CRACKING IN FIBRE CEMENT PRODUCTS

S.A.S. AKERS

AC CONSULTING, VORDERDORFSTRASSE 31, 8753 MOLLIS, SWITZERLAND

ABSTRACT

This paper provides the reader with a general insight into the problem of cracking and durability in fibre cement products. There are many types of cracks, for example cracking can occur in the stack or on the roof. An attempt is made to characterize the varied forms of cracking and at the same time propose possible mechanisms for this phenomena. This can be related to curing conditions, mix formulations and exposure to natural weathering. Finally, varied suggestions are made with regard to the prevention or reduction of the propensity for cracking.

KEYWORDS

Cracking, fibre cement

INTRODUCTION

Asbestos cement was for decades the prime example for fibre reinforced thin cement based composites. Over the past 25 years much research has been done in order to replace these asbestos fibres with alternative fibres. The types of substitute fibres, which have been investigated, vary from natural fibres to synthetic fibres. Examples of just a few of the fibre types are cellulose, carbon, kevlar, polypropylene, polyvinyl alcohol, polyacrylnitril, ceramic, glass, wood, etc. Although there has been (and still is) a tremendous thrust in research programmes to seek for more fibre alternatives, the fibre cement producers world wide have used only a few of the fibre types researched for products produced for the market today. The reason for this, is that choice of a particular fibre type is based on price, availability, compatibility with cement, durability and the reinforcing potential in the cement composite. Broadly speaking, fibre cement products used in the market place, can be manufactured in many ways, e.g. standard Hatschek process or flow-on process, injection moulding, extrusion, spray-on as used in GRC and many others. The curing process after production can also vary according to the product range. With the launch of the new generation of asbestos-free fibre cement products, unexpected problems with regard to durability and cracking were encountered and this problem had to be investigated using well designed laboratory tests.

This paper is aimed at providing an insight into cracking and durability of these newly developed fibre cement products, which can be related to many aspects such as product type, manufacture, application and exposure. Two papers previously published (Akers, Garrett and Akers, PartI) have been reviewed in order to provide examples for the cracking mechanism and durability.

DURABILITY ASSESSMENT IN FIBRE CEMENT COMPOSITES

Fibre cement products undergo physical and chemical changes when exposed to natural weathering conditions or stored in a stack in a stockyard. As these changes relate to the service life and cracking performance of the products it is important in fibre cement development programmes to investigate these aspects in greater depth.

The behaviour of the varied products in service are directly related to its type of application: e.g., a roofing product would invariably be subjected to a more harsh climatic and mechanical stress than a wall cladding. The performance standards for products are therefore adjusted according to the application of the product. Likewise it is necessary to apply different calculations and prediction methods to service life, usability and safety for roofing products and wall claddings.

A pre-requisite for the calculations involved in service life predictions is a good understanding of the mechanism of ageing and physical aspects such as hygral stability.

In fibre cement based composites the obvious changes which can take place during ageing are:

- The matrix
- The matrix fibre bond or interfacial bond and
- Fibres

Some examples of how these changes can influence the composite performance in the field are:

- Matrix "hardening" caused by hydration, carbonation and other external factors could result in an embrittlement caused by an increase in the fibre cement interfacial bond. This change results in a strength increase of the product with an associated embrittlement or decrease in toughness.
- If the fibre strength deteriorates, the composite strength will decrease.
- If the interfacial bond (fibre matrix) weakens as a result of possible wet/dry movement, the strength of the product will decrease but the toughness of the product could increase.

In general two of the most important aspects when assessing the durability of a product is to test its repeated wet/dry shrinkage properties and its reaction to carbonation. When developing any new products for the market, accelerated ageing tests are conducted, and the results compared with natural weathering tests. The correlation of the two tests is not simple and it is often difficult to predict the life of a product using accelerated ageing tests. However, general trends and warning signals can be derived from these tests and invariably prove to be reliable enough to judge the performance of the product in service. "Ballpark" numbers for the service life can be extrapolated from these tests. Important basic information to describe the material behaviour and in turn to understand and solve different technical problems in application is obtained from simple stress-strain diagrams. These, to a certain extent reflect qualitatively, plausible micro-mechanical mechanisms, which provide the first quantitative assessment of the composite material.

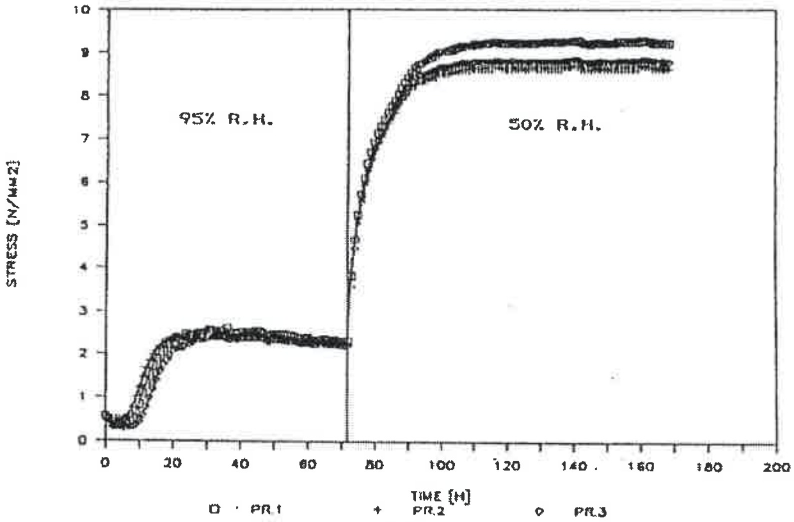
An understanding of the rate of loading dependence of the material behaviour (in particular corrugated sheets) is important with respect to walk-ability and security aspects, hail storms and handling. In general the higher the loading rate the greater is the load to failure. The influence of the duration of loading on the material behaviour is related to the kind of application of fibre cement products; particularly for corrugated sheets used as a roofing material. Here, creep effects may occur due to periodic snow loads over a longer period of time or creep of the product under its own weight and this could lead to permanent deformation or even to creep failure under extreme conditions.

Fatigue behaviour due to long term cyclic loading should be considered for practical cases resulting from transport, wind loading and persons walking on a roof, or in cases for products (e.g. pipes buried under a motorway), which are loaded by road traffic. A complete understanding of the mechanisms related to ageing therefore, is the basic requirement for predicting the cracking and durability of the product

CRACKING RELATED TO HYGRAL EXPANSION AND SHRINKAGE PROPERTIES (REVIEW OF PAPER (AKERS AND PARTL)

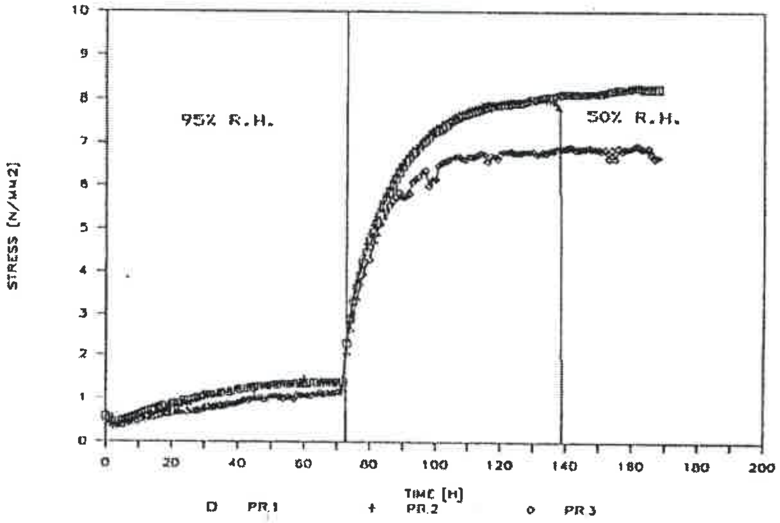
Fibre cement composites exposed to natural weathering or stored in a stack, absorb water and release water to their surroundings via a very complex inherent pore structure. Absorption and release of pore water is related to the type of application and the microclimate surrounding, the product, for example heavy rain, snow temperature, etc. The product itself can also vary depending on the application. Some are coated or impregnated. Lastly the age of the product is also a significant factor, influencing the rate of pore water exchange of the product. It is evident from the factors mentioned above that it would be an extremely difficult task (if not impossible) to describe or predict the exchange of water in the pores of a cement-based fibre composite during exposure to natural weathering and in-turn relate this to cracking in the field. Many researchers have made attempts to describe this in the past (see Goto and Roy, Powers and Brownyard, Relis and Soroka). An attempt has been made (Akers and Partl) to characterise varied products manufactured on a Hatschek process, according to water absorption and release properties. These fundamental laboratory tests have been described in detail. The water absorption and release is intern related to shrinkage and expansion of the product and the tests were designed in such a manner that a direct relationship between water movement and product shrinkage and expansion could be made. The ultimate aim of the laboratory tests was to understand the mechanism of water movement related to product movement and inturn stresses built up in the product, which could result in cracking and failure of the product in service. Two examples have been taken from the paper in order to elaborate on the difference in product properties, which can be directly related to product performance in the field. These are cracking related to expansion and contraction. The two products were made on a Hatschek machine; one autoclaved an the other air cured. Both have the same density but very different product composition. The autoclaved product consisted of 8 % cellulose fibres, cement and ground silica, whereas the air cured product consisted of synthetic fibres, cellulose fibres, cement and other minor additives.

The environmental chamber studies on the samples are described in detail and the results from these test represent the expansion / shrinkage properties of the varied products exposed to specific environmental conditions. As the test equipment could measure expansion / shrinkage and stress simultaneously, a direct relationship between change in the surrounding environment of the product and stress development with time could be established. See Figure 1 and Figure 2 below.



(a)

Figure 1 Autoclaved Product (Akers and Partl)



(b)

Figure 2 Aircured Product (Akers and Partl)

This particular series of tests was conducted on samples which were water saturated, prior to environmental chamber exposure. Subsequently the products were exposed to 95 % relative humidity at 20° C and 50 % relative humidity respectively. It is evident from the test results that the development of stresses in autoclaved products is certainly very different from aircured products of similar density. This is emphasised even more at relative humidity of 50 % and 20° C. This is one example of how products of similar density could have very different pore structures and in-turn respond very differently to water movement in the pores, resulting in unique stress developments within the product.

In this paper products of the same mix composition with varied densities were also compared and each product showed unique stress/time related characteristics. Lower density products of the same mix composition indicated slower response to stress development at a lower level to higher density products. This paper also includes a study of the influence of age (natural weathering) on stress development. The aircured product of density 1500 kg/m3 was used in this case study. The product had a history of five years' natural weathering exposure in Switzerland. For comparative purposes a non-aged equivalent was manufactured. The aim of the investigation was to assess the response of aged (naturally weathered) products to restrained shrinkage tests, and to compare these with the non-aged equivalent. An extreme laboratory exposure condition was chosen in order to test the limits of the stress build-up within aged and non-aged material. This test consisted of submerging the products in water for one week at 20° C and thereafter exposing them to an environment of 60° C and 10 % R.H. The results below indicate that the stress level development for aged products and non-aged products appeared to be similar in magnitude, however, the shrinkage properties for the aged products were significantly lower when compared with the non-aged equivalent. See fig.3 and 4 below. This is explained by the fact that the product becomes more dense with age and irreversible permanent shrinkage has already taken place with aged products.

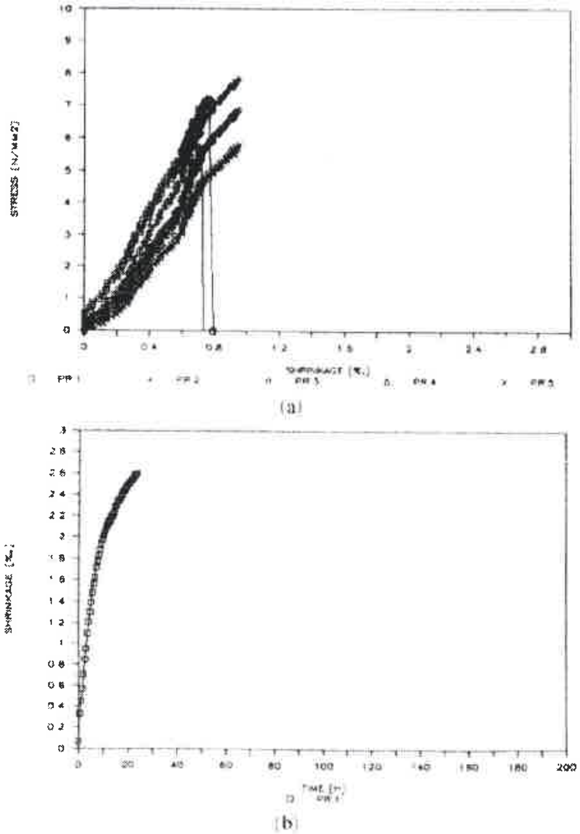


Figure 3 Shrinkage effects on non-aged products subjected to 60° C and 10 % R.H. (Akers and Partl)

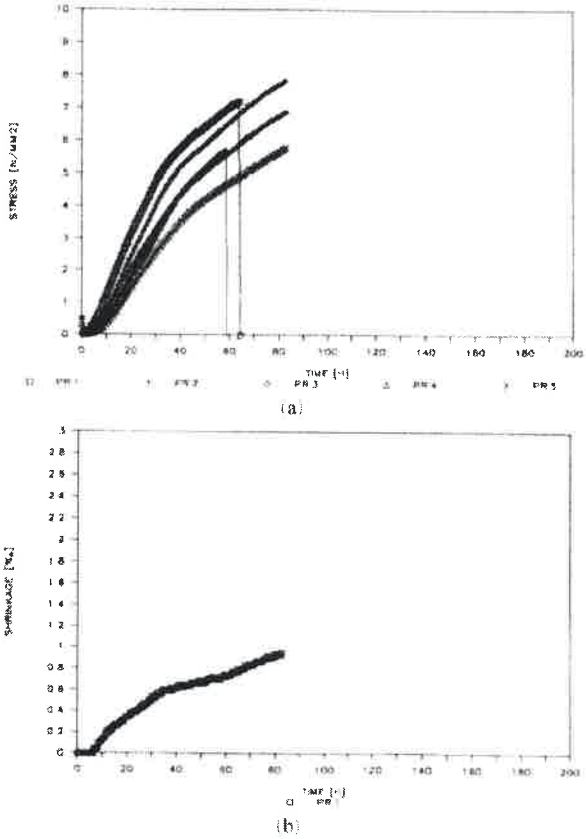


Figure 4 Shrinkage effects of aged products subjected to 60° C and 10 % R.H. (Akers and Partl)

The three most important conclusions derived from this study were:

1) Migration of the pore of fibre cement products is complex and not entirely related to the density of the material; this has a significant influence on shrinkage properties, which will impact the cracking of the product.
2) Restrained shrinkage experiments have indicated that although the stress levels at failure between aged and non aged products were similar, the rate of build-up of these stresses is much slower in aged products. Less shrinkage occurred in aged products, indicating that with age, cracking property is reduced.
3) A study of the migration of pore water within a product exposed to various environments has indicated that initial losses in pore water do not necessarily lead to greater internal stresses: more important is the rate at which the loss of water takes place and its magnitude within the product.

MULTIPLE AND SINGLE CRACK MECHANISMS (REVIEW OF PAPER AKERS AND GARRETT)

Cracking in a brittle matrix composite may occur in the form of a complex multiple cracking mechanism, which is able to cover the entire surface under stress ("multiple fracture") or it may fail by means of a single crack ("single fracture").

It was considered in the past that a single type fracture could occur predominately in ductile matrix composites whereas multiple fracture would appear to be the failure mode in most brittle matrix composites. Since the cement matrix of fibre cement composites is typically regarded as brittle, it is relevant to investigate whether "classical" multiple fracture does indeed occur specifically in order to be able to apply a suitable theory to make predictions regarding the strength and durability.

FLEXURAL STUDIES

For this purpose scanning electron microscopy was used, where direct observations were made on small flexural specimens, which were broken inside the microscope. The microscope was also used to investigate an area adjacent to the fracture surface of the tensile specimens tested in the laboratory. The results obtained from the scanning electron microscope (S.E.M.) and laboratory tests were used to examine analytical approaches to fibre cement composites in general. The experimental S.E.M. studies have been described in detail in the paper. With the specimen under flexural stress, a series of relatively large cracks (between 1 and 3 μm) were found parallel to each other and perpendicular to the major stress axis. This is illustrated by means of a montage used in Figure 5.

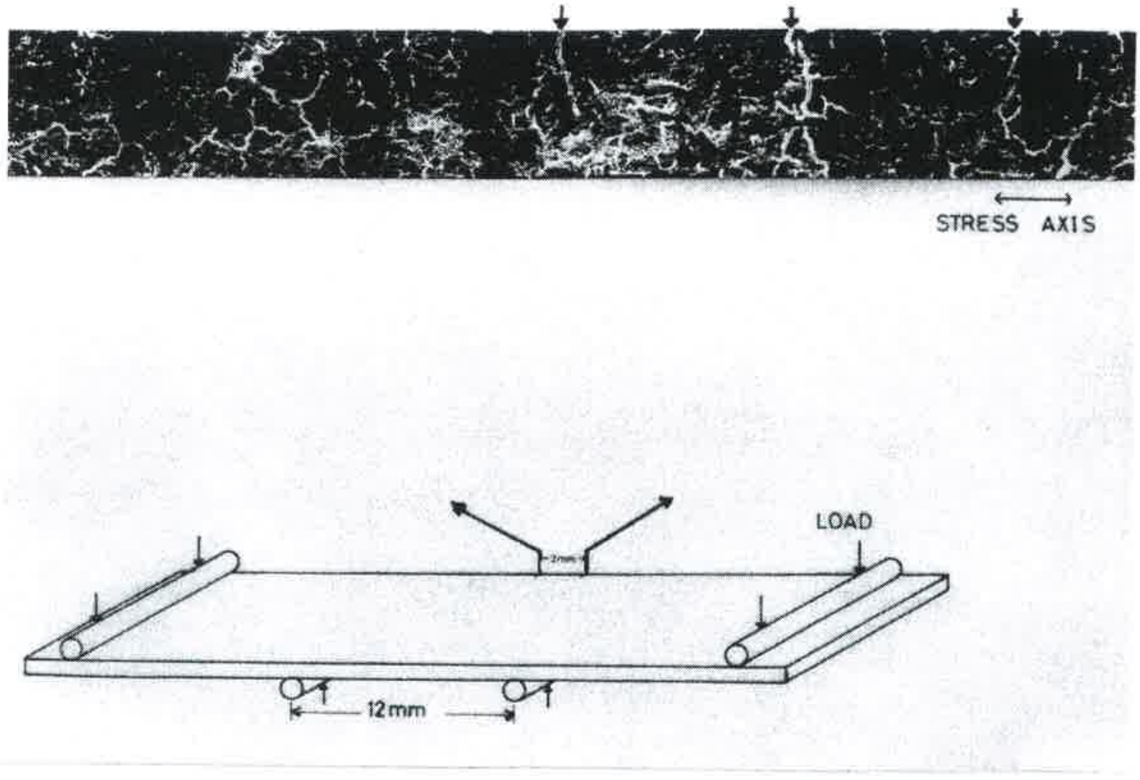


Figure 5 Montage of multiple matrix cracking, as observed in the S.E.M. (Akers and Garrett)

These cracks occur at various stages of loading and can be regarded as a typical example of multiple fracture. The cracks propagate through the brittle matrix across the surface of the specimen, and are held together by fibres bridging the cracks. The applied load is transferred to the fibres and a new crack opens parallel to the proceeding crack. The load transfer from the matrix is then repeated. This process continues until the applied load is greater than the load which the fibres are able to support. Fracture then occurs in the weakest part of the composite, i.e. the largest flaw which acts a s crack initiator. Very fine cracks, less than 1 μm in width, were also found to occur randomly throughout the stressed surface. These appeared to propagate in all directions. A higher magnification micrograph of a selected area shows this complex distribution of cracking in Figure 6.

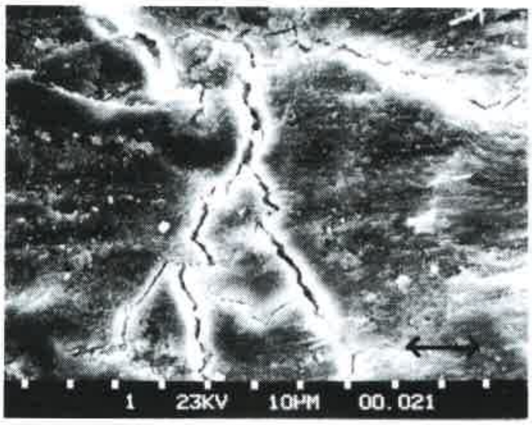


Figure 6 Complex distribution of micro cracking. Enlargement of one of the cracked areas in Figure 5

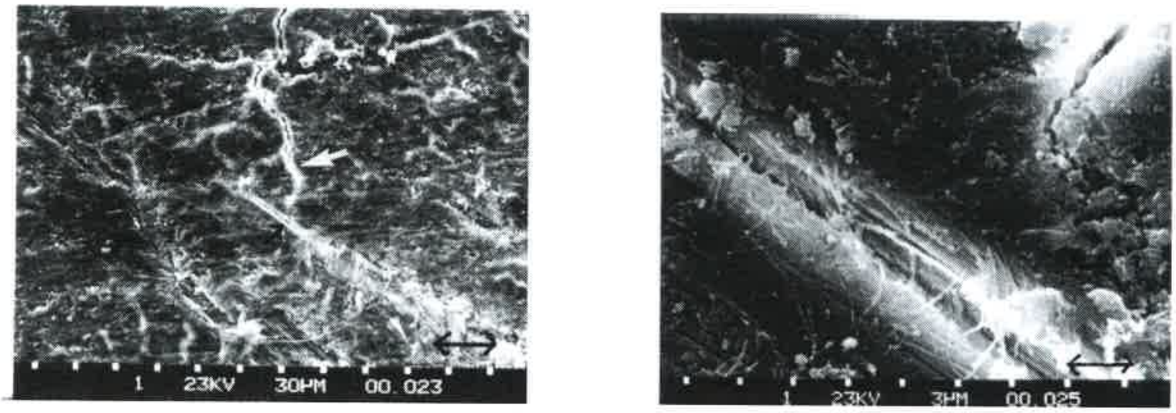


Figure 7 a

Figure 7 b

Figure 7 An example of a fibre bundle acting as a crack arrestor (a) Subsequently the crack propagates within the individual fibres of the fibre bundle (b)

In Figure 7 (a) the growth of the crack indicated by the white arrow has been restricted by the presence of a fibre bundle. It would appear that, as a result, separation of the fibres within the fibre bundle has taken place, Figure 7 (b), thus allowing the crack to continue between the individual fibres.

The efficiency of fibre strengthening in a composite is largely dependent on the orientation of the fibres bridging the crack. This would indicate the necessity for an efficiency factor when making theoretical predictions.

UNIAXIAL TENSION

A typical stress/strain curve for fibre cement composites in direct tension is shown in Figure 8.

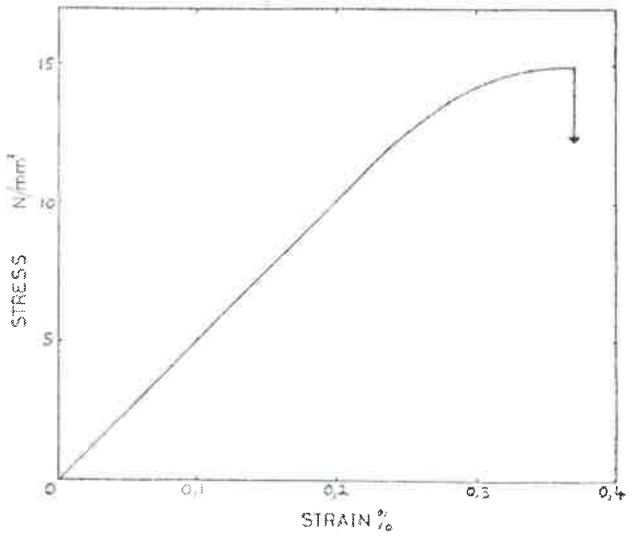


Figure 8 A typical stress-strain curve obtained in uniaxial tension

The non-linearity in this curve would suggest that multiple matrix cracking, as distinct from non-cumulative "single" fractures could be taking place. This assumption was confirmed using the S.E.M. where additional cracking was found away from the fracture surface of a tensile test specimen Figure 9.

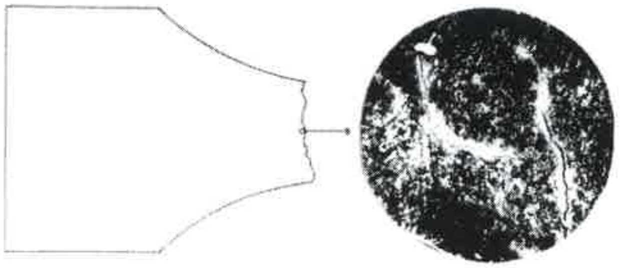


Figure 9 (Akers and Garrett) Micro cracking observed close to the fracture surface of a tensile test specimen (Mag x 1000)

The development of damage occurs progressively and is relatively easy to monitor. The multiple matrix cracking consists of a series of relatively large cracks, increasing to approx. 1 – 3 /um in width, parallel to each other and predominantly perpendicular to the major stress axis, together with finer cracks (less than 1 /um in width) randomly oriented throughout the surface under stress. As the cracks grow bridging fibres carry the load. Many of the finer, subsidiary cracks open simultaneously with the major cracks and contribute to carry the load as the product is put under continued stress.

In general therefore it can be concluded that multiple matrix cracking exists in fibre cement composites and consists of a series of relatively large cracks, which are parallel to each other and perpendicular to the major stress axis and finer cracks (less than 1 /um in diameter), which are dispersed randomly and in all directions throughout the stressed surface. The very fine cracks, which occur in addition to the nominal cracking could be due to the large variation in aspect ratios of reinforcing fibres. Cracks absorb energy during the fracture process and therefore cannot be disregarded completely when considering multiple matrix failure. The orientation of fibres bridging a crack is clearly an important aspect to consider with regard to theoretical predictions.

This type of cracking can occur in the field, if products are exposed, to extreme climates and are subjected to flexural and tensile stresses in their application.

SUMMARY AND CONCLUDING REMARKS

It is evident from over 25 years experience in fibre cement composites, which have been highlighted in the two papers reviewed that cracking in thin fibre cement composites is complex and is in certain applications inevitable unless certain precautions are taken. The major cause of cracking, whether on the roof or edge cracking in the stack is caused by stress development brought about by hygral gradients within the product.

When the products are stored in the stack (flat sheets or corrugated sheets) edge cracking is likely to occur due to the product drying out at the edges while the covered product in the stack is still wet. Moisture gradients will occur between the edge of the sheet and the centre of the sheet and could result in differential shrinkage and ultimate failure evidenced by cracking. Similar comparisons could be drawn with roofing slates exposed on the roof; the covered and exposed parts of the product subjected to different microclimates under natural weathering conditions. The obvious way to prevent or reduce cracking propensity is to protect the product from large gradients by coating the product. In the case of cracking in the stack before the product is put on the roof, the stack can be shrink wrapped with a plastic foil for example in order to prevent edge drying.

Some products inherently are more susceptible to cracking than others and is related to the density and mix composition of the product. For example autoclaved products compared with aircured products. Mix formulations can be adjusted to reduce the wet/dry movement of the products and this fine tuning of product ingredients varies within the fibre cement industry. Carbonation shrinkage should not be forgotten as this has a particular influence on the permanent shrinkage of the product.

Every fibre cement product has inherent cracks, whether these occur during curing on the roof. The major concern is the size of cracks and are they multiple or single cracks. Also it is important to have an understanding of the crack propagation or crack healing effect. This has not been dealt within this brief overview, however much evidence does exist in the fibre cement industry with regard to this issue – this obviously is the key to a durable product and one which is likely to crack and fail in the field.

REFERENCES

Akers S.A.S., G. G. Garrett, 1983. "Observations and predictions of fracture in Asbestos Cement Composites" Journal of Materials Science

Akers, S.A.S., Partl M. (Switzerland) 1989. "Hygral & Thermal Expansion/Shrinkage Properties of Asbestos-Free Fibre Cement". Cement & Concrete Composites, Vol. 12 no. 1 1990.

Goto, S., Roy, D.M., July 1981. "The effect of W/C ratio and curing temperature on the permeability of hardened cement paste". Cement & Concrete Research, 11 (4) 575-579.

Powers, T.C., Brownyard, T.L. October 1946. "Studies of the physical properties of hardened portland cement paste". In Proc. American Concrete Institute, 43 (2) 101-131.

Relis, M., Soroka, I., July 1980. "Limiting values for density and intrinsic shrinkage in hydrated portland cement." Cement and Concrete Research, 10 (4) 499 – 508.