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Metallographic investigation of the damage caused to GRP by the combined action of electrical, mechanical and chemical environments

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The use of glass fibre-reinforced polymers in electrical insulator components has gradually been taking place. Problems may arise where such insulators are in service at very high voltage, e.g. 200 kV and above, are under significant mechanical loads, and the environment (rain, and various pollutants) is able to gain access to the surface of the GRP. With the aid of optical and scanning electron microscope techniques, a detailed examination has been carried out on the nature of damage which has taken place in GRP pultruded rods that have operated for various periods of time in the above service conditions. These pultruded rods can receive significant levels of damage under the action of electrical fields, and the attendant environment; this takes the form of erosion, melting, burning and displacement of both glass and polymer phases. When a mechanical stress, which may be less than 10% of the breaking stress of the rod, is applied in conjunction with the above conditions a different form of insulator breakdown can take place. Instead of material displacement on the scale mentioned above, brittle failure of the GRP takes place. Such a failure mode can be compared with the process of stress corrosion which takes place when GRP is tested in 0.1 N acid solutions. It is suggested that the combined action of electrical activity and the presence of minor amounts of pollutants are able to influence the surface of glass fibres and promote stress corrosion in an analogous fashion to that described for concentrated acid solutions.

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1. Introduction

In recent years considerable efforts have been made to evaluate the properties and behaviour of fibre-reinforced polymers under laboratory test conditions. An important feature that has emerged from these studies is that glass reinforced plastics (GRP) are susceptible to stress corrosion cracking in an acid environment [1–3]. This can create problems with certain applications like GRP sewage pipes but with careful design the effects can be minimized. The present paper is concerned with the application of GRP in electrical insulators where it is employed because of its good insulating properties and low density. Recently such material, in the form of pultruded rod, has been used in field trials of high voltage insulators for use on towers where significant tensile loads can be imposed. After a certain period under operational conditions the breakdown of some insulators occurred and these were taken out of service for further study. This paper sets out to investigate the effects of large electrical voltages on the integrity of GRP rods whilst being subjected to different levels of mechanical load (static and dynamic) and where the environment (rain, and various pollutants) may have access to the surface of the rod.

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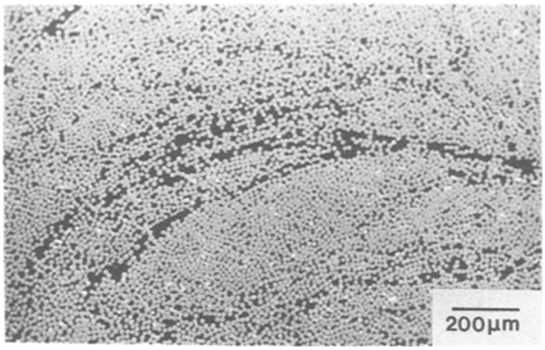

Figure 1 Resin rich areas in the pultruded rod.

2. Materials, test conditions and experimental techniques

The GRP rod had been fabricated by a pultrusion technique from coated E-glass fibres and an epoxide resin. This form of processing achieved high fibre fractions in the rod, i.e. approximately 80 wt %. The fibres were well aligned, but between individual fibre bundles some resin-rich regions existed, see Fig. 1. To form an insulator the rod was encapsulated in a cycloaliphatic epoxy resin incorporating crushed silica. The procedure involved a casting and curing operation to provide an outside profile which was made up of a series of sheds along the total length of the insulator (Fig. 2). The ends of the insulator were attached to a galvanized malleable iron casting to permit connection to the tower ("cold end") and to the conductor ("hot end").

The insulators were put into trial on a high voltage line, either as a "suspension" or "tension" insulator. The major difference between the tension and suspension conditions related to the mechanical loading and vibrational conditions. Those insulators operating under tension conditions were subjected to a maximum tensile load which was more than twice the level which suspension insulators receive in service.

Sections of damaged or failed insulators were subjected to a variety of examination techniques. These techniques included optical microscopy, scanning electron microscopy and X-ray energy dispersive analysis.

3. Results

During a trial period of one to three years, failures were observed in some of the suspension and tension insulators. The failed systems were subjected to careful examination and these provided information on the nature of insulator damage. Fracture faces and sections taken from the pultruded rods at various places along their lengths were examined. The vast majority of the insulators did not fail in the trial period and hence a number of these components were subjected to the same kind of examination as the failed systems. Initial damage in the insulator could in every case be traced back to interfaces between shedding and cast iron endpieces or to cracks initiating and growing in the shedding material at various places along the insulator. A detailed description of this initiating damage will not be given here but it was apparent that the presence of this damage did allow ingress of the environment (rainwater, pollutants) as well as promoting electrical activity at the surface and in the interior of the pultruded rod.

3.1. Examination of rods subjected to low mechanical stresses

Evidence was found of electrical puncture marks through the shedding which initiated at either the hot or the cold ends of the insulator and

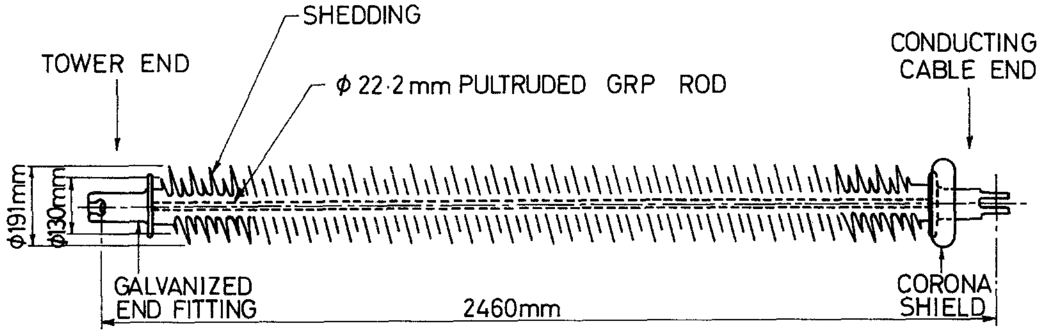

Figure 2 Outline sketch of electrical insulator, showing the position of the GRP rod.

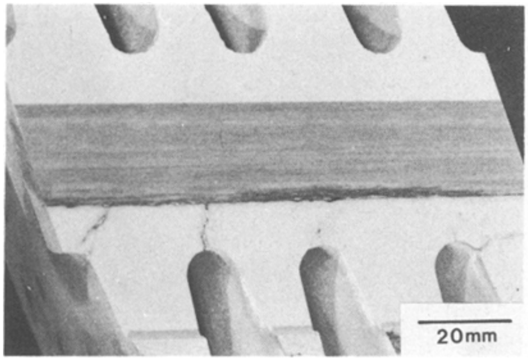

Figure 3 Electrical damage at the interface between the GRP rod and the surrounding shedding. Some of the electrical activity has punctured through the shedding.

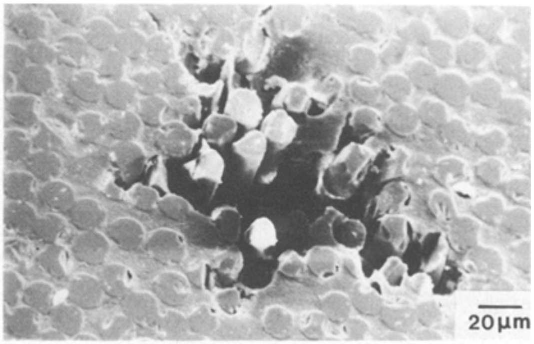

Figure 5 Electrical damage within the GRP showing the absence of resin around the glass fibres.

then proceeded to varying distances along the component. Longitudinal sectioning of the insulator in the vicinity of the punctures revealed electrical damage also at the rod–shed interface and within the rod itself. As Fig. 3 shows, the damage to the rod and its surface links together the puncture holes in the shedding. Transverse sections taken within the electrically damaged region show evidence of longitudinal cracking and the formation of porous regions. Fig. 4 shows that there is a tendency for some of the damage to be associated with the resin-rich regions in the rod. Higher magnification examination of the longitudinal cracks reveal that they are not just simple mechanical cracks, but regions where resin material in the rod has been transported away (Fig. 5).

Where the electrical damage was more severe, for example at the surface of the GRP rod, it is apparent that relatively large amounts of both glass and resin have been transported away (Figs. 6 and 7). Higher magnification examination of the outer surface of the GRP rod in damaged regions revealed fusion and fracture of both resin and glass (Fig. 8) whilst at an adjacent position partial erosion of the fibres had occurred (Fig. 9). Characteristic honeycombing of the resin was also produced in regions of high electrical activity (Fig. 10).

Removal of shedding from the GRP surface in electrically damaged regions sometimes revealed material different in composition to both glass and resin. A particular example of this is shown in Fig. 11, where a deposit of fine plate-like crystals can be seen. These crystals have been subjected to X-ray analysis and shown to contain appreciable quantities of zinc. Such crystals have resulted from either vapour transport or dissolution–deposition processes in aqueous solution. It is probable that they came, in the first instance, from the galvanized end fittings to the insulator and that electrical energy has assisted

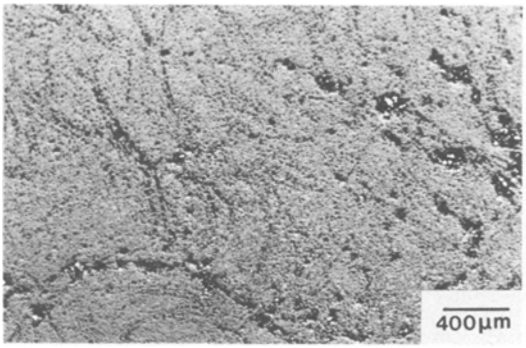

Figure 4 Electrical damage within the GRP rod. Some of the damage is associated with the resin rich regions in the rod.

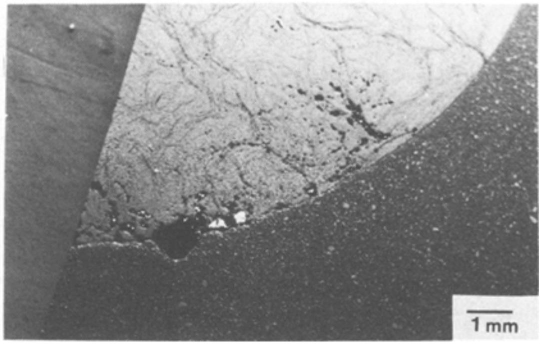

Figure 6 Electrical damage at the surface of the GRP rod showing the absence of both glass fibres and resin at the interface.

Figure 7 Longitudinal section of Fig. 6. Electrical damage has occurred along the outer surface and within the GRP rod.

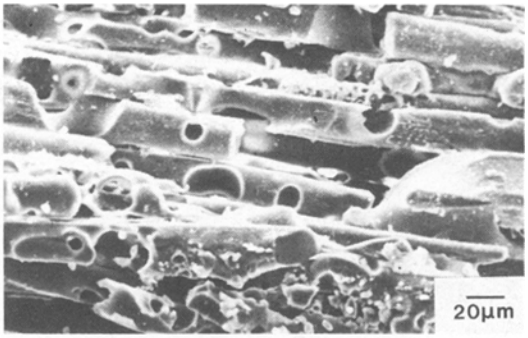

Figure 9 Electrical damage along the surface of the GRP rod showing partial erosion or puncturing of the glass fibres.

both the transportation and deposition processes along the rod surface. X-ray emission studies on other parts of the GRP rod surface revealed on frequent occasions the presence of chlorine, sulphur and sodium in small quantities. The chlorine may have arisen from the resin, but the other elements are likely to have arisen from the atmosphere prior to the onset of electrical damage.

The build-up of electrical damage as described above eventually leads to the total breakdown of the component which then requires replacement.

3.2. Examination of rods subjected to high mechanical stresses

Under these conditions the rod was subjected to a higher tensile load which could consist of static and variable components, the latter being caused by vibration and wind loading. Calculations indicated that the maximum loading could not have exceeded one tenth of the failure load of the GRP rod.

Some form of electrical activity was found on each rod that was examined, but in no case was the degree of electrical activity as severe as that observed in suspension insulators. Failure in these tests was not by electrical breakdown but by a complete mechanical break across the section of the rod, usually at the "hot end" of the insulators. The nature of this fracture is shown in Fig. 12. Fracture has initiated at the top left hand side of the rod in this picture and the crack has spread out to give a characteristic fan-like appearance. Fracture usually initiated at more than one point leading to multiple transverse cracks on the surface of the rod (Fig. 13). Crack propagation took place from one or two of these initiation points leading to a very flat type of fracture surface. Electrical damage is associated with this fracture in the form of breakdown at the GRP rod–shed interface. This can be seen in Fig. 12 at position A, i.e. close to the point of fracture initiation.

Longitudinal sections taken through the failed

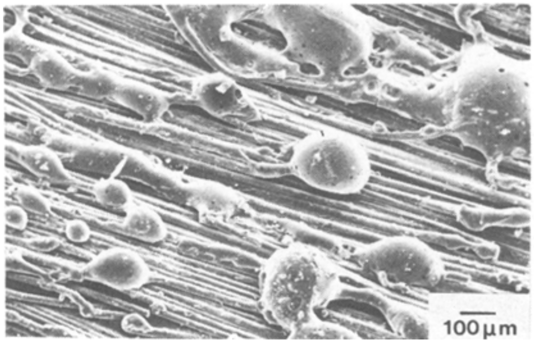

Figure 8 Electrical damage along the surface of the GRP rod showing fusion and fracture of the glass fibres.

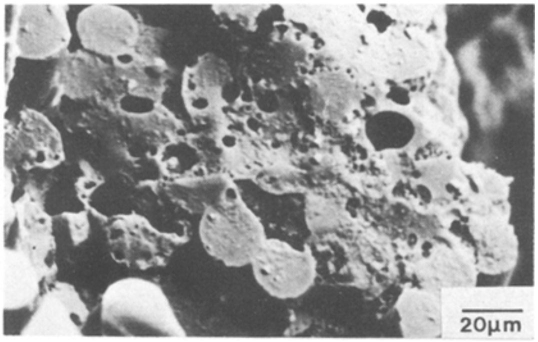

Figure 10 Electrical damage in the GRP rod showing puncturing of the resin.

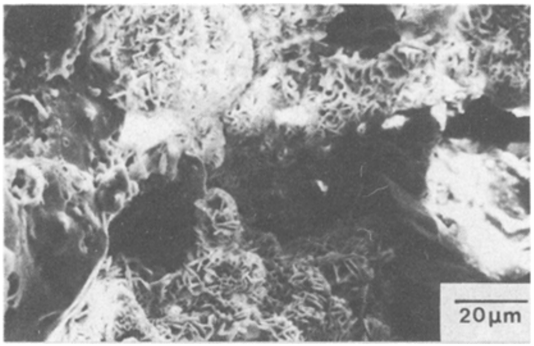

Figure 11 Debris at the surface of the GRP rod at the point of electrical breakdown. The small platelike crystals are very rich in zinc.

rod and shedding at a position between the hot end of the insulator and the fracture referred to above, revealed evidence of electrical damage at the interface and within the GRP rod in the form of longitudinal cracks. Many of these longitudinal cracks follow the joining line between bundles of fibres (Fig. 14). Transverse cracks were also present in the GRP rod, some running in from the surface and others from the longitudinal splits (Fig. 15).

Removal of the shedding from the regions where the electrical damage and debonding had occurred at the rod–shed interface revealed evidence of erosion of the rod surface, localized melting, and brittle fracture of the glass filaments (Figs. 16 to 18).

3.3. Fractography of high stress failures

The observation of multiple cracking on the surface of the GRP rod indicates that crack initiation can take place in several adjacent planes. However, on each plane it is quite clear that the local fracture path is extremely flat, see Fig. 19. The steps on the surface produce characteristic river markings, leading back to the point of crack initiation. Closer examination of the steps, see Fig. 20, reveals evidence of undercutting of fibres where the crack at that position has propagated at two levels. The two levels are linked by a small vertical wall or step. Thus the macroscopical flat regions of failure are made up of a series of flat regions linked by a series of microsteps which may be 50 to 100 μm in height.

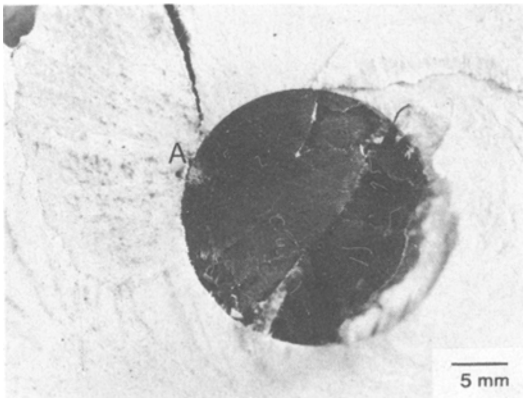

Figure 12 Brittle fracture face of GRP rod and shedding material which was subjected to the higher tensile loads in a tension insulator.

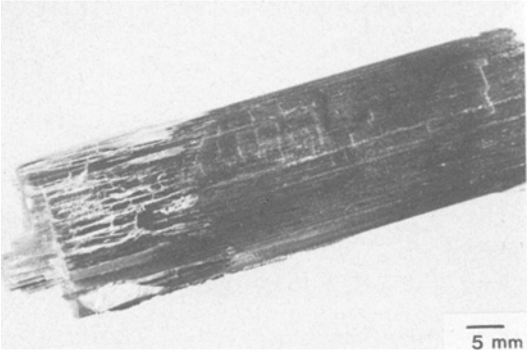

Figure 13 Multiple transverse cracks on the surface of a GRP rod (tension insulator).

Close examination of the fracture surfaces of the individual glass fibres reveals many features. Where surfaces are relatively clean, brittle fracture of the glass appears to have taken place with the formation of a single crack propagating with a semicircular front thus forming a so-called mirror region, see Fig. 21. This has been followed by the

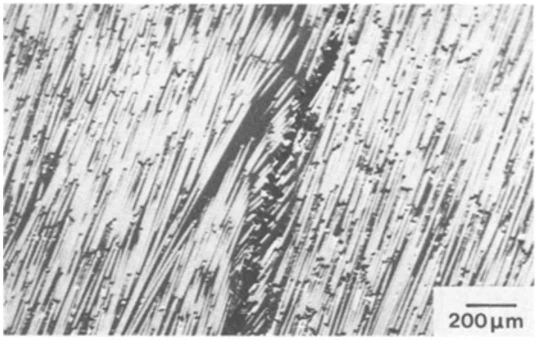

Figure 14 Longitudinal crack, which has occurred between bundles of fibres, brought about in part by electrical tracking in the rod.

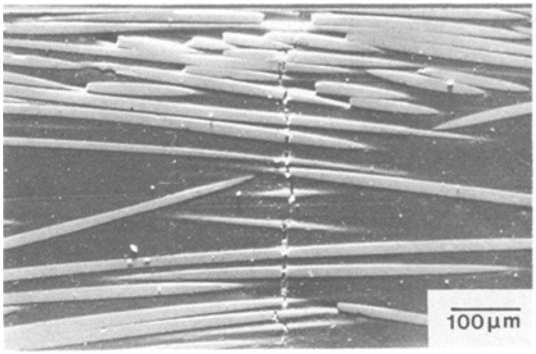

Figure 15 Transverse crack which has initiated internally in the rod from the kind of longitudinal crack shown in Fig. 14.

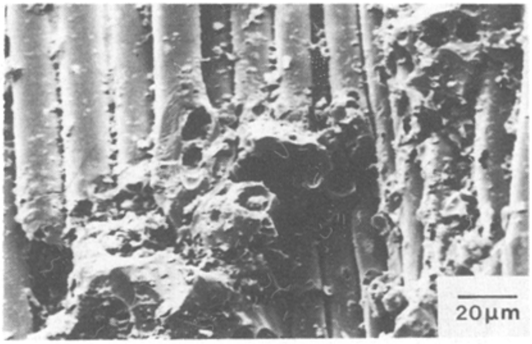

Figure 17 Puncturing of resin and glass fibre in region shown in Fig. 16.

bifurcation of the crack in the vertical plane with the subsequent formation of "glass wedges", see Fig. 21, some of which have remained on the fracture surface. These wedges have a comparatively rough surface and represent the so-called hackle region of failure on bulk glass. X-ray analysis on the fractured glass fibres reveals small differences in glass composition when comparison is made with fibres sectioned away from the fracture surface. The calcium and aluminium content at the fracture face is lower whilst the silicon content is increased.

Foreign particles and glass debris were present on parts of the fracture surface, see Fig. 22. The particles have been analysed using X-ray dispersive analysis. Two groups of particulate matter could be recognised on the basis of this analysis: (a) those containing sodium, magnesium, aluminium, silicon, sulphur, chlorine, potassium and calcium; and (b) those containing aluminium, silicon and calcium. The level of calcium and silicon found in (b) group particles was greater than in the (a) group debris.

Some areas of the fracture surface are very smooth, see Fig. 23, and individual glass fibres can no longer be detected. Chemical analysis of this surface reveals similar compositions to that found in the glass wedges, with additional chlorine and sulphur. This would suggest the smooth region has either been molten or glass debris has been compacted and burnished into a continuous layer.

On a number of fracture surfaces X-ray analysis provided evidence of small concentrations of zinc. It is possible that the transport of zinc may have occurred along electrical damage paths to the fracture surface in a manner similar to that described for the suspension insulators.

4. Discussion

4.1. Electrical–chemical damage

The nature of the damage found in the suspension insulators was caused by electrical discharge in service. The electrical energy available in the

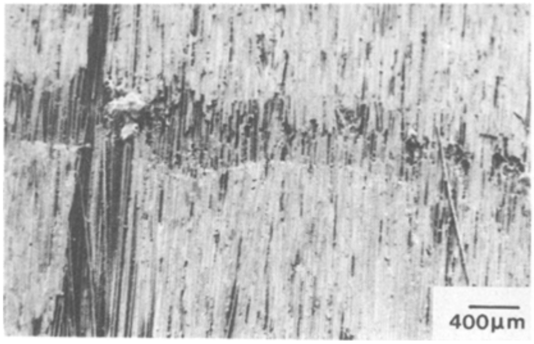

Figure 16 Erosion of the surface of the GRP rod by electrical activity (shedding has been removed).

Figure 18 Higher magnification picture of transverse cracks in the surface regions of the rod shown in Fig. 16.

Figure 19 Low magnification picture of river markings (steps) on the fractured rod surface, each of which runs towards the point of crack initiation (tension insulator).

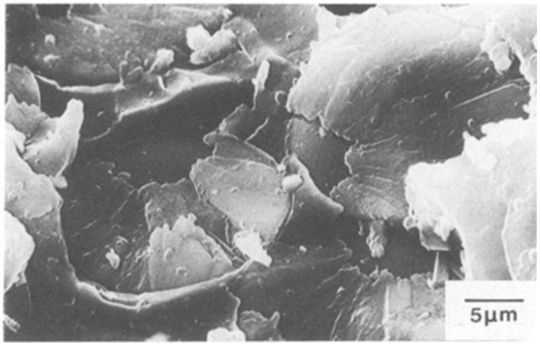

Figure 21 Higher magnification picture of the fracture surface showing the existence of glass wedges on the surfaces of most of the fractured glass fibres.

275 kV insulators is more than sufficient to provide heat to cause melting and vaporization of the resin and glass or promote chemical reaction of these components with the environment, e.g. burning. Once resin and/or glass have transformed from the solid state to the liquid or gaseous state, then material transport out of the system through the observed puncture holes can take place readily. This leaves behind the kind of damage shown in Figs. 4 to 10 inclusive.

The question arises as to how initiation of damage occurs in what is essentially classed as an insulating material. The nature of the breakdown of dielectric solids is complex; the resultant conductivity can either be electronic or ionic in origin [4]. Electronic conductivity tends to have constant high dielectric breakdown strengths at low temperatures; as the temperature rises the breakdown strength falls off. It is believed that in normal operation the insulators are not subjected to significant elevated temperature levels and therefore it is unlikely that electronic breakdown is taking place. Ionic breakdown could come from the nature of the interfaces exising in GRP. In the present situation this would be principally the GRP rod/shedding interface or microvoid defects in the resin in the rod and shedding which are built in at the manufacturing stage.

Kadotani [5] and Cotinaud *et al.* [6] have demonstrated experimentally that the dielectric properties of GRP depend on (a) how the resin is cured, (b) the ability of the cured resin to take up water, (c) the presence or otherwise of glass surface finishes, and (d) the orientation of the fibres relative to the direction in which the electrical property was measured. The ability of the resin to take up water and its role at the interface appears to be the key issue, e.g. coated glass fibres tend to reduce the effect of water on the dielectric properties of GRP. In the design of the insulator studied in the present work it is envisaged that electrical damage starts at the end of a GRP rod adjacent to the metal end fitting and then makes

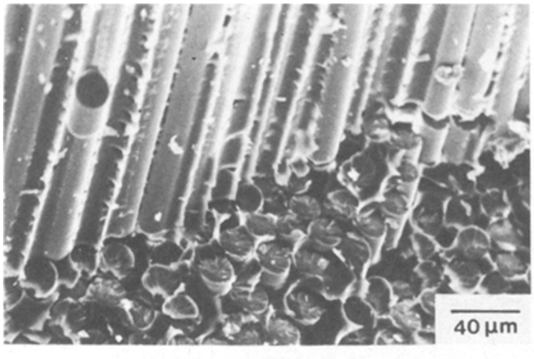

Figure 20 Detail of the steps on the fracture surface showing undercutting of the fibres at the base of the steps (tension insulator).

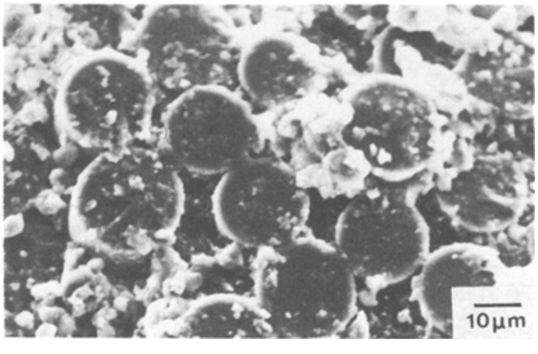

Figure 22 Foreign particles and debris on the fracture surfaces of the GRP rod (tension insulator).

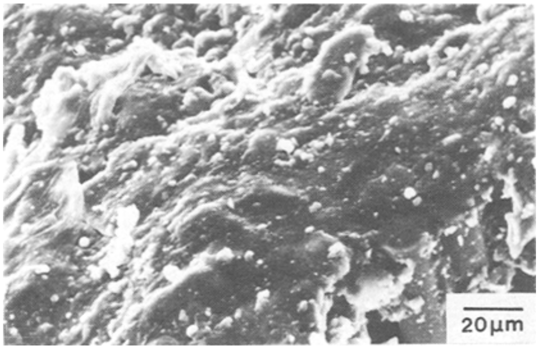

Figure 23 Micrograph of smooth areas observed on some fracture faces of the GRP rods (tension insulator).

its way along the rod, possibly with the assistance of absorbed water from the atmosphere. The path of the damage is principally at the rod/shedding interface but occurs also within the GRP rod itself especially if weak regions are present, e.g. those which are resin-rich. Assistance may be given to the propagation of damage at the early stages by several factors which include the number of discharges, the surface regions on to which the discharges are focused, the presence of conducting layers on internal surfaces, and the presence of certain gaseous species [7]. A process of surface erosion begins to form microchannels between 2 and 10 μm diameter (see Fig. 10) under these conditions. As the microchannels branch a "treeing pattern" emerges; the damage shown in Figs. 6 and 7 probably represents sections through the "tree pattern" in these insulators. Eventually breakdown escalates and local thermal effects start to take place, resulting in gross movement of material by burning, melting and vaporization, etc. as shown in Figs. 8 and 9. Where the shedding material is at minimum thickness, see Fig. 3, the electrical activity comes to the outside surface again leaving a punctured hole in the cycloaliphatic resin.

4.2. Electrical–chemical–mechanical damage

In circumstances where the mechanical load is sufficiently high, then brittle fracture of the GRP rod takes place before electrical damage has caused breakdown of the insulator. In all cases of brittle fracture, evidence of electrical damage was also found adjacent to the region where fracture initiation had taken place. In these circumstances electrical effects could have initiated failure. The electrical damage can take the form of erosion and melting of fibres and this localized damage can then lead to cracking of fibres (Figs. 8 and 9). Cracks can also initiate inside the rod section if electrical damage has occurred adjacent to that region. However, it is difficult to understand how electrical activity on its own could account for the extremely planar nature of the fracture surface.

Since electrical damage is associated with a continuous path to the environment it is possible for moisture and contaminants, e.g. water, inorganic salts, organic compounds, to be brought to the rod surface. In particular, the surfaces of glass fibres may become contaminated. Evidence has been provided of significant quantities of zinc or its compounds which probably came from the end fittings, as well as minor evidence of chlorine, and sulphur on the fracture surfaces. Therefore, in the current investigation, it is virtually impossible to dissociate an electrical and chemical effect. In fact, the two may combine, for example in an electrochemical fashion, or by electrical energy causing heating which in turn can concentrate certain pollutants at critical positions, e.g. on the glass surfaces and at crack tips.

It is known that glass fibres are susceptible to static fatigue in moist environments and that degradation processes take place in GRP if moisture ingress occurs at the resin/fibre interface. Significant damage [8] due to this ingress can occur in short periods of time if the water temperature is increased. As stated in Section 1, problems of strain corrosion fracture have arisen when using GRP in sewage pipes. ASTM D3263 [2, 9] specifies the conditions under which this strain corrosion may be simulated, i.e. by testing in sulphuric acid. The fracture surfaces of strain-corroded GRP samples bear a close relationship to the fracture surfaces shown in Figs. 12 and 19. Schmidt and Metcalfe [10] consider that ion exchange takes place between surface cations in the glass and hydrogen ions from the acid. This exchange can produce tensile stresses in the surface of the glass fibres, thus leading to their premature failure.

The very close similarity between the fracture surfaces of the GRP insulator and the fracture surfaces of GRP rod tested under stress and strain corrosion conditions indicates that the fracture of the insulator is by an environment assisted process. However, it is unlikely that strong mineral acid conditions prevail generally in the environment when the insulator operates in service. There was no evidence from the fracture surfaces of strong concentrations of such acids. The probability of electrical energy playing a part in the failure mechanism therefore becomes stronger. If an electrochemical effect does take place, the crack tip could be cathodic and local hydrogen ion generation is feasible. Support for such an effect can be found in some work carried out by Scarisbrick [11] on high voltage epoxy resin insulator surfaces in salt laden atmospheres. When local heating takes place in association with electrical damage, contaminants could become more concentrated and thus provide a micro climate of acid conditions at the crack tip. Fracture evidence of the individual glass fibres, see Fig. 21, suggests that the initial fracture region results from relatively slow crack propagation which may be associated with the chemical attack, followed by crack bifurcation and fast propagation [3]. Evidence does exist of chemical changes in the glass fracture surfaces which indicate the removal of certain cations from the glass, principally calcium and aluminium.

5. Conclusions

1. E-glass fibre-reinforced epoxy rods may be damaged by the combination of (a) electrical and chemical activity resulting in a breakdown in dielectric properties, and (b) electrical, chemical and mechanical effects resulting in brittle fracture of the rod.

2. Electrical damage is encouraged initially by weak interfaces, voidage, and possibly by the absorption of moisture. Once the damage is established local heating effects may occur which promote more significant changes by the processes of fusion, erosion and vaporization. This results in glass and resin being transported through and out of the system.

3. At higher loads failure occurs by brittle fracture before gross electrical breakdown can take place. Nevertheless, some electrical damage is always found adjacent to the regions where the brittle fracture initiates.

4. Electrical damage allows moisture and contaminants to reach the glass fibre surfaces and it is probable that electrical and chemical effects work together to promote glass fibre failure at stresses well below the breaking strength.

5. The conjoint action of electrical and chemical effects operate to provide the correct chemical environment to produce a stress corrosion failure of the GRP rod.

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