A new approach was recently developed, which might be considered intermediate between surface treatment and matrix modification. It involves treating the glass fibre strands in a silica fume slurry, prior to their incorporation in the matrix[10][11][12]. This method is based on the special structure of the reinforcing unit, which is a strand consisting of an assembly of about 200 filaments, that are closely spaced (Fig. 1a). This structure is maintained in the composite, since the filaments are not separated from each other in the production. During immersion of the strand in the slurry, the small silica fume particles (0.1μm in diameter) fill the spaces between the filaments (Fig. 1b), and they are thus positioned in the place where they are most needed, i.e. at the fibre surface. Here, their high pozzolanic activity can be most effectively used, to prevent formation of CH crystals at the interface and they may also provide some reduction in the alkalinity of the matrix in the vicinity of the fibres. This treatment was found to be effective in improving the preservation of strength and toughness, compared to only modest improvement achieved when silica fume was used only as partial substitution of the portland cement in the matrix[11].

In the previous work, the silica fume treated specimens were prepared by dipping individual strands or rovings, and then laying them in the composite, between layers of paste matrix.

The present paper describes an extension of this study, to evaluate a preparation method which could be used in a full scale operation and not limited to laboratory tests only. It is based on the use of fabrics of AR glass fibres, which are dipped in the silica fume slurry and then hand-laid in the composite. The evaluation of the composite included the comparison of the aging performance of GFRC prepared with continuous strands and with fabrics. Specimens with and without treated fibres were tested.

EXPERIMENTAL

All the glass fibres used in the present work were of the AR type. The fabric was a product of Nippon Electric Glass Co., Japan, labelled type TD 5x5, with a density of 0.145 kg/m^2. Its structure is shown in Fig. 2. The continuous strand was AR glass produced by Owens Corning, USA.

ASTM Type I portland cement produced by Nesher, Israel, was used. The silica fume slurry was a product of Elkem Chemicals, containing about 50% water.

The treatment in silica fume was based on dipping the strands or the fabric for 10 minutes in the slurry followed by air drying for an additional 15 minutes.

The composites were prepared by hand lay-up of the fibres, using a special mold and spacers. The matrix between the fibre layers was a 0.35 w/c ratio paste.

The composites with continuous strands consisted of 2 layers of strands and 3 layers of paste, each with thickness of 3mm. The total thickness of the composite was about 10mm, and it was prepared as bars, 110mm long and 20mm wide. The fibre content was about 1.5% by volume.

The composites with fabric reinforcement consisted of 4 layers of fabrics, and 5 layers of paste, each with a thickness of 1.5mm. The total thickness of the composite was about 10mm and it was prepared as slabs, 110mm long and 150mm wide. The fibre content was about 2.5% by volume.

The specimens were demolded after one day and then kept continuously in lime water at 20°C until 28 days. At 14 days, the fabric reinforced slabs were cut into strips of 20mm wide to obtain, in this case too, bars with a width of 20mm and length of 110mm.

At 28 days, the composites were exposed to accelerated aging conditions, in lime water at 50°C, for periods up to 9 months. The mechanical properties of the composites, before and after accelerated aging were determined by means of flexural test. Four point loading at a span of 90mm was applied, and the load-deflection curve was recorded. Flexural strength was calculated and the toughness was evaluated as the area under the load-deflection curve, to the point where the load dropped to 75% of its maximum. This area will be referred to as work of fracture. The values reported are the average of at least 6 specimens, with the coefficient of variations being 5-15% for strength, and 10-20% for work of fracture.

RESULTS AND DISCUSSION

The effects of the silica fume treatment on the performance in accelerated aging is shown in Fig. 3 for the composite with continuous strand reinforcement, and in Fig. 4 for the composite with fabric reinforcement.

The treatment with silica fume increased the durability performance in both of the glass systems (strands and fabric), but the improvement seemed to be more dramatic in the strand reinforcement (Fig. 3). Here, the silica fume eliminated strength reduction and enabled preservation of considerable toughness even after 5 months of accelerated aging. It should be noted that in the control most of the toughness was lost within one month of accelerated aging, whereas in the treated composite there seems to be stabilization after about one month, with the work of fracture remaining constant at a level of approximately 50% of the initial toughness.

In the case of the fabric reinforcement (Fig. 4), the treatment with silica fume slowed down the rate of reduction in flexural strength and work of fracture; however, after 6 months of aging the values in both composites (control and silica fume curves in Fig. 4) reached the same levels, and stayed constant thereafter.

For a valid comparison of the influence of the silica fume treatments in both reinforcing systems, one should account for the differences in the properties of the composites prior to aging. The fabric system has a larger content of fibres (2.5% vs. 1.5%); yet half of them are oriented in the transverse direction. Thus, in the main longitudal direction, both composites are reinforced with fibre contents that are different by only 20%. This accounts for the same order of magnitude of flexural strength and work of fracture values prior to aging, which is in the range of 17.5 to 21 MPa for flexural strength, and 800 to 1400 Nmm for work of fracture. Yet, the differences, in each of these ranges, are not negligible. In order to normalize for these variations, the flexural strength and work of fracture were plotted as the values relative to the properties prior to aging (Fig. 5).

The curves in Fig. 5 indicate several important characteristics:

1. The aging in the untreated (control) fabric reinforced composite is significantly slower than that of the untreated (control) strand reinforced system. This is particularly evident when the work of fracture is considered: After prolonged aging, 30% of the initial toughness was retained in the fabric system, which showed considerable pull-out and post-cracking load bearing capacity (Fig. 6). In contrast to that, the strand reinforced composite (control) became brittle within 1 to 3 months of accelerated aging (Fig. 7).

2. The treatment with silica fume enhanced the strength retention in the strand reinforced composite to a greater extent than in the fabric reinforced system (Fig. 5). When the work of fracture is considered, the silica fume had a different influence on the shape of the curves, but eventually, after 5 months of accelerated aging, the toughness retention was similar in the fabric and strand system, with both having 40 to 50% retention (Fig. 5). Yet, the increase in toughness, when comparing the systems with and without silica fume treatment, is greater in the strand reinforced composite, as can be readily seen from Fig. 5, and the load deflection curves in Fig. 7: In the strand system, the silica fume changed the behavior after aging from essentially a brittle one, to a composite with significant post-cracking load-bearing capacity. In the fabric reinforced composite, considerable post-cracking performance after aging was evident even without silica fume treatment, and the role of the treatment was to enhance this performance modestly.

The differences in the effectiveness of the silica fume in the two reinforcing systems may be associated with the ability of the tiny silica fume particles to penetrate between the filaments. In the strand system this occurred readily, with effective impregnation of the small spaces separating between the filaments in the strand

(Fig. 1). However, it seems that this penetration is hindered in the fabric reinforcement. Microscopical observations indicate that, in this case, the strands were heavily coated with polymeric material (Fig. 8). This coating seemed to be particularly thick at the intersection of longitudial and transverse fibres (Fig. 8a,b) suggesting that its purpose is to stabilize the fabric. However, even in zones away from the fibres intersection, some polymeric material could be seen between the filaments (Fig. 8c). Observations of the fibres after immersing in the silica fume slurry showed accumulation of silica fume around the strand, but much less penetration of this material in-between the filaments (Fig. 9), compared to the massive infiltration in the strands (Fig. lb). The limited penetration may be due to physical constraints induced by the polymer (occupying the space between the filaments) and possibly to changes in the surface properties, reducing the wetting characteristics of the fibres with respect to the silica fume slurry.

It was suggested that the effectiveness of the silica fume is closely linked with its ability to penetrate in-between the filaments and to be positioned at the fibre surface[10]. Therefore, silica fume replacement in the matrix only was inefficient, while the slurry treatment of the fibres was extremely effective in enhancing durability[11]. This hypothesis may account for the observation that in the fabric reinforced composite the silica fume treatment was not as effective as in the strand reinforcement, because of the influence of the polymer coating in the fabric, to limit silica fume penetration during slurry immersion. On the other hand, the presence of the polymer coating, with perhaps protective effect, may account for the improved durability of the control fabric composite relative to the control strand composite.

CONCLUSIONS

1. Treatment of AR glass fibres in silica fume slurry, prior to the incorporation of the fibres in the composite, was shown to be an effective means for improving the durability performance of GFRC composites.

2. The effectiveness of the silica fume treatment was found to be greater in the strand reinforcement. This was attributed to the observation that, in this system, the silica fume particles were able to penetrate into the spaces between the filaments during the immersion treatment, whereas in the fabric reinforcement the presence of polymer coating hindered this penetration. Thus, the surface treatment of the glass fibres is an important factor which must be taken into account in such treatments.

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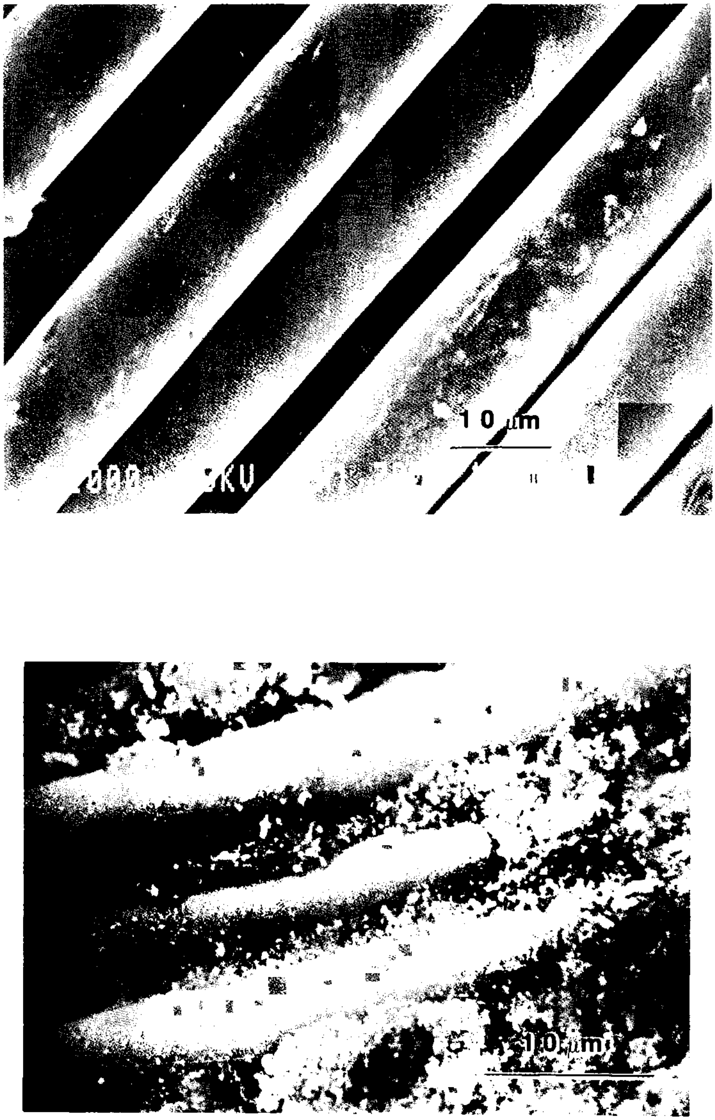

Fig. 1: Glass Fibre Strands
(a) A portion of a strand prior to silica fume treatment.
(b) Penetration of silica fume particles into the spaces between the filaments in the strand, after treatment in silica fume slurry.

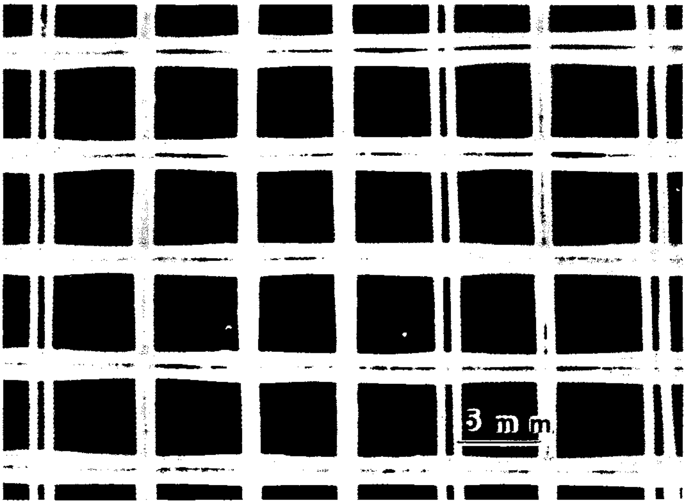

Fig. 2: The structure of the AR glass fabric.

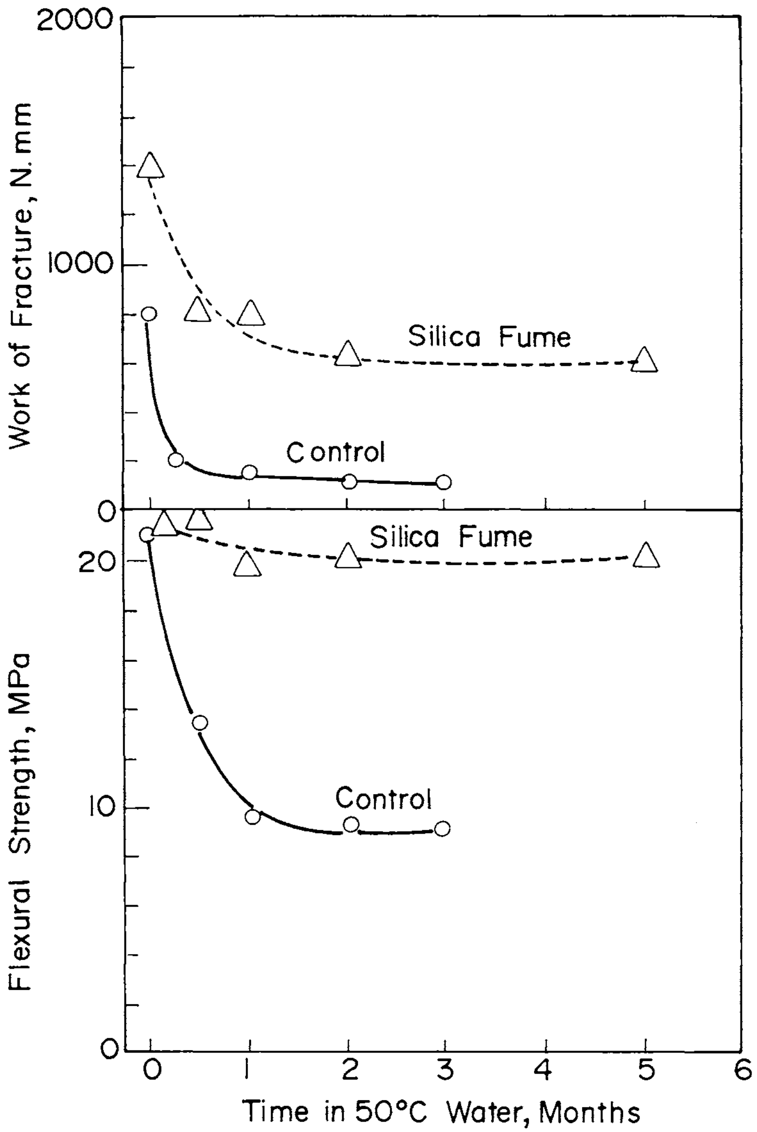

Fig. 3: Effect of accelerated aging in 50°C water on the flexural properties of GFRC composites reinforced with continuous AR strands which were untreated (control) or treated with silica fume slurry (silica fume).

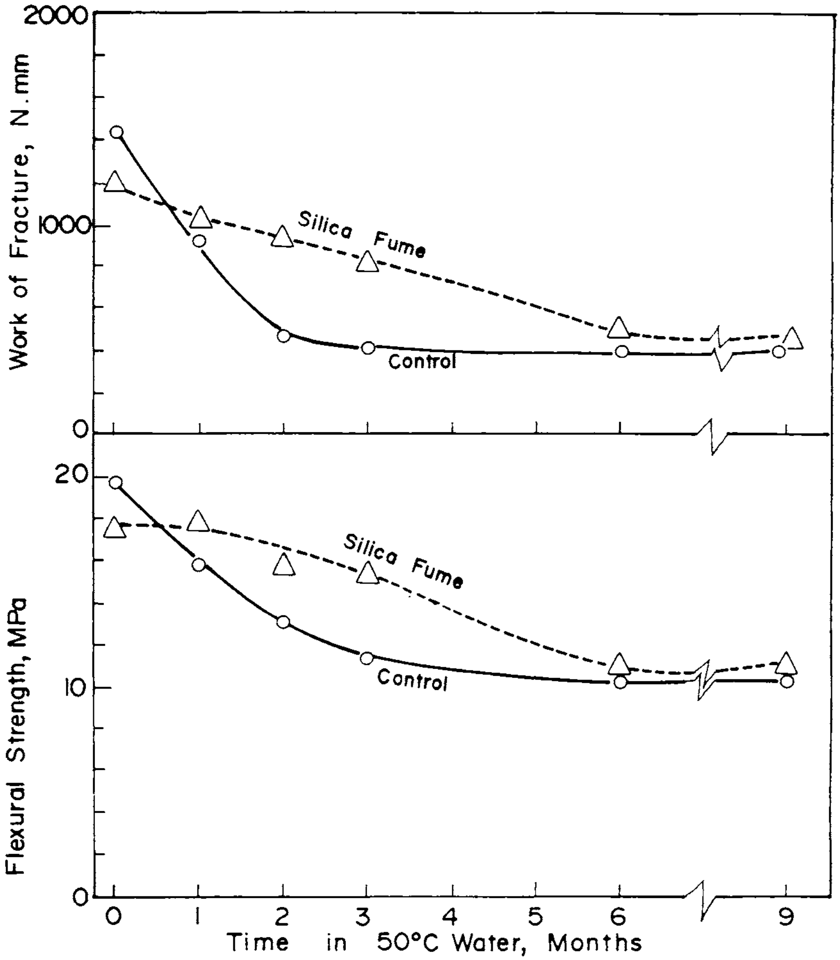

Fig. 4: Effect of accelerated aging in 50°C water on the flexural properties of GFRC composites reinforced with AR fabric, which was untreated (control) or treated in silica fume slurry (silica fume).