Analysis of glass fiber reinforced cement (GRC) fracture surfaces

Alejandro Enfedaque *, David Cendón, Francisco Gálvez, Vicente Sánchez-Gálvez

Departamento de Ciencia de Materiales, Universidad Politécnica de Madrid, c/ Profesor Aranguren s/n, 28040 Madrid, Spain

ABSTRACT

Glass fiber reinforced cement (GRC) is a composite material produced by the union of a cement mortar matrix and chopped glass fibers. Its good mechanical properties deteriorate with time. This phenomenon has been studied performing a tensile test program on both young and aged samples of GRC produced by using different chemical additives. Once the tests were carried out, a microstructural analysis of fracture surfaces was performed using a scanning electronic microscope (SEM). Pictures taken showed that the addition of metakaolin enables more fibers to be pulled out from the matrix instead of being broken in aged GRC samples. However, the increase in the number of such fibers pulled out did not prevent the embrittlement of GRC. Also, all the other chemical additions used did not show any improvement in the mechanical properties of GRC.

Keywords:
Glass fiber reinforced cement
GRC
SEM
Accelerated aging
Fracture surface

1. Introduction

Glass fiber reinforced cement (GRC) is a composite material made up of the union of two materials with different mechanical properties: cement mortar and chopped glass fibers. In GRC production glass fibers are randomly sprayed in two directions [1]. The combination of these materials creates a composite material that merges the best mechanical properties of both, improving the behavior of the materials on their own. Glass fibers improve cement mortar tensile strength and ductility, while cement mortar avoids buckling of glass fibers when compressing them. Therefore, through merging both materials a composite material with improved ductility and tensile strength with respect to the cement mortar mechanical properties and high compressive strength, is obtained [2].

GRC elements do not require steel rebar reinforcement. In addition, GRC members can be produced with any shape with a thickness of only 10 mm approximately. Therefore, GRC is a versatile material that is suitable for many architectural and civil engineering applications [3–6].

Unfortunately, the mechanical properties of GRC deteriorate with time. Such a phenomenon (known as GRC aging) has been previously observed in different studies [7–9]. The ductility of GRC decreases heavily, with it becoming a brittle material and tensile strength hence being reduced as time passes. Many researchers have pointed to corrosion in glass fibers, due to the highly alkaline environment of the cement mortar matrix, as the main cause of the change in the mechanical properties of GRC [10]. Alkali resistant glass fibers (called AR glass fibers) were developed in an attempt to solve this problem, though GRC aging still took place. More recently, the embrittlement of GRC has been termed a *static fatigue* process [11].

In order to reduce the effects of time on GRC, cement mortar with different chemical additions was examined and used in GRC manufacturing [12,13]. An artificial pozzolan, metakaolin, and certain acrylic resins provided promising results in these studies. However, the results obtained in such work were scattered, due to the different additions and contents used.

To relate GRC behavior and GRC microstructure, a test program was carried out through use of GRC modified formulations. Micrographs of the fracture surfaces were taken to analyze the effects of the additions used on the microstructure of the GRC.

2. Test program

A test campaign was carried out on GRC with five different formulations, using three different chemical products to characterize aged GRC behavior. The additions used in cement mortar production were: silica fume, metakaolin and acrylic resins. Components and contents used in GRC production can be seen in Table 1.

A series of 10 test boards were made in collaboration with PREINCO S.A. Test boards were 1.2 m long by 1.2 m wide and 10 mm thick. A frame of 5 cm, near the test board borders, was cut and discarded to avoid testing GRC with bent fibers. Rectangular 300 × 50 mm samples were cut from each test board. Tests were performed on samples cured in an climatic chamber at 20 °C and

Table 1
Cement mortar formulations.

	Cement (kg)	Sand (kg)	Water (kg)	Plasticizer (l)	Addition (kg)
Control	50	50	20	0.5	–
Metakaolin	50	50	22	0.5	5
Silica fume 10%	50	50	23	0.5	5
Silica fume 20%	50	50	27	0.5	10
Acrylic resins	50	50	20	0.5	2

98% of humidity for 28 days, as well as after a period of 40, 80 and 120 days of accelerated aging by immersion in hot water at 50 °C.

Accelerated aging by immersion in hot water has been studied by Litherland et al [14] in GRC produced with ordinary Portland cement. Equivalences between natural exposure time in UK and immersion time in water at different temperatures were obtained in the referenced research. These equivalences are summarized in Table 2.

However, more recent studies have been carried out dealing with a relation between natural exposure and accelerated aging methods [15]. Some of them have examined accelerated aging process using immersion in hot water [16]. These studies pointed out that the equivalences established earlier by Litherland were not valid for GRC made with modified cement matrix. Acceleration factors were not accurate in GRC modified with additions because different chemical reactions might happen during the aging process. The acceleration factors valid for water at 50 °C according to these authors [16] can be seen in Table 3.

No acceleration factors have been found in literature for GRC with silica fume addition. Also, GRC formulations used in this test program were not equal to those found in literature. It was not possible to claim that GRC after accelerated aging had an equivalent age to GRC exposed to natural weather a certain time for any formulation used.

3. Tensile tests

GRC samples were stored in a climatic chamber at 20 °C and 98% humidity after aging. Between aging and testing of GRC samples no more than a month passed. Therefore, the additional aging that took place in the climatic chamber between aging and testing was not significant when compared to GRC age.

As has been previously cited, GRC 300 × 50 mm rectangular samples were 10 mm thick approximately. The thickness of samples changed from one point to another due to the manual production process of GRC. Thickness variations of a few millimeters were found in almost every sample.

Table 2
Accelerated aging equivalences.

1 day at (°C)	Days of natural exposure in UK
80	1672
70	693
60	272
50	101

Table 3
Acceleration factors.

	1 day at 50 °C is…days of natural exposure in UK
Ordinary portland cement GRC	120
OPC + 20% metakaolin	18
OPC + 5% acrylic Polymer	18

Tensile tests were carried out in a universal testing machine, equipped with a 25 kN load cell with samples being held by using a pair of mechanical jaws. The strain of the samples while testing was obtained using two extensometers, facing one another, placed in the center of the sides of the samples. The distance between the blades of the extensometers was modified using extensions, in order to increase the possibility of recording the strain of the fracture area during the tensile tests. When the fracture was located in this zone, strain data that describes how the fracture developed was then recorded.

Tests were performed using position control and the movement of the jaws limited at a speed of 1 mm/min.

In Fig. 1, a sketch of how the tests were performed can be seen.

Tensile tests were carried out up to the point of complete failure of the sample. The samples were broken into two different parts,

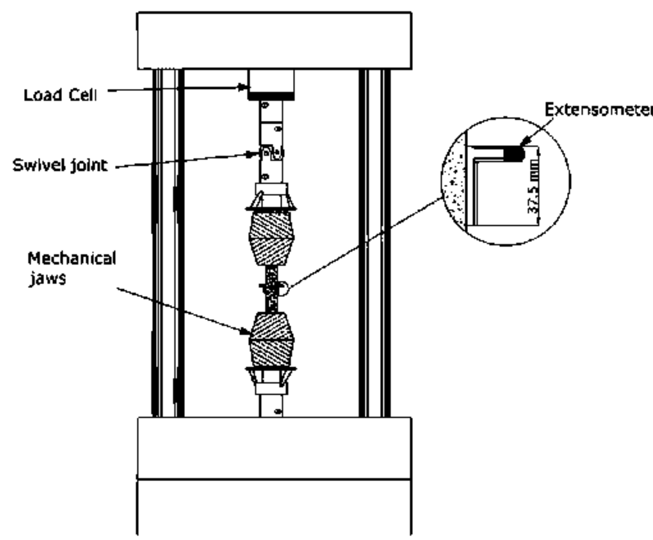

Fig. 1. GRC tensile test.

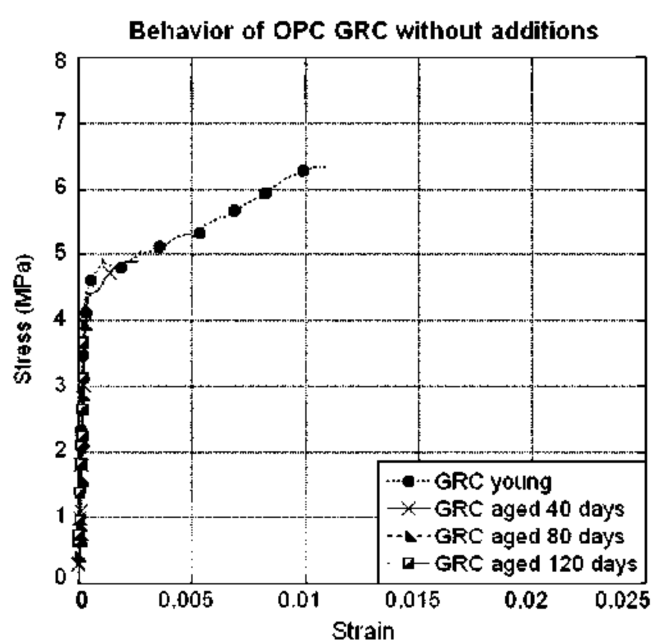

Fig. 2. Stress–strain curve OPC GRC.

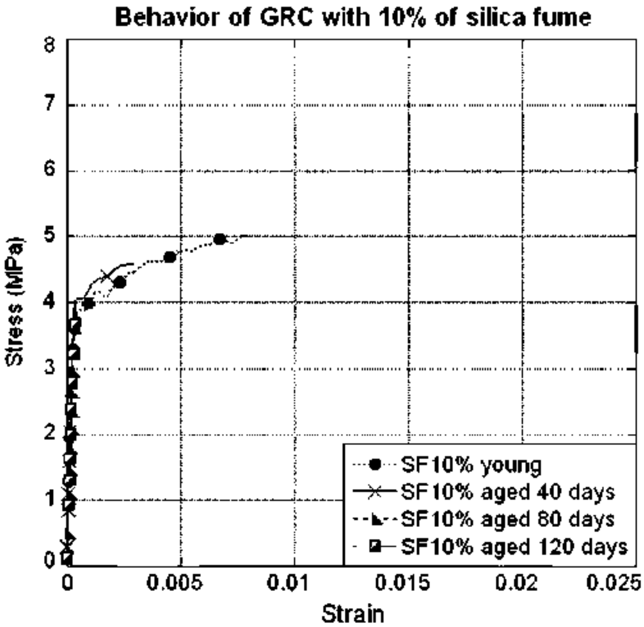

Fig. 3. Stress–strain curve GRC with 10% silica fume.

without the fibers bridging them. Stress vs. strain curves obtained in the tests of the five different GRC formulations can be seen in Figs. 2–6. In these figures young and aged GRC behavior can be seen.

The behavior of young GRC is linear elastic the limit of proportionality (LOP) is reached. Before reaching the LOP no damage can be seen in the samples. After LOP, the slope of the stress–strain curve decreases and GRC becomes a less stiff material. In this zone, multiple microcracks appear, grow and arrest when the crack tip finds a fiber. This process is clearly reflected in the stress–strain curve as a small serrated curve. Focusing in one of these peaks, stress rises when one microcrack is arrested and decreases when a microcrack grows or a new microcrack appears elsewhere. This process continues until the stress level is high enough to produce

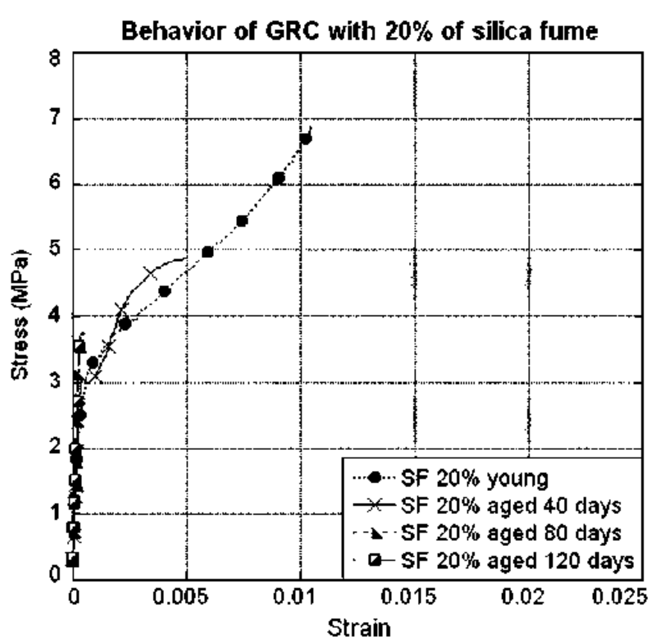

Fig. 4. Stress–strain curve GRC with 20% silica fume.

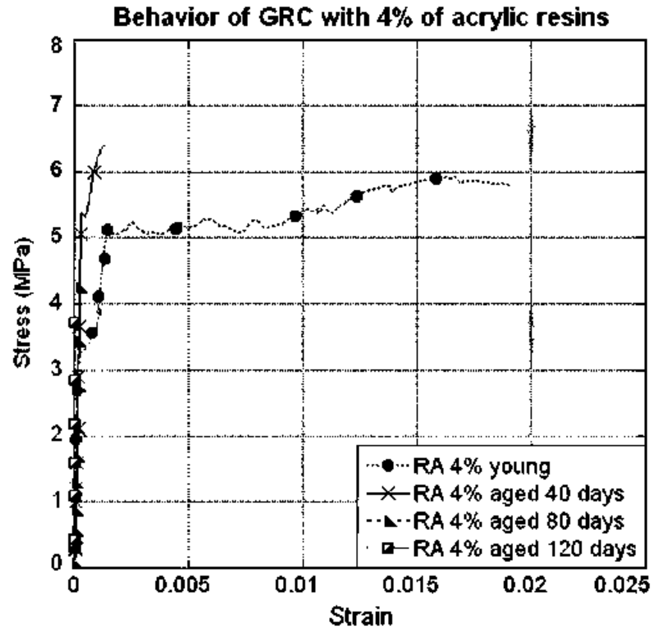

Fig. 5. Stress–strain curve GRC with 4% acrylic resins.

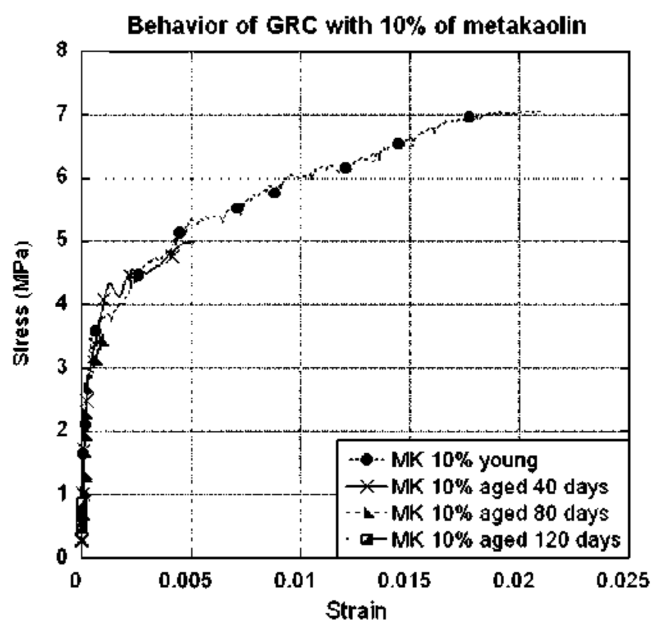

Fig. 6. Stress–strain curve GRC with 10% metakaolin.

a visible crack formed from the weakest microcrack. This stress is called "Bend Over Point". From this point the stress continues to increase although with a much lower slope and the elongation is growing while the crack is opening, the load is being supported by the fibers bridging the crack. This zone is long for young GRC, the fibers exhibiting a great pull out from the matrix before the collapse of the sample.

All five GRC formulations behaved in a different manner when samples were about 28 days old. GRG produced with 10% metakaolin addition showed a failure strain that doubles the failure strain of GRC produced without additions. Not only GRC with metakaolin addition had greater failure strain, but also failure strength was increased from 6.3 MPa to 7 MPa when compared with GRC without any addition. GRC produced with a 10% of silica fume showed a decrease both in failure stress and strain respect to GRC produced without additions. GRC produced with 20% of silica fume behaved in a similar way to the control GRC formulation.

After 40 days of accelerated aging, crack propagation after the BOP has almost disappeared from stress–strain curves in all formulations. Accordingly, failure strain in plain GRC is only about 20% of the failure strain registered in the tests performed with young plain GRC. Failure stress has also decreased respect to the values previously registered and it is close to the BOP values.

Although failure strain of the GRC produced with 10% metakaolin aged during 40 days is only about 25% of that registered in the tests carried out in the same material without aging, it still doubles the failure strain of the aged plain GRC. However, failure stress in aged samples is similar in both formulations. Stress–strain curve of GRC produced with a 10% of silica fume and aged during 40 days clearly show lower values of failure strain and stress than plain GRC aged 40 days. No major differences were found between GRC produced with 20% of silica fume and aged 40 days and the control formulation aged 40 days.

After 80 days of aging all formulations, except GRC produced with 10% metakaolin addition, showed an elastic behavior and no capability of multicracking. Stress–strain curves come to their end when the LOP is reached. In GRC produced with 10% metakaolin, tested samples showed a limited multicracking behavior. LOP in all formulations was about 4 MPa.

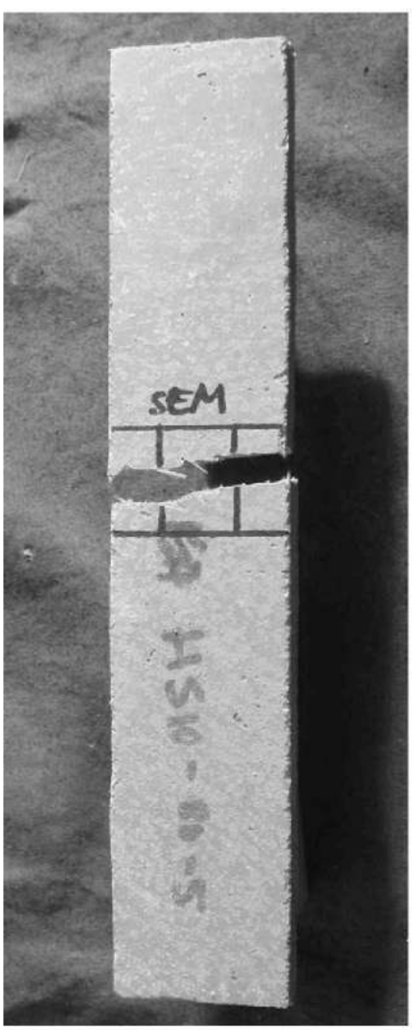

Fig. 7. Tested sample.

Samples aged during 120 days showed an elastic behavior in all formulations. Multicracking was no more observed even in tests performed on GRC samples produced with 10% of metakaolin addition.

4. Specimen preparation

Once the tests were done, the fracture surfaces of the samples were analyzed to find differences and similarities among GRC formulations. The behavior of GRC in tensile tests was related with the fracture surface appearance in all GRC formulations. A tested sample can be seen in Fig. 7.

In Fig. 7, a sample broken during a tensile test is shown. The broken samples were divided in two different parts, and there were

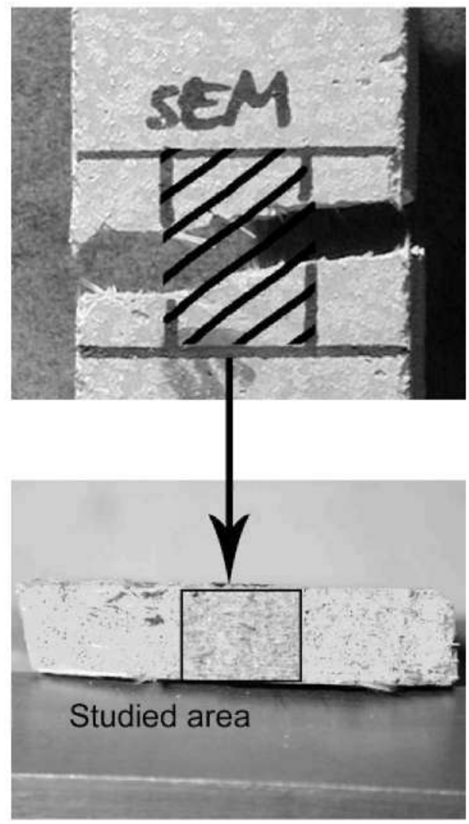

Fig. 8. Studied area.

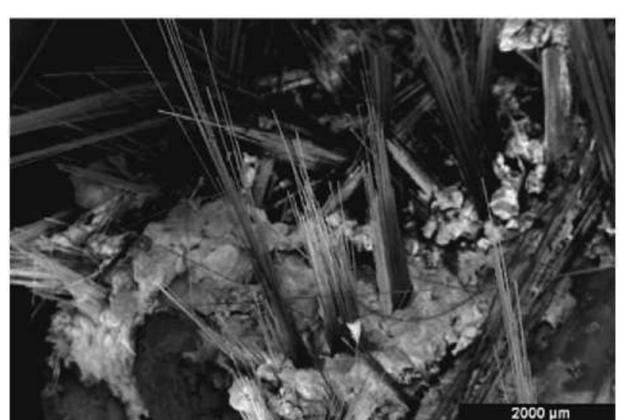

Fig. 9. Young GRC without additions.

no fibers bridging these parts. Due to the limited size of the scanning electronic microscope (SEM), the entire fracture surface could not be analyzed. Therefore, the fracture surfaces were divided in three parts as can be seen in Fig. 8. In the upper part of the figure the part of the sample chosen to be studied in the SEM is striped. In the lower part of this figure a detailed picture of fracture surface studied is shown. Only the central part was studied. Rejecting the side parts, stress concentration due to boundary effects that might have appeared during the tensile tests, was not studied. A gold deposit was made on the central part of the fracture surfaces. Afterwards, the fracture surface specimens were studied in a SEM.

5. Pictures obtained

Fracture surfaces of young GRC samples can be seen in Figs. 9 and 10.

The fracture process occurred in both samples in a similar way. In all the pictures taken there are many fibers pulled out and only a few of them were broken. Therefore, the GRC fracture process is greatly influenced by fiber pull-out strength. GRC failure surface is jagged and abrupt. This kind of fracture surface fits with the fracture process theories developed for young GRC. According to these theories, microcracks grow until in front of them appear a material area that is capable of bearing the concentrated stresses of the crack tip. This area might have a greater amount of fibers than the nearby ones. The crack growth stops and another microcrack grows. During the creation and growth of microcracks, the load that the sample bears increases. When the strength of the sample is reached, fracture starts to grow from the weakest microcrack, forming, eventually, the fracture that will divide the GRC sample in two pieces.

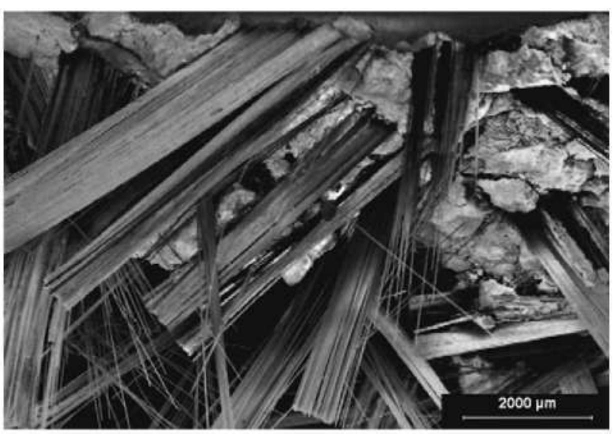

Fig. 10. Young GRC with 20% silica fume.

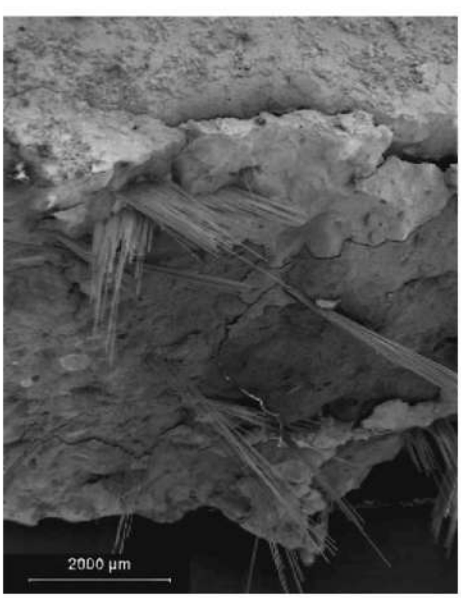

Fig. 11. GRC aged 40 days with 20% silica fume.

Fig. 12. GRC aged 40 days with 10% metakaolin.

Fig. 13. GRC aged 80 days with 10% silica fume.

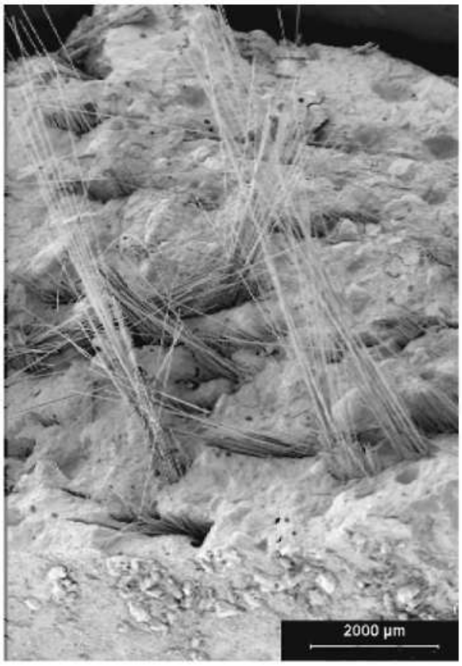

Fig. 14. GRC aged 80 days with 10% metakaolin.

Fig. 16. GRC aged 120 days with 10% metakaolin.

In Figs. 11 and 12 pictures taken of GRC samples aged 40 days by immersion in hot water are shown.

The fracture process in these samples is completely different from the process that took place in young GRC. Abrupt topology of young GRC sample fracture surfaces have disappeared. Fracture surfaces are even, without steep slopes on them. Glass fibers have almost disappeared from the fracture surfaces shown in pictures 11 and 12. Most glass fibers were broken during the tensile tests. Glass fibers were cut right at the same level as the cement mortar fracture surface. Fracture surfaces of four GRC formulations were similar (control GRC, GRC with 10% silica fume, GRC with 20% silica fume and GRC with 4% of acrylic resins). Fracture surfaces of samples of GRC produced with 10% of metakaolin addition showed a greater amount of fibers pulled out.

Fig. 15. GRC aged 120 days with 4% acrylic resins.

Pictures taken of GRC samples aged 80 days by immersion in hot water can be seen in Figs. 13 and 14.

In these pictures almost all characteristics shown in pictures of GRC samples aged 40 days appear again. Fracture surfaces are even more regular. A greater amount of glass fibers were broken during the tensile tests. In GRC produced with 10% metakaolin, there were more fibers pulled out than in the rest of the GRC formulation samples. Therefore, the tendency identified for samples aged 40 days, is confirmed for samples aged 80 days. In GRC manufactured with 10% of metakaolin there are more fibers than in the rest of GRC samples but, comparing GRC with metakaolin addition aged 40 and 80 days it is clear that in the samples aged 80 days there are fewer fibers pulled out.

All the previously mentioned tendencies are confirmed in the pictures taken of GRC samples aged 120 days. The positive effect of metakaolin still appears in samples aged for 120 days. Comparing Figs. 15 and 16, a greater amount of glass filaments can be seen in the samples produced with 10% of metakaolin.

6. Conclusions

The pictures obtained show how the addition of metakaolin to GRC cement mortar modifies the microstructure of the material, increasing the number of fibers pulled out in a tensile test. However, the amount of fibers pulled out were not enough to prevent aged GRC fragile behavior, as is clearly shown in the stress–strain curves obtained in the tensile tests.

Chemical products used (silica fume and acrylic resins) in GRC production had no significant effect, either in the behavior of GRC during tensile tests or in the fracture surfaces obtained. All GRC formulations showed a fragile behavior after 80 days of immersion in water at 50 °C. Damage in glass fibers occurred mostly during the first 40 days of immersion. Jagged fracture surfaces were obtained when a large number of glass fibers were pulled out. Consequently, irregular fracture surfaces were obtained only when testing GRC in its early stages of life. Even fracture surfaces appear as result of massive glass fiber rupture.

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