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Effect of pozzolans on the performance of fiber-reinforced mortars

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Abstract

Randomly oriented short fibers have been shown to increase tensile strength and retard crack propagation of cement based materials such as fiber-reinforced mortars for diverse applications, especially in aggressive environments. In the case of reinforced concrete, it is very important to produce a ''high quality'' cover in order to prevent corrosion of the rebars. In order to obtain a high performance material the use of a pozzolan is advisable because low permeability is achieved. The objective of this research was to determine the effect of pozzolans such as silica fume (SF), fly ash (FA), and metakaolin (MK) on the properties of fiber-reinforced mortars. Different types of natural and synthetic fibers were used. A superplasticizer was used to keep the same workability as that of the control mortar. Results of the mechanical and durability properties of the fiber-reinforced mortars are reported. The results show that a loss of resistance due to embedding fibers in mortar is compensated for by the increase in strength caused by silica fume or metakaolin additions to the mortar. The addition of 15% of SF or MK produces an improvement of up to 20% and 68%, respectively, when compared with those mortars without addition. There is a significant decrease in the coefficient of capillary absorption and chloride penetration when a highly pozzolanic material is incorporated into the matrix. In general, these materials, especially SF and MK, improve the mechanical performance and the durability of fiber-reinforced materials, especially those reinforced with steel, glass or sisal fibers. The fly ash addition had a different performance, which could be attributed to its low degree of pozzolanicity.

Keywords: Fiber-reinforced mortars; Pozzolan; Fly ash; Metakaolin; Silica fume; Natural fibers; Synthetic fibers

1. Introduction

It is very important to obtain high performance mortars for utilization in some applications, for instance as a material to be used for shotcreting in repair and rehabilitation applications. Considerations about the durability of the material are very necessary, particularly when a structure is subjected to severe marine and industrial environments [1,2].

Incorporation of fibers in cementitious materials has gained importance, in part because of the reduction of shrinkage cracking, which it can improve the durability of the materials. The arresting shrinkage cracks may help diminish the permeability of a material. However, it is well known that, in general, the compressive strength of the material reduces and the permeability increases because of the embedding of some types of fibers into matrixes. To compensate for these changes, an important option is the use of supplementary materials, which can lead to densification of the mortar.

The main task of this investigation was to determine the effects of the incorporation of various supplementary materials on strength, permeability, and chloride diffusion of a Portland cement mortar, with and without the fiber reinforcement. Both natural and synthetic fibers were studied. Also, the electrochemical behavior of reinforcing bars (rebars) incorporated in such mortars was determined.

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2. Experimental program

A Portland cement which is marketed as ASTM Type V was used. Its properties, together with those of four supplementary cementing materials are reported in Table 1. These additions were a commercial silica fume (SF); a blast furnace slag (GGBS) from Companhia Siderurgica Tubarão in Brazil; a metakaolinite (MK), obtained by thermal activation of a Kaolin from Antioquia (Colombia); and a fly ash (FA) from Manizales (Colombia). The silica fume, metakaolinite and fly ash were added at amounts of 15% by weight relative to the cementitious material content (Portland cement + addition), while the GGBS was proportioned at 70% of the cementitious fraction. The mixes used were prepared by blending the Portland cement with each one of the mentioned pozzolans. The cementitious matrixes were all mortar mixes. A graded natural river sand with a maximum particle size of 6 mm was used. The sand–cement ratio (by weight) of the mixes was 3:1. Superplasticizer–cement ratio fluctuated between 0.015 and 0.03. The amount used for each mix was that necessary to achieve a specified range of mortar flow between 100 and 115 (NTC 111). Because of this fact, the water—(Portland cement + addition) ratio varied between 0.52 and 0.64.

Six different types of natural (Fique, F; Sisal, S; and Coir, C) and synthetic (Steel, St; Glass, G; and Polypropylene, PP) fibers were used. Fique is a native Colombian plant from which a fiber is extracted. Sisal and coir (coconut) fibers were sourced from Brazil [3]. The fibers were chopped into 10 mm lengths. These were embedded in the blended cement mortars in the proportion of 2.5% by weight of the cement. The designations of the various mortar mixes are noted in Table 2.

A conventional food mixer was used to prepare the mixes which were cast in specimen moulds as follows:

- 50 mm cubic specimens were prepared for the measurement of compressive behavior at 3, 7, 28, 60, and 90 days of normal curing according to ASTM C39.

Table 1
Properties of Portland cement and supplementary materials

Component	Cement	GGBS	FA	MK	SF
SiO_2	20.99	33.19	56.73	52.52	96.85
Fe_2O_3	3.64	0.6	6.58	1.84	0.50
Al_2O_3	5.24	15.74	19.30	44.65	1.88
CaO	63.99	42.11	5.54	0.34	–
MgO	1.78	7.89	2.98	0.00	0.00
Loss on ignition	2.22	0.00	6.51	1.71	0.43
Density, kg/m^3	3140	2880	2500	2570	2270
Pozzolanic activity index with cement at 28 days	–	98.4[a]	75.2[b]	92.6[b]	103.6[c]

[a] ASTM C989.
[b] ASTM C618.
[c] ASTM C1240.

Table 2
Designation of mixes

Mix type	Matrix
M1	Cement mortar without addition
M2	Cement mortar + 15% silica fume (SF)
M3	Cement mortar + 15% metakaolin (MK)
M4	Cement mortar + 15% fly ash (FA)
M5	Cement mortar + 70% ground granulated blast furnace (GGBS)

- 50 × 100 mm (diameter × height) cylindrical specimens were prepared for total absorption and percentage permeable void volume testing at 31 days of curing according to ASTM 642, and for the determination of the capillary absorption coefficient at 45 water curing days following an European standard procedure [4].
- 95 × 50 mm (diameter × height) cylindrical specimens were prepared for Chloride penetration testing at 30 standard curing days according to ASTM C1202.
- Specimens for electrochemical monitoring were prepared by casting and compacting mortar with a steel bar located centrally in a 50 × 100 mm (diameter × height) cylindrical mould. The ends of the bar had previously been wrapped with insulating tape, leaving an exposed area of 1600 mm^2. After demoulding, specimens were partially immersed in a 5% NaCl solution. The corrosion potential (E_{corr}) and corrosion rate (I_{corr}) of each of the embedded bars were monitored over eight months by, respectively, the half-cell potential (ASTM C876) and linear polarization resistance (ASTM G59) techniques. The value of I_{corr} was calculated from the Stern–Geary equation:

$$I_{corr} = B/R_p \quad (1)$$

where B is 26 mV, the value recommended for the active or corroding steel, and R_p is the polarization resistance.

3. Experimental results and discussion

3.1. Compressive strength

Some of the additions were observed to enhance the compressive strength of the Portland cement mortar (M1) as can be seen in Fig. 1. The incorporation of SF, GGBS, and MK increased the average compressive strength by 23%, 19%, and 6%, respectively.

As expected, the incorporation of fibers in the plain mortar caused a reduction in its compressive strength. For comparative purposes the results obtained at 90 curing days are presented in Fig. 2. In the case of steel fibers a small decrease (6.6%) was noted, but for PP and sisal a considerable reduction (~30%) was observed. However,

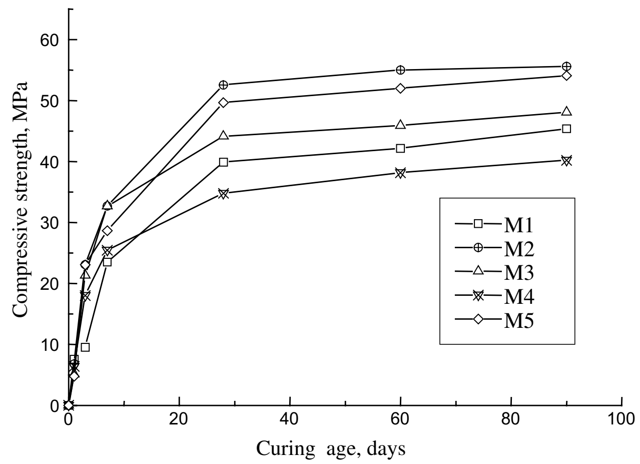

Fig. 1. Effects of additions on the compressive strength of the plain mortar.

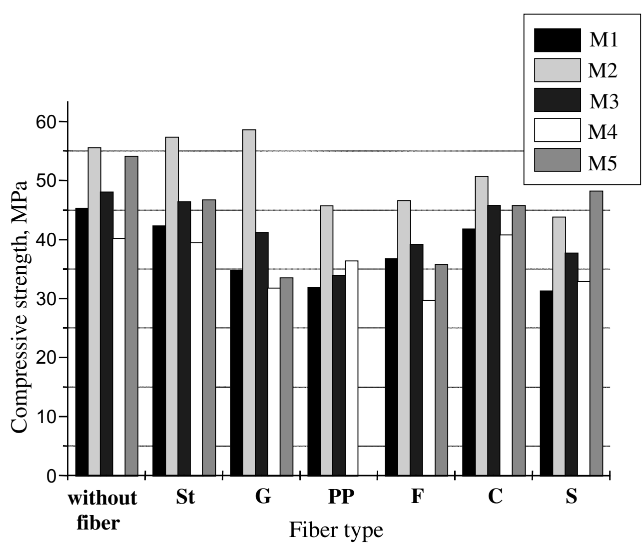

Fig. 2. Effects of the incorporation of the fibers on the compressive strengths of mortars at 90 days.

the incorporation of a highly active pozzolan or slag tended to compensate for this loss of performance, causing in some cases an overall increase in strength of 30%. Such was the case when SF was added to the matrix reinforced with steel or with glass fibers.

The compressive strength of the matrix reinforced with glass fibers gained an increment of 68% when SF was included as a part of the cementitious material. However, the introduction of FA did not cause any effect. This behavior of the additions is directly related to their respective Pozzolanic activity index values, determined in accordance with ASTM C618 and C989 and reported in Table 1.

3.2. Water absorption

The steel fiber reinforced material with the inclusion of SF showed the lowest percentage of water absorption, evaluated according to ASTM C642. In general, the incorporation of SF improves the water absorption properties of the material because of the reduction of permeable voids. The same behavior was reported by Aguilar et al. [5] when they studied steel and nylon fiber reinforced Portland cement matrices with additions of SF and GGBS.

The coefficient of capillary absorption (K) was also determined, following the Fagerlund method [4]. This coefficient is directly related to the internal pore structure. Values of K for the different hardened mixes are presented in Table 3. A reduction in the K value is expected when a pozzolanic material is added to the matrix. SF addition had the greatest effect, followed by MK addition.

The greatest capillary reductions were generated by the inclusion of SF to the glass, sisal and steel fiber reinforced materials and the inclusion of MK to the natural fiber reinforced materials. This behavior is in accordance with findings reported by several authors [6,7], who recommend the addition of SF and MK in order to increase the durability of glass fiber reinforced mortars because of the alkaline attack of the reinforcement and therefore improve durability. These researchers also recommended the utilization of SF for steel fiber and natural fiber reinforced materials.

A comparison suggests that higher compressive strengths results correlate with lesser capillary absorption coefficients. Glass fiber features strong bond with the cementitious interface, which result in the highest compressive resistance and the minor value of the capillary absorption coefficient, if compared to the other reinforcing fibers when density of its interface is increased with a very active and fine pozzolan as is the silica fume.

3.3. Chloride penetration

The results of the chloride penetration determinations are shown in Fig. 3. This figure illustrates the increments or reductions in the total ampere-seconds (coulombs) of charge passed through a cylindrical specimen when a potential is applied during a monitoring period. The charge is directly related to the resistance

Table 3
Coefficient of capillary absorption, $kg/m^2 s^{1/2}$

Mix	M1	M2	M3	M4
Without fiber	0.0226	0.0043	0.0098	0.0184
Steel	0.0219	0.0123	0.0175	0.0188
Glass	0.0264	0.0062	0.0290	0.0239
Polypropylene	0.0239	0.0148	0.0294	0.0184
Fique	0.0249	0.0137	0.0133	0.0248
Coconut	0.0166	0.0165	0.0090	0.0171
Sisal	0.0220	0.0103	0.0098	0.0183

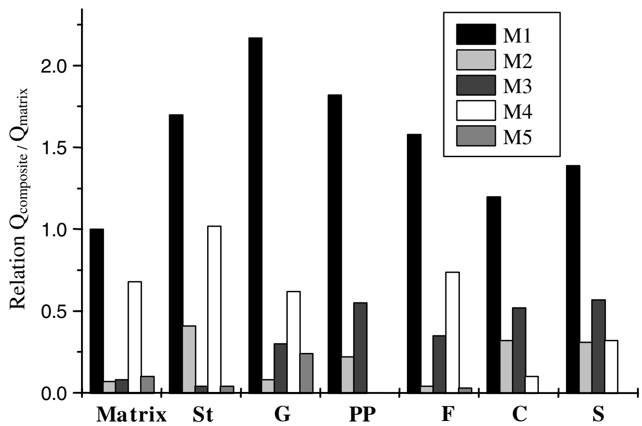

Fig. 3. Chloride ion penetration of neat and fiber-reinforced mortars.

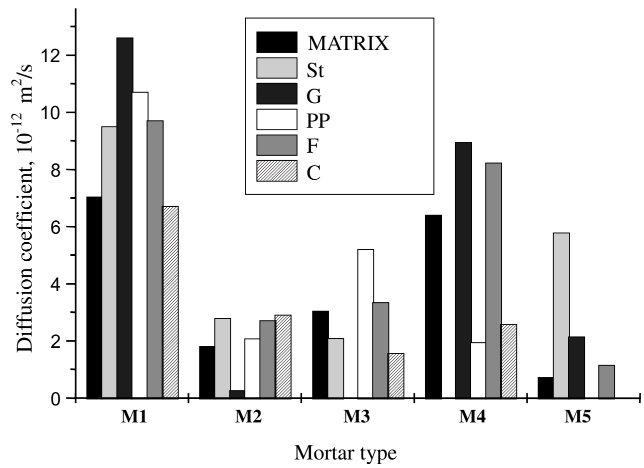

Fig. 4. Chloride diffusion coefficient in neat and fiber-reinforced mortars.

of the hardened cementitious specimen to the penetration of the chloride ion. It can be seen that the pozzolanic materials and the slag were effective in reducing the permeation of chloride ion. The greatest effect on the plain matrix was produced by the SF addition followed by the additions of MK, GGBS, and FA. It was also noted that the fiber inclusion negatively affects the penetration of chlorides because of the increase in capillary porosity. This was observed for both synthetic and natural fiber reinforced specimens. However, the negative effect did not change the positive effects generated by pozzolan and slag additions which again reduced chloride ion movement through the material. The greatest reduction in penetration of chlorides was produced by the incorporation of SF into a matrix reinforced with glass fibers. The lowest observed effect corresponded to the FA addition. Its relatively poor performance is attributed to its low pozzolanic activity. The results of this research are in agreement with those obtained by Soroushian et al. [8] who reported a 75% reduction in the permeability to chloride ions when polypropylene fibers were used together with SF in a Portland cement matrix.

The increase in absorption and capillary porosity produced by incorporating fibers into a matrix is compensated for by the compactness generated by pozzolan additions. An highly active pozzolan or blast furnace slag can also reduce chloride diffusion [9]. This effect was examined by taking measurements in a diffusion cell, the results of which are presented in Fig. 4. The decrease in the coefficient of chloride diffusion was 98% when SF was added to the glass fiber reinforced mortar. Significant reductions in the coefficient were also obtained when MK and GGBS were included in the matrix.

The positive effects of the active additions reported in this study could be attributed to the increase in density and reduction in capillary porosity caused by reaction products such as calcium silicates and calcium aluminates, which change the material microstructure. Thus passage of aggressive agents through the material is controlled.

3.4. Electrochemical evaluation

In order to evaluate the corrosion of steel bars embedded in the fiber reinforced mortars, with and without additions, two techniques were utilized. As mentioned earlier the methods used were the half-cell potential (ASTM C876) and linear polarization resistance (ASTM G59) procedures. The results obtained from experimentation with synthetic and natural fibers are presented in Figs. 5–8. The point of initiation of the corrosion process is considered to be when the steel goes from a passive to an active state, which corresponds to a potential of −270 mV with respect to a saturated calomel electrode. As a criterion to evaluate the level of corrosion, it is considered that an I_{corr} less than 0.2 mA/cm^2 indicates a state of no corrosion at all [10].

After studying the matrices and many of the fiber-reinforced composites, the better performances corresponded to those with SF additions, followed by those with MK incorporation. The performance is defined in terms of the time to cause a break down of the passive film because of the chloride ion action. The inclusion of FA in the mixes did not improve its hardened behavior. In some aspects its performance was worse than that shown by the plain mortar.

It should be noted that the steel bar in contact with the matrix containing SF and reinforced with steel or glass fibers, maintained its passive state after exposure to a chloride medium for 8 months.

The experimental observations from the current study agree with those reported by Andrade et al. [11], who found that a steel fiber reinforced concrete with SF addition had low capillary suction, a much reduced

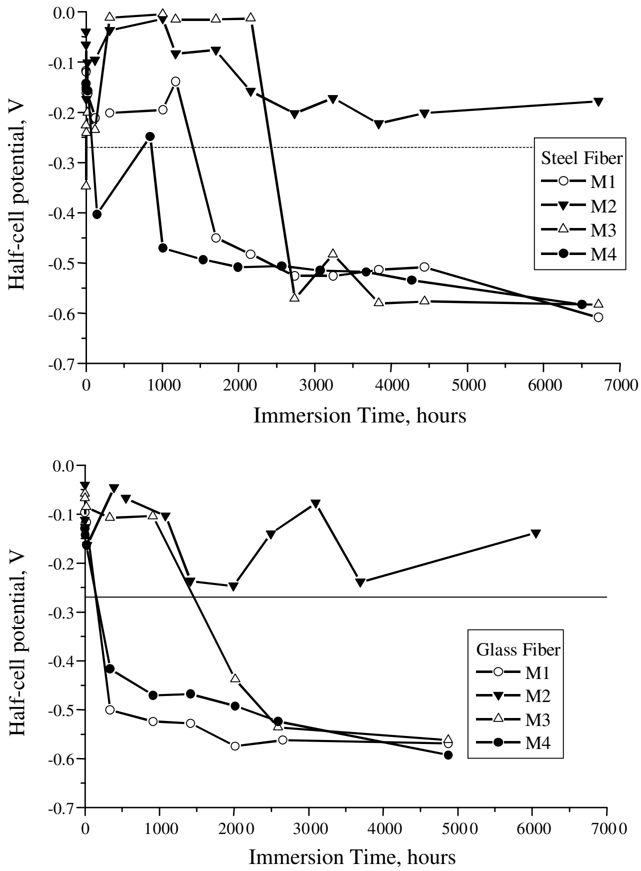

Fig. 5. Half-cell potentials (E_{corr}) of reinforcing bars in mortars.

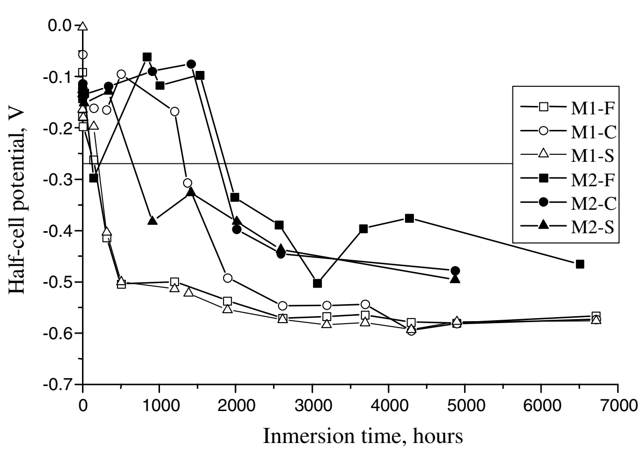

Fig. 6. Half-cell potentials (E_{corr}) in natural fiber reinforced mortars.

diffusion coefficient, and almost no velocity of corrosion. Also, Ping et al. [12] found that there was no significant corrosion of the reinforcing steel when silica fume and slag were added to concretes after 6 months of exposure to a 3.4% solution of sodium chloride.

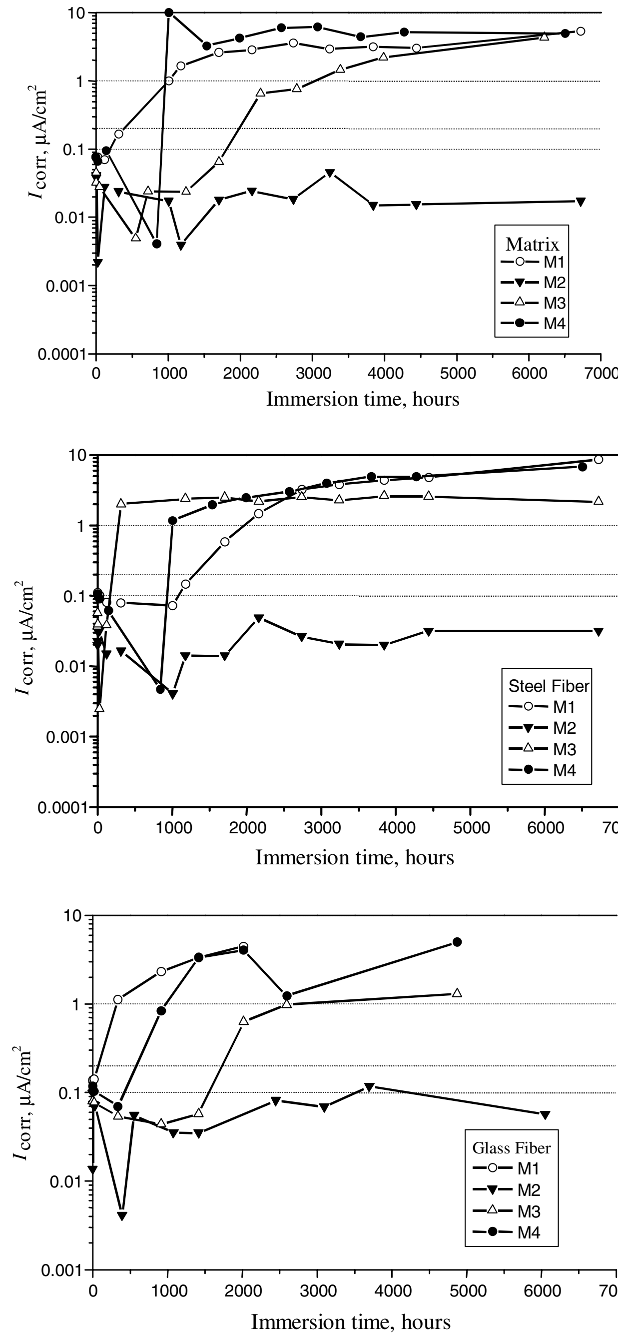

Fig. 7. Corrosion rate (I_{corr}) of reinforcing bars in mortars.

4. Conclusions

Based on the experimental results of this investigation the following conclusions can be drawn:

- In general, incorporating fibers into plain mortar caused a reduction in compressive strength, although it was lesser when steel fibers were added. However, the addition of a highly active pozzolan or slag can

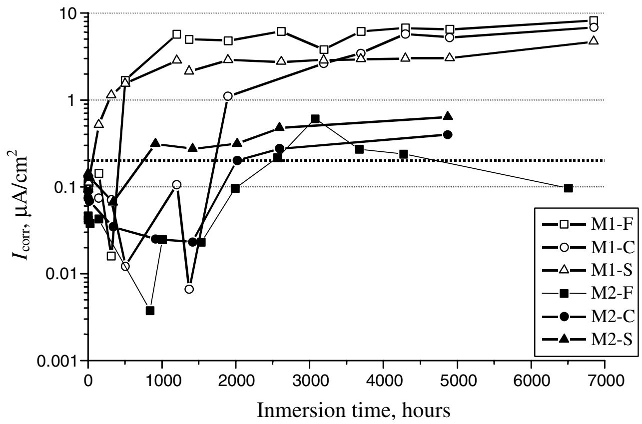

Fig. 8. Corrosion rate (I_{corr}) of reinforcing bars in natural fiber-reinforced mortars.

help to compensate for this loss of performance. In the case of glass and steel fibre reinforced mortar, the addition of SF improved performance over that of the plain mortar.

- In general, the incorporation of SF improved the water absorption properties of the Portland cement based material because of a reduction of permeable voids.
- It is noted that the coefficient of capillary absorption (*K* value) was lowered when a pozzolanic material was added to a cementitious matrix. The effect is very pronounced in the case of SF and to a lesser extent for MK.
- A large reduction of capillary was generated by inclusion of SF in glass, sisal and steel fiber reinforced cement-based materials.
- Pozzolanic materials and blast furnace slag were effective in reducing the permeation of chloride ions. The greatest effect was produced by SF addition followed by additions of MK, GGBS, and FA. It was also observed that the inclusion of fibers in mortars increases the penetration of chlorides because of the increase in the capillary porosity.
- Additions of SF and MK retarded the action of chloride ions which cause a break down of the passive film surrounding in steel reinforcing bars placed in mortars.

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