

ASSESSMENT OF THE USE OF SILICA FUME ON DURABILITY OF CONCRETE IN A CORROSIVE ENVIRONMENT

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ABSTRACT

Concrete deterioration in the Persian Gulf region has become a major problem in the last decade, requiring the use of special maintenance, repair materials and techniques. The unique aggressive environmental conditions in the region cause concrete deterioration, mainly by corrosion of reinforcing bars. An evaluation of durability of repair materials under the specific environmental conditions is necessary to ensure a successful repair.

Silica fume has proven to be a highly efficient supplementary cementitious material, improving both the physical and durability characteristics of mortar and concrete.

This research paper assesses the use of silica fume in a cementitious repair mortar, under laboratory and simulated Persian Gulf conditions, to evaluate its durability performance in a hot and humid environment.

Keywords: concrete deterioration, repair mortar, durability, silica fume, cementitious repair mortars, hot and humid environment.

1. INTRODUCTION

The severe environment of the Persian Gulf region causes rapid concrete deterioration, mainly to marine and off-shore structures, such as ports and marine decks. This region is mostly characterized by adverse geomorphic and climatic conditions such as elevated ambient temperatures with wide daily and seasonal fluctuations of heat and humidity, causing progressive micro-cracking, unusual high concentrations of aggressive salts which attack both reinforcement and the cement matrix respectively and also inadequate specifications, poor materials and concrete practices [1]. The sum of these aggressive conditions and their interactive relations affect the durability of concrete structures in the Persian Gulf region and can cause significant concrete deterioration, namely corrosion of reinforcement, corrosion caused by chloride and sulfate attack, salt weathering and environmental non-structural cracking, in a relatively short period of time [2].

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Also, when the severity of the environmental conditions are compounded with poor quality concrete, e.g. inadequate design specifications, contaminated raw materials and defective too construction practices, the deterioration processes increase interactively and become very rapid [3].

Compatibility in a repair system is the combination of properties between the repair material and the existing concrete substrate which ensures that the combined system withstands the applied stresses and maintains its structural integrity and protective properties in a certain exposure environment over a designated service life [4]. Dimensional stability, chemical, electrochemical and permeability properties of the repair material and the repair substrate are the main aspects of compatibility.

The dimensional stability is probably the most important factor which controls the volume changes due to shrinkage, thermal expansion, the effects of creep and modulus of elasticity [5]. The chemical and electrochemical properties include attack due to alkali-silica reaction, sulphate content, pH, electrical resistivity, chloride and carbonation induced corrosion, whereas the permeability and diffusion characteristics of both materials and at the interface between them are the main consideration for a durable combined system.

The strength-associated characteristics of a repair mortar largely allow it to match the concrete substrate. Cementitious repair mortars generally have similar characteristics in terms of modulus of elasticity, coefficient of thermal expansion and creep. Adhesion of the two materials relates to the integrity of the repair and bonding primers also ensure good adhesion to the concrete substrate.

The shrinkage of repair mortars are of the most important properties of a repair system, as high shrinkage leads to cracking, de-bonding and indeed can cause total failure of the repair material.

Permeability characteristics of repair mortars reduce the ingress of chloride ions and carbon dioxide, which are the main cause of damage in reinforced concrete structures.

Various research show that silica fume has proven to be a highly efficient supplementary cementitious material, improving concrete durability. Extensive research has also shown that by using silica fume, the permeability of concrete is reduced, resulting in very durable concrete, even suitable in very aggressive environments [6].

Permeability of concrete is one of the most critical parameters in the determination of concrete durability to aggressive substances. As the permeability of the concrete is lowered, its resistance to the ingress of harmful chemicals increases. Extensive investigations have shown that by using silica fume in concrete, the water permeability is reduced significantly [7]. This is primarily due to the refined pore structure both in the cement paste as well as the interfacial zone between paste and aggregate. Research also shows that the effect of silica fume is more pronounced for low dosage of silica fume and low cement content [8].

Also, intensive laboratory investigations confirm the beneficial effect of silica fume on the resistance of concrete against sulphate, acid and chloride attacks, due to the improved durability of the pore structure and reduced permeability and also the reduced content of calcium hydroxide and increased incorporation of aluminum in the reaction process; silica fume concrete has a reduced amount of aluminum available for ettringite production [9].

In the presence of silica fume, the capacity of the cement paste to bind chlorides is reduced [10], thus concrete containing silica fume has a lower threshold value for the critical chloride content compared to that of ordinary portland cement.

While the compressive strength of a repair mortar may be a useful guide for indicating

compatibility between the concrete substrate and repair material; now it has been comprehended that quite a number of other properties are important for a durable repair. These properties include low shrinkage and low permeability of the repair material [8]. Due to movements caused by loading or changes in temperature and humidity, it is necessary that the repair mortar has similar modulus of elasticity values to the concrete substrate, which in turn tends to indicate similar compressive strength values. A great difference in these properties may result in failure of the repair due to differential movement. The thermal compatibility of the two materials is important and changes in temperature such as thermal cycles may cause de-bonding of the two materials.

The durability of a repaired structure is much more than the durability of the repair material. The composite structure, consisting of the old concrete structure and the new repair mortar must be able to withstand mechanical and thermal stresses, wetting and drying cycles and most importantly the effect of shrinkage of the new material pasted on the old, already shrunk concrete, without any significant deterioration. In fact, the most significant deterioration likely to occur for repaired structures is the de-bonding of the new repair material, at or near the bonding plane, that often is the weakest point of the composite structure. This interfacial zone is not only the preferential zone of rupture, but it is also the most stressed zone of the composite structure and it has a composition different from that of the two materials that are linked. The durability of the bonding of the two materials is thus very different from the durability of both the old and new concretes.

A common approach to the selection of repair materials is based on assessment of individual properties against defined criteria; which has limited value as the relationship between different properties of the repair, between the repair and substrate and also exposure conditions normally determine field performance [9]. The mix design, including selection of appropriate materials significantly influences the performance of the repair. To achieve a good, compatible and durable repair, it is necessary to study and understand the performance characteristics and also limitations of the application of repair materials. In order to evaluate the suitability of using repair materials, it is essential to assess their properties, interaction of these properties and also their actual behavior in service conditions, prior to use.

In this research study the durability performance of a repair system containing silica fume is compared to a control mortar, under simulated hot and normal laboratory environments, in order to evaluate the behavior of these mortars in actual service conditions in the south of Iran.

2. EXPERIMENTAL WORKS

The experimental study carried out includes determining the properties, simulation of mechanical and durability characteristics of the two repair mortars in two different curing environments (laboratory and Persian Gulf environment).

The repair mortars studied in this project were as follows :

- Control mortar, referred to as "SH" mix
- Modified cementitious mortar containing silica fume, referred to as "MS" mix

2.1 Materials

Chemical analysis of the type II Portland cement and silica fume used in this study is shown in Table 1.

Table 1 Chemical analysis of Portland cement and silica fume

Chemical analysis	Portland cement %	Silica fume %
SiO ₂	20.52	91.1
Al ₂ O ₃	5.5	1.55
Fe ₂ O ₃	4.3	2.00
CaO	62.78	2.24
MgO	1.6	0.60
NaO ₂	0.5	-
K ₂ O	0.4	-
Ignition Loss	1.74	2.10
Free lime	0.84	-
SO ₃	1.44	0.45

Natural siliceous sand was used in all mixes, with a maximum size of 4mm. A superplasticizer based on melamine sulphonate naphthalene was also used where needed, to adjust the flow of the mixes.

2.2 Mix design

Details of the mix design of the repair mortars considered in this study are shown in Table 2. The water-cement (w/c) and cement-aggregate (c/a) ratios were kept constant in all the mixes.

Table 2 Mix proportions and properties of mortars

Mix	C/A *	W/C *	SP ** %	Silica * Fume %	Flow cm	Density kg/m ³
SH	1:1.25	0.35	0.5	-	13	2205
MS	1:1.25	0.35	1	7	14	2153

* by weight of cement

** Melcret superplasticizer

After casting and demolding, the specimens were fog cured at 20°C for seven days, then transferred to the two curing conditions:

(A) - Laboratory conditions (20°C, 45% RH)

(B) - Simulated Persian Gulf environment (35°C, 65%RH)

2.3 Test procedures

The tests performed on the repair mortars in this study included the following:

- Compressive and flexural strengths, in accordance with ASTM and British Standards
- Drying shrinkage, in accordance with the ASTM Standard

- Capillary water absorption, in accordance with the RILEM Standard
- Initial surface water absorption (ISAT) test in accordance with the ASTM Standard
- Chloride penetration, in accordance with ASSHTO specifications: 15cm cubes were immersed in a 15.7% NaCl solution at the age of 28 days, and tested at various ages.
- Permeability and porosity tests in accordance with the DIN Standards
- Bonding strength: Substrate concrete specimens (30×40×20cm³ blocks) were sand blasted and repaired with each mix, using suitable primers and bonding strength was tested after 28 days by drilling core samples and using the pull-off test method.

3. TEST RESULTS AND DISCUSSION

3.1 Compressive and flexural strength

The compressive strength development of the mixes for both curing conditions are shown in Figure 1. As it can be seen, the samples cured in the hot simulated environment had lower values than those cured in the laboratory.

Repair mortars with high initial compressive strengths will also have a high dynamic modulus of elasticity, resulting in the increase of stress at the substrate-repair interface, therefore this parameter is not a suitable guide for indicating compatibility between the concrete substrate and repair material.

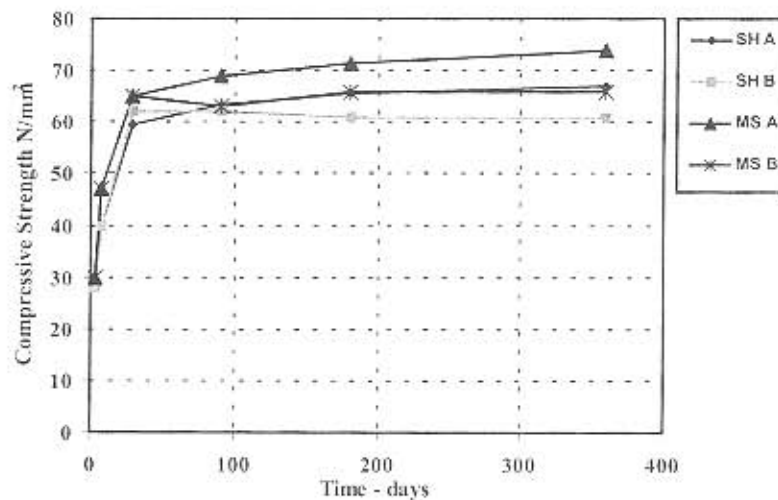


Figure 1 Compressive strength test results

The flexural strength for the two mixes (cured in both A and B conditions) is shown in Figure 2 respectively. In both tests the silica fume modified samples had the higher strengths. The simulated Persian Gulf environment caused loss of strength in all mixes, this effect was less noticeable for the mortar containing silica fume, compared to the control mix.

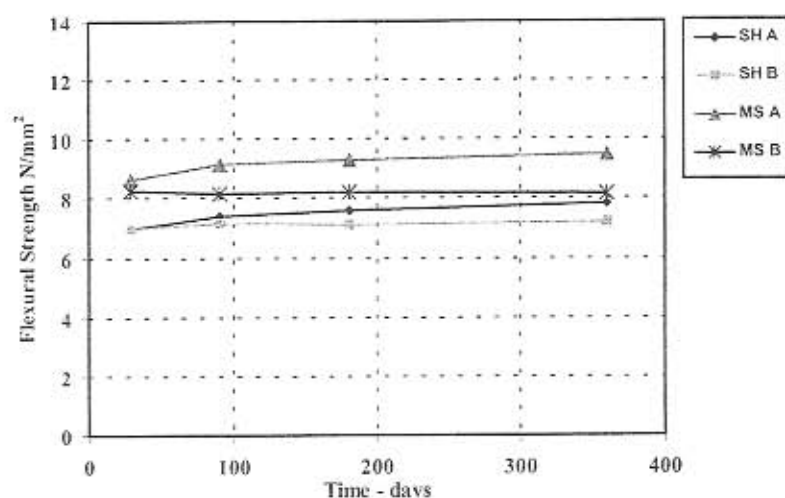


Figure 2 Flexural strength test results

Table 4 shows flexural/compressive strength ratios for the two mixes. This ratio is an important indicator of improving the repair mortar characteristics, specifically ductility, that indicates increased stress capacity in these mortars. These results indicate that silica fume addition to the repair mortar increases this ratio.

Table 4 Flexural/compressive strength ratios for mixes

Mortar		Flexural/Compressive Strength Ratio (%)			
		28 days	90 days	180 days	360 days
SH	A	11	11.6	11.6	11.7
	B	11	11.5	11.6	11.8
MS	A	2.6	2	1.5	2.3
	B	2.6	2.6	1.2	1.2

3.2 Drying shrinkage

The drying shrinkage curves for the mixes considered in this investigation are presented in Figure 3. The MSA mix had the lowest and the SHB mix showed the highest drying shrinkage. All mixes cured in the simulated hot environment had higher amounts of drying shrinkage.

3.3 Capillary water absorption

The capillary water absorption (at 72 hours) test results is shown in Figure 4. The results indicate that addition of silica fume significantly decreases the absorption characteristics of the repair mortars. The SHB and MSA mixes had the highest and lowest amounts of absorptivity. The test results show that by using silica fume in the mixes, the capillary water absorption decreases dramatically.

These results may be attributed to the pore-filling characteristics of silica fume, when incorporated into concrete or mortar mixes, inside the cement matrix, blocking off paths that water may permeate through, thus decreasing the penetration of water into the mortar.

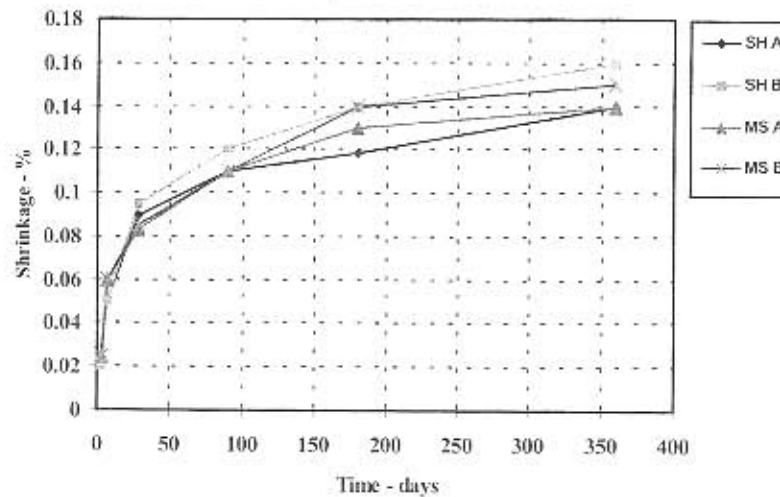


Figure 3 Drying shrinkage test results

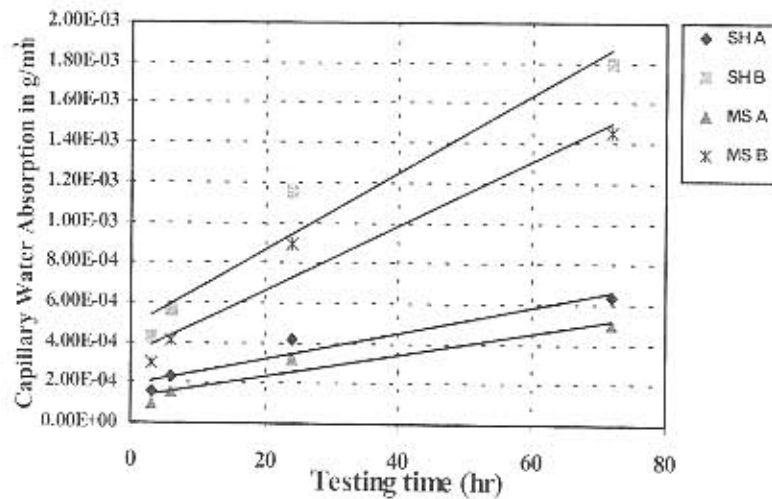


Figure 4 Capillary water absorption test results

3.4 Initial surface water absorption

The initial surface water absorption test results are shown in Figure 5. The results indicate that addition of silica fume significantly decreases the absorption characteristics of the repair mortars. The SH B and MSA mixes had the highest and lowest amounts of absorption.

These results may also be attributed to the pore-filling characteristics of silica fume, when

incorporated into concrete or mortar mixes. The fine silica fume particles fill in the voids in the cement matrix, thus the paths that water may permeate become limited, decreasing the penetration of water.

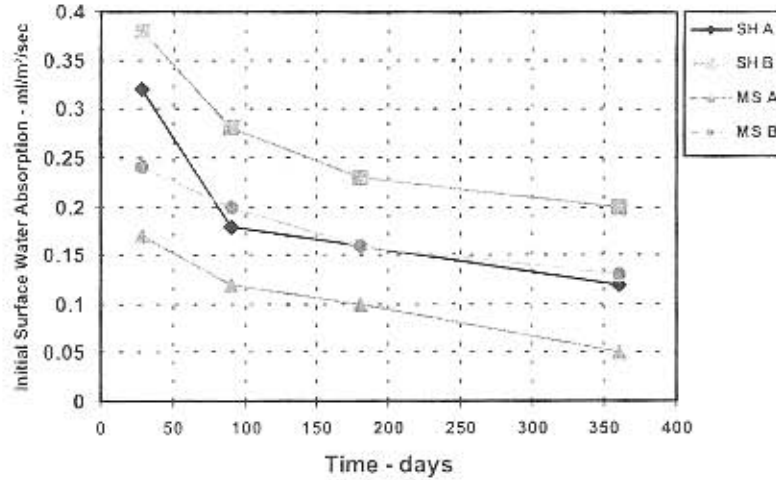


Figure 5 Initial surface water absorption test results

3.5 Chloride penetration

The chloride penetration test results (obtained after 60 days immersion in chloride solution) for the mixes are shown in Figure 6. It can be seen that addition of silica fume increases the chloride penetration resistance of the repair mortar. This reduction in permeability can be attributed to the fact that silica fume particles, being much smaller than the sand and cement particles, fill the smaller pores, thereby improving impermeability characteristics of the repair mortar.

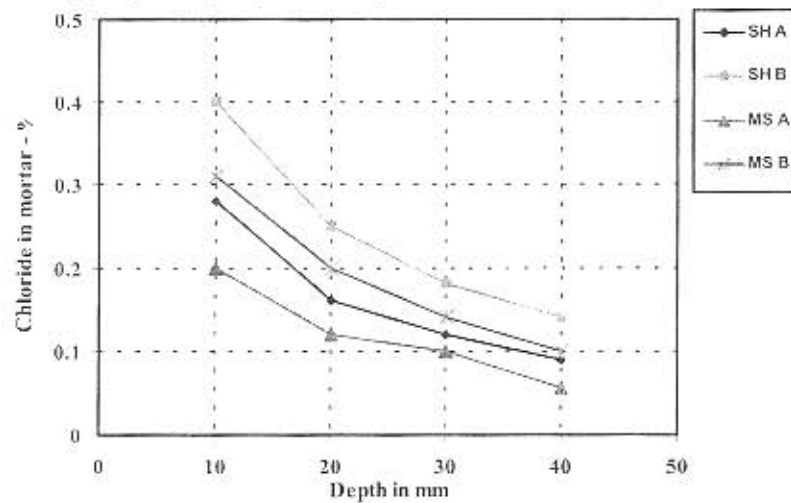


Figure 6 Chloride profile for all mixes

3.6 Permeability and porosity

The permeability and porosity test results for all mixes are shown in Figure 7 and Table 4 respectively. It can be seen that the simulated hot environment (B) causes an increase in the permeability in most of the mixes. The porosity of all the repair mortars also increases in the hot environment. The results show that silica fume reduces the permeability and porosity of the repair mortars. This can be attributed to pore-modifying characteristics of silica fume, reducing the penetration of water (and therefore harmful substances) into the mortars.

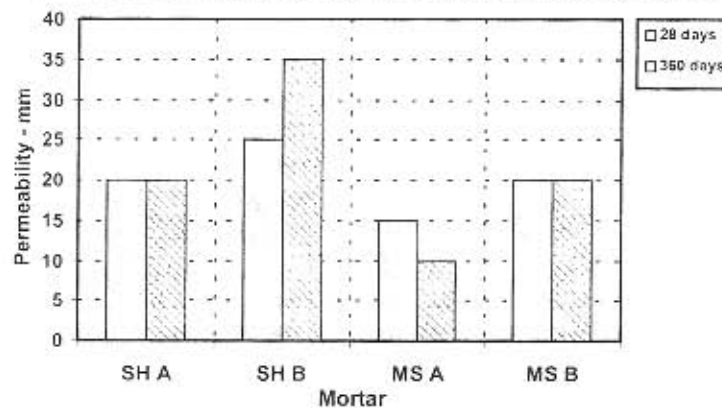


Figure 7 Permeability of repair mortars

Table 4 Porosity of repair mortars

MORTAR	Porosity - %	
	Laboratory Conditions (A)	Simulated Hot Environment (B)
SH	13	16
MS	6.9	9.3

3.7 Bonding strength

The bond strength results obtained from the pull-off test for the mixes in this study are shown in Figure 8. It can be seen that the hot environment (B) causes lower bonding strength in the mixes. The results also show that using silica fume in the bonding primer enhances bonding strength of the repair mortar to the concrete substrate. This can be attributed to improved bonding and adhesion between the modified repair mortar and to the old concrete.

4. CONCLUSIONS

From the test results in this study the following conclusions may be drawn:

The addition of silica fume enhances the physical properties and durability of repair mortars, in comparison to the control mix.

- The hot simulated Persian Gulf environment has a negative effect on the characteristics of all the mixes, which is mainly due to accelerated hydration, resulting in non-uniform distribution of hydration products in samples cured in the hot environment, increasing the porosity of these mixes. It is essential to reduce the permeability of repair mortars in such a detrimental environment, to decrease the penetration of harmful substances into the concrete.
- Addition of silica fume to the samples tested in this study caused a reduction in the porosity and permeability of the repair mortars, thereby limiting the penetration of corrosive substances into the concrete.

REFERENCES

1. Rasheeduzzafar, D. and Gahtani, A.S., "Corrosion of Reinforcement in Concrete Structures in the Middle East", *Concrete International, American Concrete Institute*, No.9, 7(1985)48-55.
2. Al-Rabiah, A.R., Rasheeduzzafar, D. and Baggott, R., "Influence of Cement Type and Mix Composition on Concrete Deterioration in the Marine Persian Gulf Environment", *Proceedings of the 3rd International Conference on Deterioration and Repair of Reinforced Concrete in the Persian Gulf*, Oct. 1989, Bahrain, Vol. I. pp. 493-528.
3. Rasheeduzzafar, Dakhil, F.H. and Bader, A.M., "Toward Solving the Concrete Deterioration Problem in the Gulf Region", *The Arabian Journal of Science and Engineering*, Theme Issue on Concrete Durability, No.2, II(1986) 131-146.
4. Ohama, Y., Demura, K. and Pareek, S.N., "Evaluation of Corrosion Inhibiting Properties of Polymer-Modified Mortars", *Proceedings of the 3rd International Conference on Deterioration and Repair of Reinforced Concrete in the Persian Gulf*, Oct. 1989, Bahrain, Vol. I, pp. 581-590.
5. Ohama, Y. and Demura, K., "Carbonation Resistance of Polymer-Modified Mortars", *Transactions of the Japan Institute*, 9(1987) 195-202.
6. Ohama, Y., Notoya, K. and Miyake, M., "Chloride Permeability of Polymer-Modified Concretes", *Transactions of the Japan Concrete Institute*, 7(1985) 165-172.
7. Decter, M.H. and Humphrey, M.J., "Primary Properties of Cementitious Repair Mortars to Achieve Long-Term Durability", *Proceedings of the 4th International Conference on Deterioration and Repair of Reinforced Concrete in the Persian Gulf*, Oct. 1993, Bahrain, Vol. II, pp. 855-872.
8. Bamforth, P.B., "BRITE-EURAM Project 3291: The Development of Standardized Performance Tests and Criteria for Concrete Repair Systems", *BRITE-EURAM Workshop on Construction*.
9. Pocock, D.C., "The Selection of Cost-Effective Repair Strategies for Corrosion Damaged Concrete Structures", *Proceedings of the 5th International Conference on Deterioration and Repair of Reinforced Concrete in the Persian Gulf*, Oct. 1997, Bahrain, Vol. II, pp. 147-161.