Construction and Building Materials 146 (2017) 464–474

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of sea water and $MgSO_4$ solution on the mechanical properties and durability of self-compacting mortars with fly ash/silica fume

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HIGHLIGHTS

- Self-compacting mortars (SCMs) with fly ash and silica fume were exposed to water, sea water and $MgSO_4$ solution.
- Fresh properties of SCMs were evaluated.
- The mechanical properties of SCMs were investigated in water, sea water and $MgSO_4$ solution.
- Sorptivity and porosity of SCMs were investigated.
- FA10 has the best resistance in sea water.

ARTICLE INFO

Article history:
Received 1 January 2017
Received in revised form 2 April 2017
Accepted 13 April 2017

Keywords:
Self-compacting mortar
Silica fume
Fly ash
Magnesium sulfate
Seawater
Fresh properties
Mechanical properties
Durability

ABSTRACT

This experimental study was carried out to investigate the mechanical properties of self-compacting mortars (SCMs) containing binary and ternary mixtures of silica fume (SF) and fly ash (FA) immersed in sea water and 10% by weight magnesium sulfate ($MgSO_4$) solution. 14 series of mortar specimens including control mixture were prepared by replacing Portland cement with 10%, 20% and 30% by weight of C class fly ash (FA) and 6%, 9%, 12% and 15% by weight of silica fume (SF). Ternary mixes were produced by replacing 10% of FA containing 6%, 9%, 12% and 15% of SF and 20% replacement of FA with 6% and 9% of SF. A total of 182 samples of 40 × 40 × 160 mm mortar were prepared and cured in water at 3, 28, 56 and 180 days and immersed in sea water and magnesium sulfate ($MgSO_4$) solution at 28, 56, 90 and 180 days to observe SCMs behavior in hardened conditions**.** Durability properties were evaluated by capillary absorption (sorptivity and porosity tests). Mini slump flow diameter, viscosity and mini V-funnel flow time tests were performed to assess the fresh properties of SCMs containing FA and SF. The results showed that all binary and ternary mixes of SCMs and control specimens exposed to $MgSO_4$ solution have increasing compressive and tensile strength up to 90 days then tend to decrease at the age of 180 days. The control specimens exposed to sea water showed the best resistance in terms of tensile strength. Porosity of SF binary blended SCMs cured in water at 28 days have higher values than ternary blended SCMs and the control specimens cured in water at 28 days have the lowest porosity. The SCMs exposed to magnesium sulfate solution, some deterioration such as crack formation due to surface softening was observed.

1. Introduction

Concrete structures may be exposed to sulfate and chloride salts and various pollutants due to environmental pollution. For this reason, the changes in the physical and chemical properties of the mortars and cements as well as the microstructure by interacting with acids and various salts should be investigated [1,2]. Research on the deterioration of concrete caused by the presence of sulfate ions has been going on for decades. Sulfate attack on concrete is a complex process and many factors can affect sulfate resistance, such as cement type, sulfate cation type, sulfate concentration and exposure time. Sulfate attack generally causes sulfate ions to react with calcium hydroxide and calcium aluminate hydrate resulting in the formation of gypsum and ettringite, which causes expansion, cracking, deterioration and degradation of concrete structures [1–3]. Several attempts have been made to reduce the porosity (high cement content, low w/c ratio) or to

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http://dx.doi.org/10.1016/j.conbuildmat.2017.04.108
0950-0618/

increase the resistance of concrete to sulfur attack using more resistant binder types (sulfate-resisting Portland cement, addition of pozzolans and blast furnace slag). Chemical erosion with ettringite and gypsum can be prevented mainly by limiting the content of C3A, C3S, adding additive material and controlling minimum cementitious materials and other methods [4]. Many authors have reported that the cement is partially replaced by silica fume increases the resistance of concrete to sulfate attack. This beneficial effect is attributed to the reduction in $Ca(OH)_2$ and alumina required for gypsum and ettringite and to the improvement of pore structure [5,6]. Some authors studied the effect of fly ash on the resistance of concrete/mortar to sulfate attack and pointed out that using sufficient amount of fly ash, especially low-calcium or F class fly ash can effectively increase the resistance of the concrete against sulfate attack [3,7–9]. Nie et al. and Irassar et al. [10,11] investigated that mineral admixtures such as fly ash and blast furnace slag or additional admixture cementing materials (SCM) can be used in Portland cement concrete and have been documented to improve the durability of concrete such as sulfate resistance. Sumer [12] noticed that, regardless of the fly ash type, the fly ash addition increases the resistance of the concrete to sulfate attack. Tikalsky [13] concluded that concrete containing fly ash with a low calcium was more resistant to sulfate attack than concrete containing other fly ashes or no fly ash. The durability of concrete in the marine environment has attracted the attention of engineers and scientists for a century. Because seawater movement can cause great damage to marine and offshore structures[14]. Seawater contains about 2800–3000 mg SO_4^- per liter and when those ions move into the concrete, they will react the solution of calcium hydroxide to form solid ettringite called as delayed ettringite [15]. Usually, the nucleation and growth of the delayed ettringite occur in the micro voids in cement mortar materials [13–16]. If the delayed ettringite will grow and touches to the boundary of the voids, producing an expansion force to cement mortar materials. Under the influence of the expansion force, the nucleation and growth of micro cracks will also happen in concretes [6,8,15–17]. Prevention of chemical erosion with ettringite and gypsum can be achieved mainly by limiting the content of C3A, C3S, adding mineral additives and controlling minimum cementitious materials and other methods. Mineral additives are used to improve the mechanical properties of the mixture due to pozzolanic and/or self-cementing [18]. Self-compacting concrete (SCC) has recently emerged as a new concrete technology and its use has increased rapidly over the last three decades and reflected in the number of published works. Self-compacting mortar (SCM) exhibits similar mechanical and durability properties to SCC and can be used to examine the performance mechanisms of the SCC. Mortar forms the basis of the workability properties of self-compacting concrete (SCC) and these properties can be evaluated with self-compacting mortars (SCM). In fact, evaluating the properties of the SCM is an integral part of the SCC design [19,20]. Magnesium sulfate is more harmful than other sulphates because it does not only react with hydrated calcium aluminates, such as calcium hydroxide and other sulphates, but at the same time, hydrated calcium silicates completely break down into a cracked mass. For this reason, magnesium sulfate was selected for the study of sulfate resistance in this study [21]. The test results show that the degree of deterioration of the concrete in the magnesium sulfate solution is more severe than the deterioration in the other sulfate solutions. The presence of chloride ions in the composite solution reduces the rate of deterioration of the concrete and the damage level of the concrete can be effectively avoided [22]. The main objective of this paper is to investigate the mechanical properties of SCMs containing binary and ternary mixtures of silica fume (SF) and high-calcium fly ash (FA) immersed in sea water and 10% magnesium sulfate ($MgSO_4$) solution. 14 series of mortar specimens including control mixture were prepared by replacing Portland cement with 10%, 20% and 30% by weight of C fly ash (FA) and 6%, 9%, 12% and 15% by weight of silica fume (SF). In ternary mixes, 10% replacement of FA incorporating 6%, 9%, 12% and 15% of SF and 20% of FA with 6% and 9% of SF were produced. A total of 182 samples of 40 × 40 × 160 mm mortar were prepared and cured in water at 3, 28, 56 and 180 days and immersed in sea water and magnesium sulfate ($MgSO_4$) solution at 28, 56, 90 and 180 days to observe SCMs behavior in fresh and hardened conditions. Mini slump flow diameter, viscosity and mini V-funnel flow time tests were performed to assess the fresh properties of SCMs containing FA and SF. Sorptivity and porosity tests were performed on to observe the durability properties of SCM samples containing FA and SF.

2. Experimental program

The main purpose of this study is to investigate the strength and durability properties of self-compacting mortars (SCM) by combining high-calcium fly ash and silica fume cured in water and immersed in sea water and magnesium sulfate solution. For this purpose, 40 × 40 × 160 mm specimens were cast with various fly ash and silica fume contents for compressive and flexural testing of SCMs. In this paper, effect of sea water and $MgSO_4$ solution on the mechanical properties of SCMs was studied. Two type mineral additives, FA and SF were used as binary and ternary combinations in mixtures. The mini slump flow and mini V-funnel flow tests recommended by EFNARC [23] were carried out to determine the characteristics of fresh properties of SCM. In addition, viscosities of fresh mortars were measured. The tensile strength in bending and compressive strength tests were performed on SCM mixtures cured in water and immersed in sea water and $MgSO_4$ solution. Furthermore, Sorptivity coefficients and porosity were determined on 50 mm cube samples cured in water for 28 days.

2.1. Materials

An ordinary Portland cement (CEM I 42.5N) was used to produce the various SCM mixtures. Class C fly ash (FA) obtained from Soma Thermal Power Plant and silica fume (SF) obtained from Antalya Electro Metallurgy Enterprise were used as mineral admixture. The chemical components and physical properties of cement and mineral additives are presented in Table 1.

The fine aggregates used in the mixtures were natural river sands with specific gravity, fineness modulus and water absorption of 2.63 g/cm^3, 3.29 and 1.91% respectively. The maximum particle size of sand was 4.00 mm (Fig. 1).

In addition, a modified polycarboxylate-based polymer type superplasticizer (SP) is required to achieve a suitable consistency with a low water/binder (W/B) ratio. The specific weight of SP used

Table 1
Properties of Portland cement and mineral additives.

Chemical components (%)	PC	FA	SF
SiO_2	21.12	42.14	91.0
Al_2O_3	5.62	19.38	0.58
Fe_2O_3	3.24	4.64	0.24
CaO	62.94	29.96	0.71
MgO	–	1.78	0.33
SO_3	2.66	2.43	–
Na_2O	–	–	–
K_2O	–	1.13	–
CI	0.0044	0.0010	–
Loss in ignition	3.52	1.34	1.84
Physical properties			
Specific gravity (g/cm^3)	3.1	2.20	2.2
Specific surface area (cm^2/g)	3490	2900	96.5% < 45 μm