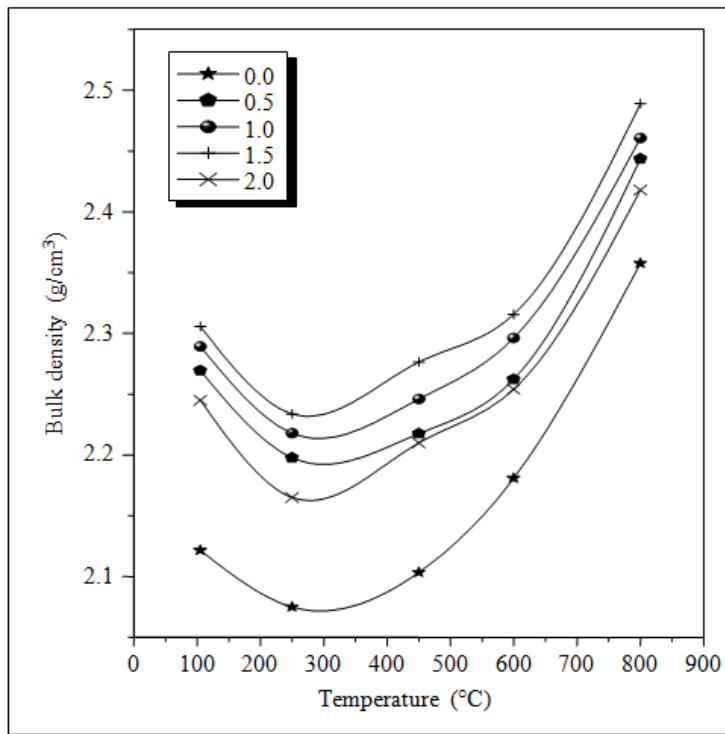

Fig. 2. The bulk density of cement pastes in presence of different dosages of SAF as a function of treatment temperature
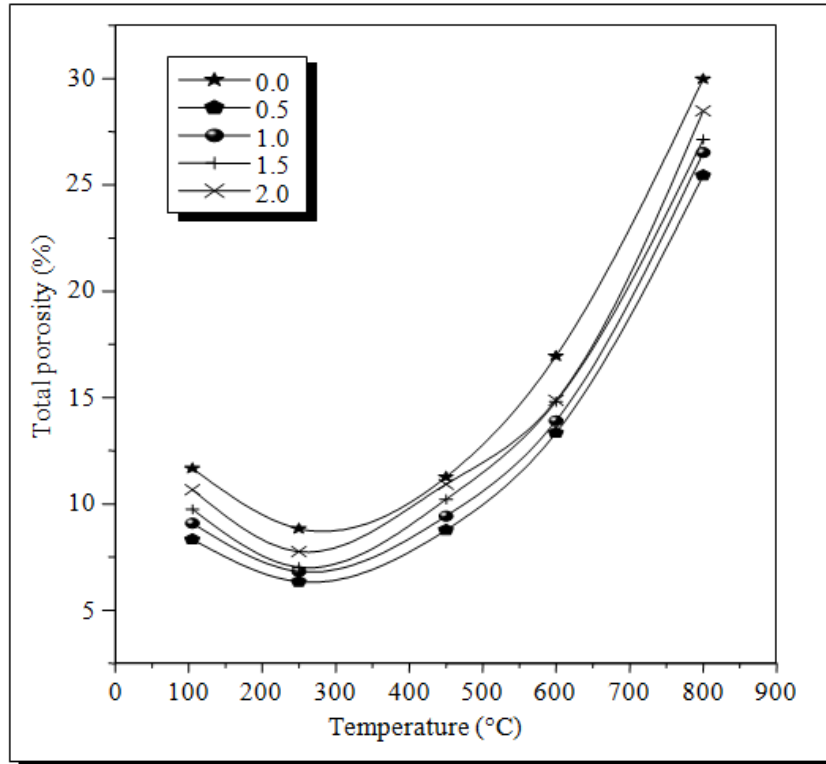
Fig. 3. The Total porosity of cement pastes in presence of different dosages of SAF as a function of treatment temperature
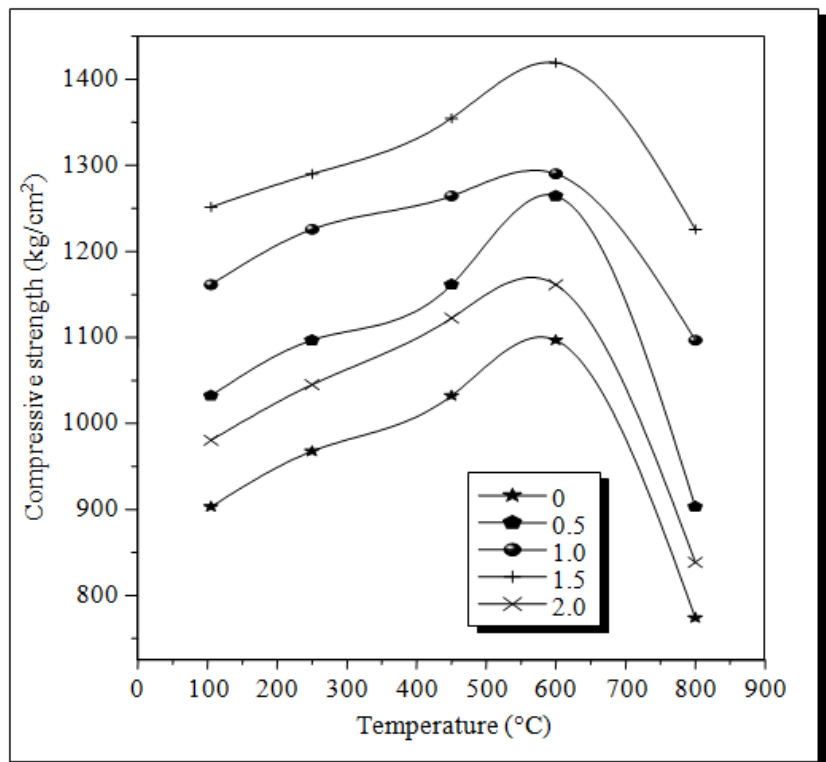

Fig. 4. The compressive strength of cement pastes in presence of different dosages of SAF as a function of treatment temperature

Magnesium sulphate has a more far-reaching action that other sulphates and decomposes the hydrated calcium silicates in addition to reacting with the aluminates and calcium hydroxide. If tri- or β-dicalcium silicate is placed in a magnesium sulphate solution, formation of gypsum crystals occurs rapidly. The hydrated calcium silicates react in the following general manner:

$$3CaO.2SiO_2.3H_2O + 3(MgSO_4 7H_2O) \rightarrow$$
$$3(CaSO_4.2H_2O) + 3Mg(OH)_2 + 2SiO_2 gel$$
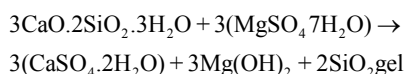
The reason why this reaction proceeds completely, while with sodium sulphate does not occur, is to be found in the low solubility of magnesium hydroxide and resulting low pH value of its saturated solution (Greene, 1962; Mohammed *et al.*, 2014b; Radwan *et al.*, 2012a; Yeon *et al.*, 2013; Radwan *et al.*, 2012b; Fiertak and Stryszewska, 2013). The hydrated magnesium silicate appears to have no binding power, in contrast to calcium silicate hydrate and its formation represents therefore a final stage in the deterioration of concrete attacked by magnesium sulphate solution.

The effect of 4% $MgSO_4$ and 4% $MgCl_2$ on cement pastes admixed with various dosages of Sulfonated Acetone Formaldehyde (SAF) up to one year has been studied. The cubes of cement pastes were immersed in distilled water for 28 days (Zero time), then immersed under the aggressive medium up to one year. The solutions were renewed every month to keep the concentration nearly constant. The relative resistance of hardened cement pastes against the aggressive solutions was assessed by determining compressive strength, bulk density, total porosity, total sulphate and total chloride contents of the attacked cement pastes.

Magnesium Sulphate Solution

Bulk Density

Bulk density of the cement pastes admixed with various dosages of Sulfonated Acetone Formaldehyde (SAF) immersed under 4% $MgSO_4$ solution up to one year are graphically represented in Fig. 5. The results show that bulk density of different cement pastes increases up to 1 month and then decreases up to one year. The increase of bulk density for all cement pastes is due to activation action of sulphate solution and formation of additional hydration products which precipitated into the pores of the pastes and therefore the bulk density increases. The decrease of bulk density after 1 month is due to formation of ettringite crystals, which tend to grow and expand resulting in internal stresses that causes low bulk density. Also, $MgSO_4$ reacts with the liberated Ca $(OH)_2$ and deposits $Mg(OH)_2$ with the decomposition of CSH, which can be decomposed by

$MgSO_4$. These two reactions lead to decrease bulk density of the hardened cement pastes. As the amount of the SAF increases up to 2.0 wt% the bulk density increases due to the filling effect and the acceleration of hydration; more hydration products are formed and then the pores decreases between the cement particles to produce more compact structure.

Total Porosity

The results of total porosity of cement pastes admixed with various dosages of SAF immersed under 4% $MgSO_4$ solution up to one year are shown Fig. 6. It is clear that the total porosity of different cement pastes decreases up to 1 month and then increases up to one year. The decrease of total porosity for all cement pastes is due to the precipitation of the hydration products in the open pores that leads to decrease the total porosity. The increase of total porosity after 1 month may be due to the formation of gypsum and ettringite which are formed due to the action of sulphate solution. The ettringite gives expansion and then the total porosity increases. Consequently there is no disruption, but only increase in total porosity. On the other side, as the amount of SAF increases up to 2.0 wt% the corresponding total porosity decreases. This is due to the acceleration of hydration which forming more hydration products precipitated in the open pores of the cement pastes.

Compressive Strength

The compressive strength values of hardened cement pastes admixed with various dosages of SAF immersed under 4% $MgSO_4$ solution up to one year are shown Fig. 7. It is clear that the compressive strength of different cement pastes increases up to 1 month and then decreases up to one year. The increase of compressive strength is regarded to the progress of hydration as well as sulfate ions activate the hydration of cement pastes and formation of ettringite which fill some of pores and then the compressive strength increases (Chindaprasirt *et al.*, 2014; Binici *et al.*, 2012). The decrease of compressive strength after 1 month may be due to that the sulfate ions migrate from the aggressive medium to the interior of the hardened cement pastes and react with calcium aluminate hydrate and ferrite forming ettringite and/or monosulfate hydrate which expands at later ages causing cracks and deterioration of cement paste. Also $MgSO_4$ reacts with CSH to produce gypsum, silica gel and brucite (Ye *et al.*, 2014). Gypsum reacts at later ages with C_3AH_6 to form additional amounts of ettringite and/or monosulfate hydrate whereas brucite attacks CSH to form CH and MSH which has no binding properties. As the amount of SAF increases up to 2.0 wt% the compressive strength increases. This is mainly due to the acceleration of hydration which increases the amount of hydration products especially

tobermorite-like gel (CSH). Generally, as the amount of accelerator increases the hydration of cement paste enhances and then the pozzolanic reaction between SF and CH increases. Therefore, the bulk density and compressive strength increases as well as the total porosity of the cement paste decreases.
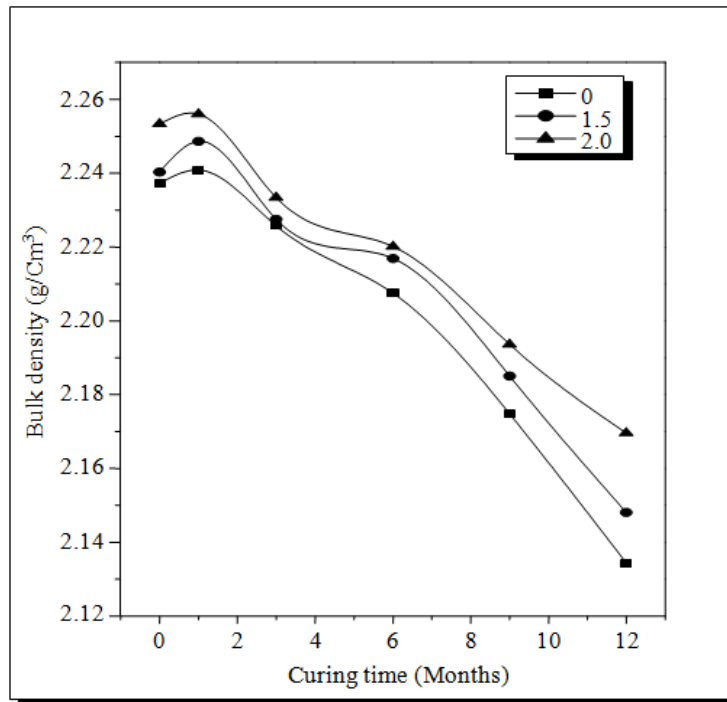

Fig. 5. Bulk density of cement pastes in presence of different dosages of SAF immersed under 4% $MgSO_4$ solution up to one year
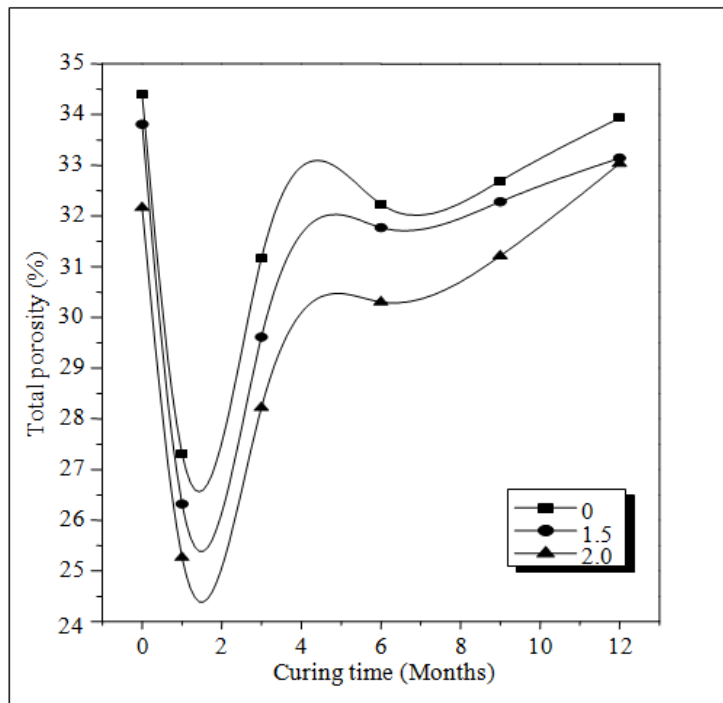

Fig. 6. Total porosity of cement pastes in presence of different dosages of SAF immersed under 4% $MgSO_4$ solution up to one year
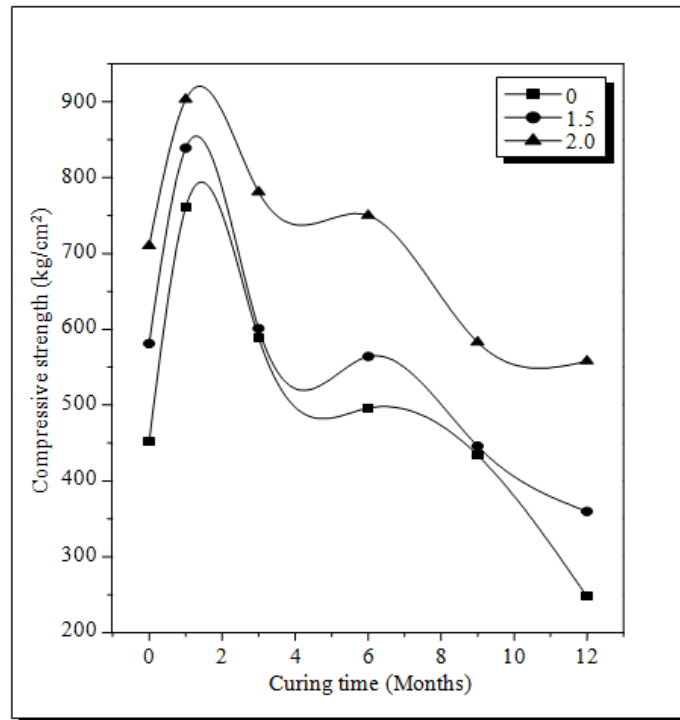
Fig. 7. Compressive strength of cement pastes in presence of different dosages of SAF immersed under 4% MgSO$_4$ solution up to one year

Total Sulphates

The total sulphate of cement pastes admixed with various dosages of SAF immersed under 4% MgSO$_4$ solution up to one year are given in Fig. 8. It is clear that the total sulphate content increases with immersing time up to one year. This is mainly due to the migration of the sulphate ions from the aggressive medium (MgSO$_4$ solution) to the cement pastes which reacts with C$_3$A and Ca (OH)$_2$ forming ettringite and/or calcium monosulphoaluminate hydrate. Also, MgSO$_4$ reacts with calcium silicate hydrate to produce gypsum, silica gel and Mg (OH)$_2$. Gypsum produced reacts furtherly with 3CaO.Al$_2$O$_3$.6H$_2$O to form calcium sulphoaluminate hydrate (ettringite) and/or monosulphate hydrate. As the amount of the SAF increases up to 2.0 wt% the total sulphate content decreases due to the acceleration of hydration; more hydration products are formed and then the pores decreases between the cement particles to produce more compact structure. This is confirmed from the bulk density, total porosity and compressive strength.

Magnesium Chloride Solution

Bulk Density

The results of bulk density of cement pastes admixed with various dosages of SAF immersed under 4% MgCl$_2$ solution up to one year are graphically plotted in Fig. 9. It is clear that bulk density of all cement pastes increases up to 6 months and then decreases up to one year. The increase of bulk density up to 6 months is due to the accelerating action of chloride to the hydration of calcium silicate or calcium aluminate hydrates. So, these hydration products will precipitate into the pores of the paste which lead to increase the bulk density. The decrease of bulk density after 6 months up to one year for all cement pastes is mainly due to the formation of hydration products such as chloroaluminate hydrate which decreases the bulk density. As the amount of the SAF increases up to 2.0 wt% the bulk density increases due to the filling effect and the acceleration of hydration; more hydration products are formed and then the pores decrease between the cement particles to produce more compact structure.

Total Porosity

Total porosity of cement pastes admixed with various dosages of SAF immersed under 4% MgCl$_2$ solution up to one year are given and graphically plotted in Fig. 10. The results show that total porosity of different cement pastes decreases up to 6 months and then increases up to one year. The decrease of total porosity for all cement pastes up to 6 months is due to the accumulation of the hydrated products which fill a part of the originally filled spaces. The increase of total porosity after 6 months up to one year is due to the formation of calcium chloroaluminate hydrate which makes softening, therefore, total porosity increases. This is also due to the formation of Mg(OH)$_2$ as a gelatinous material that

increases the total porosity. On the other side, as the amount of SAF increases up to 2.0 wt% the corresponding total porosity decreases. This is due to the acceleration of hydration which forming more hydration products precipitated in the open pores of the cement pastes.

Compressive Strength

The compressive strength of cement pastes admixed with various dosages of SAF immersed under 4% $MgCl_2$ solution up to one year are given in Fig. 11. It is clear that the compressive strength of all cement pastes increases up to 6 months and then decreases up to one year. The increase of compressive strength is attributed to that chloride ions activate the hydration of cement. Hence formed hydration products fill some of pores then the total porosity decreases and compressive strength enhances. The increase of compressive strength at early ages may be also due to the adsorption and incorporation of a part of Mg^{2+} ions in to the CSH particles which enhance the crystallization of CSH as well as the strength of cement paste. The compressive strength decreases for all cement pastes due to the combination of $MgCl_2$ with CH forming $CaCl_2$ and $Mg(OH)_2$. $CaCl_2$ reacts with C_3A to form chloroaluminate hydrates. While $Mg(OH)_2$ dissociates CSH to form MSH and CH. Both of chloroaluminate hydrates and MSH possess no binding properties and are accompanied by softening and loss of strength, consequently, the strength of hardened cement pastes decrease. The values of bulk density and total porosity are in a good agreement with those of compressive strength at all ages of immersion. The amount of diffused $MgCl_2$ increases with curing time and as a result, deterioration of cement paste enhanced. As the amount of SAF increases up to 2.0 wt% the compressive strength increases. This is mainly due to the acceleration of hydration which increases the amount of hydration products especially tobermorite-like gel (CSH).

Total Chloride

The total chloride contents of cement pastes admixed with various dosages of SAF immersed under 4% $MgCl_2$ solution up to one year are plotted in Fig. 12. The chloride content gradually increases with time up to one year for all cement pastes. This is due to the chemical reactions between chloride ions and the hydrated components, such as calcium aluminate ferrite and Ca $(OH)_2$. The diffusion process of chloride ions in cement pastes is influenced by the cement composition and total porosity. As the amount of the SAF increases up to 2.0 wt% the total chloride content decreases due to the acceleration of hydration; more hydration products are formed and then the pores decreases between the cement particles to produce more compact structure. This is confirmed from the bulk density, total porosity and compressive strength. The reaction of Cl^- ions goes with high rate at early ages due to the decrease of its radius. Therefore the Cl^- content is sharply increases at early ages.
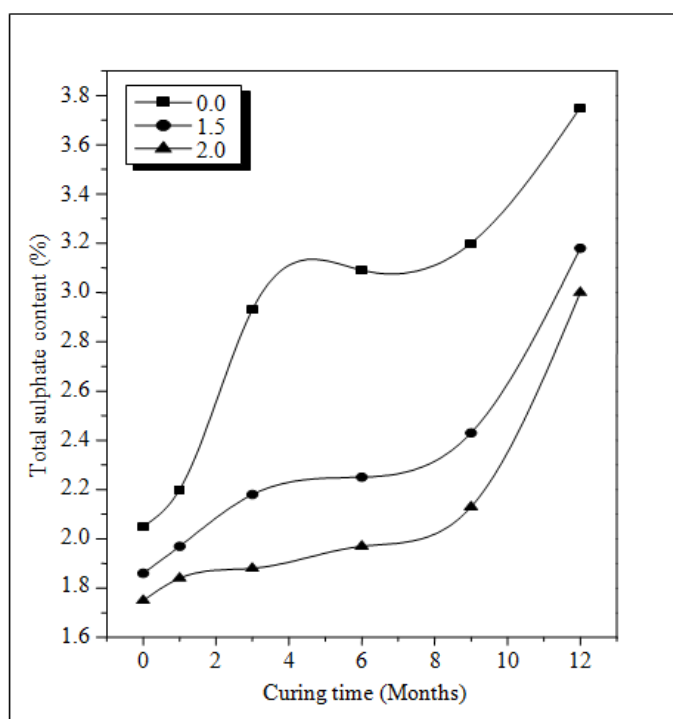

Fig. 8. Total sulphate content of cement pastes in presence of different dosages of SAF immersed under 4% $MgSO_4$ solution up to one year
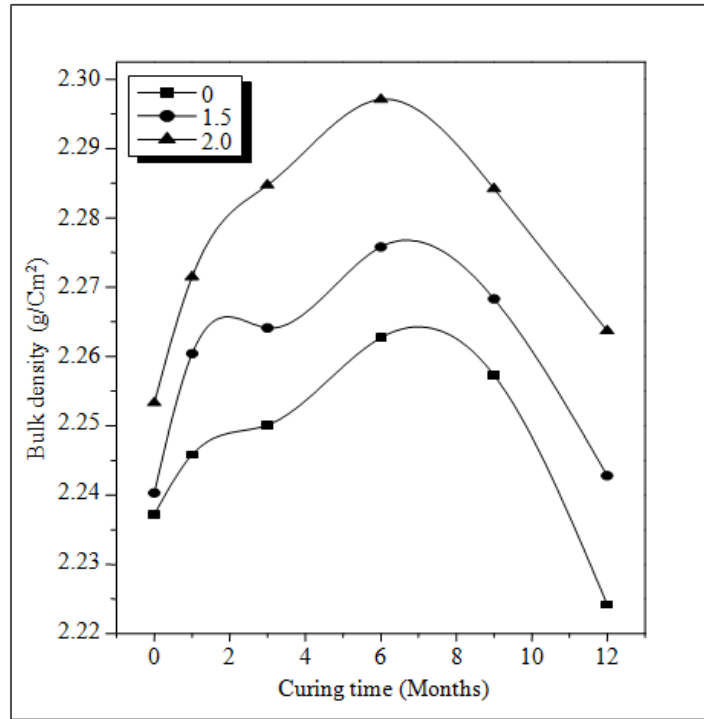
Fig. 9. Bulk density of cement pastes in presence of different dosages of SAF immersed under 4% $MgCl_2$ solution up to one year
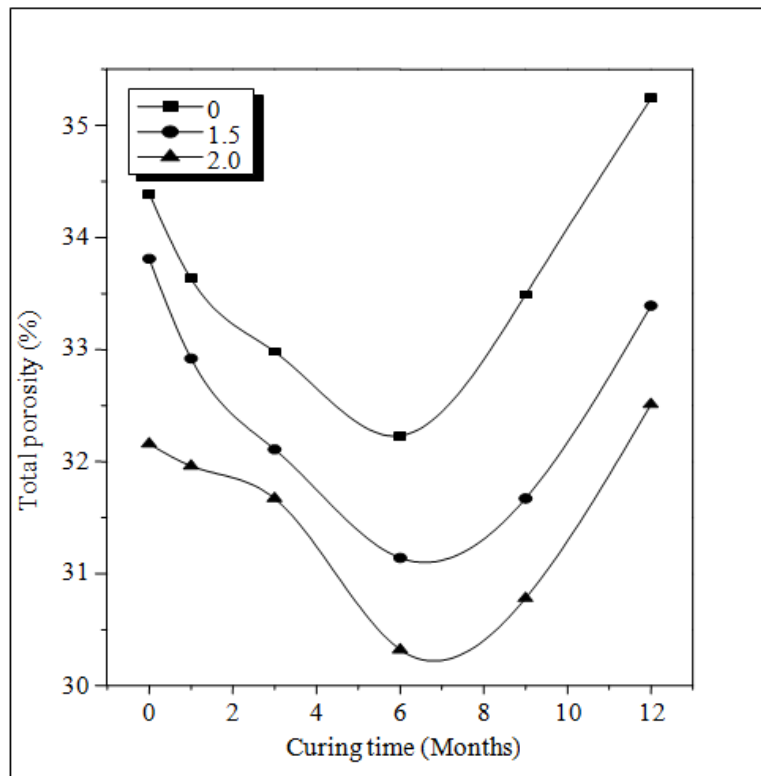

Fig. 10. Total porosity of cement pastes in presence of different dosages of SAF immersed under 4% $MgCl_2$ solution up to one year
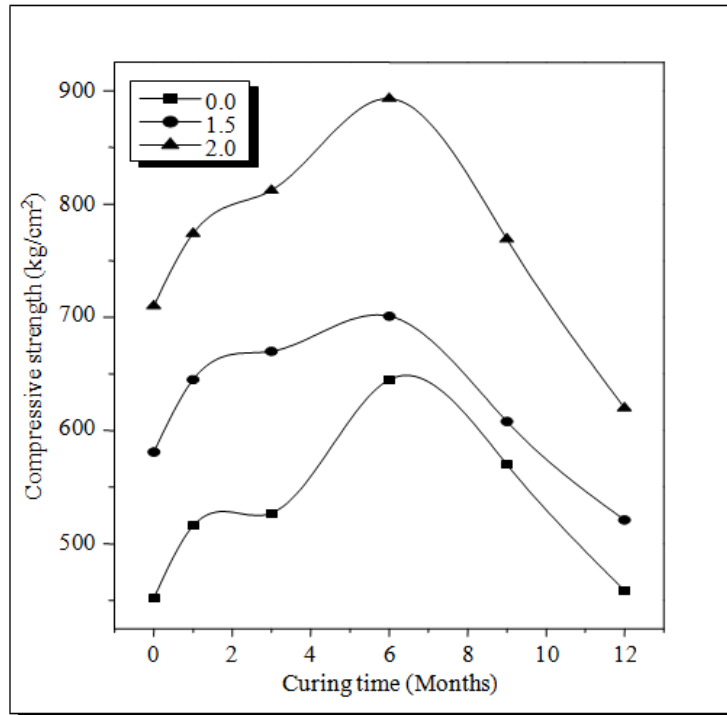
Fig. 11. Compressive strength of cement pastes in presence of different dosages of SAF immersed under 4% $MgCl_2$ solution up to one year
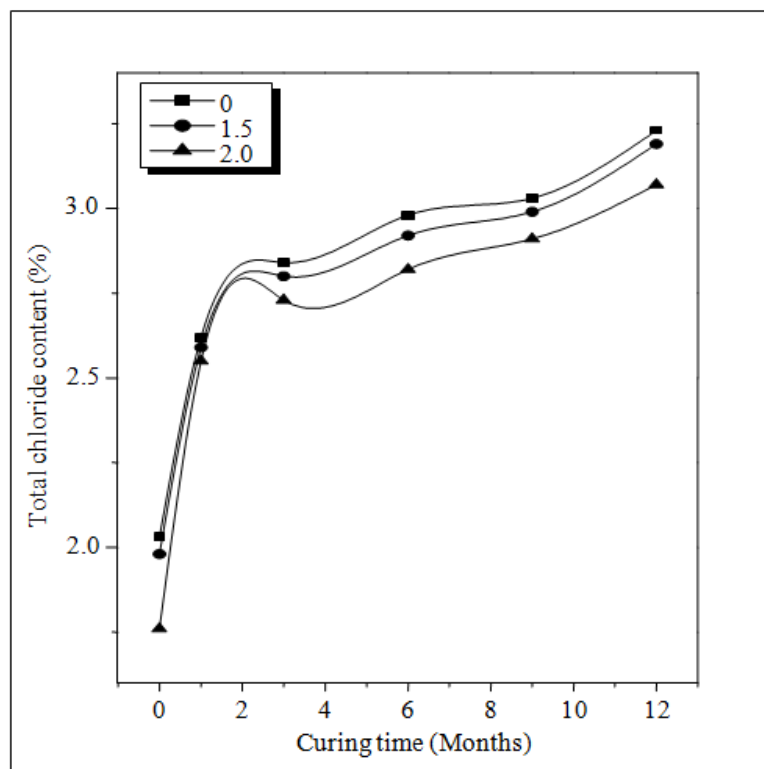

Fig. 12. Total chloride of cement pastes in presence of different dosages of SAF immersed under 4% $MgCl_2$ solution up to one year

Conclusion

Based on the results of experimental study concerning the effectiveness of laboratory prepared SAF superplasticizer dosage up to 2 mass% on the hydration kinetics, total porosity, bulk density, compressive strength and durability of SRC pastes containing 10% SF cured in salt solutions (immersed in 4% $MgSO_4$ or 4% $MgCl_2$) and at elevated temperatures up to 800°C. Several recommendations and conclusions can be derived and presented as follows:

- The total chloride and sulphate contents decrease with SAF content up to 2.0%, due to the pozzolanic reaction of SF with CH forming additional calcium silicate hydrate to fills some open pores, thereby inhibiting the chloride and sulphate ions penetration
- The compressive strength of thermally treated cement pastes admixed with 1.5% SAF increases up to 600°C and then decreases up to 800°C. The increase of compressive strength up to 600°C may be due to the acceleration of the hydration of pozzolanic reaction. The decrease at 800°C is due to the decomposition of cementitious materials and the coarsening of pore size distribution, which drastically increases the total porosity and decreases the bulk density
- SRC-SF composite admixed with 1.5% of SAF is more durable against fire up to 800°C and 4% Mg SO_4 or 4% $MgCl_2$ solutions

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Author's Contributions

All authors equally contributed in this work.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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