Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Application and Evaluation -, October 2002

DUCTILE FIBRE-CEMENT COMPOSITES : ASSESSMENT OF DURABILITY WITH PARTICULAR REFERENCE TO FATIGUE, CREEP AND AGEING

Stephen Aubrey Stuart AKERS*

ABSTRACT: This paper describes the relevance of the stress / strain relationship in a young product and its change with ageing in a natural weathered environment. The results presented are based on experience in the field and laboratory tests on fibre reinforced cement pipes. Particular emphasis is placed on durability, ageing, creep and fatigue. An attempt is made to describe the behaviour of the material and it will be shown that the fatigue and creep behaviour of pipes in particular is not the same. Different safety factors need to be applied when describing fatigue and creep. The paper is based on industrial experience and practical studies with a new generation of "ductile" materials.

KEYWORDS: durability, ageing, creep, fatigue, pipes, fibre reinforced cement

1. INTRODUCTION

Using fibres to reinforce brittle cementitious materials is well established and is considered to be standard practice in thin fibre reinforced cementitious materials. The choice of a particular fibre type however can be complex and requires in the first instance a fundamental understanding of the reinforcing potential of the fibre, interfacial bond and matrix properties. This can be achieved by practical laboratory experiments where fibres are mixed with varied modifications of the cement matrix. The problem with hand made laboratory samples however is that it may only be used for comparative purposes for fibre composite design. The transfer of these laboratory experiments to an industrial fibre cement composite requires a great deal of experience and practical experimentation. It may happen that laboratory type tests could even be misleading as an input to the industrial process. There are many industrial processes available for the production of fibre cement composites; the largest being the Hatscheck and Mazza process for flat sheets and pipes respectively.

Each industrial process needs to be evaluated with regard to the fibre type most suited to the process and obviously the economic aspects a well. This paper describes the fibre cement material properties of products produced on the Mazza process. Particular emphasis is placed on the ageing, creep and fatigue behaviour of the material. The products used for this case-study are pipes produced in Switzerland with PVA and Cellulose fibres.

---

* Eternit AG, 8767 Niederurnen, Switzerland and Dr. Stephen A.S. Akers, Consultant in Materials Engineering, Vorderdorfstrasse 31, 8753 Mollis, Switzerland

2. MECHANICAL PROPERTIES AND AGEING

A typical stress/strain relationship from a ring crushing test for a 600 mm diameter pipe with a 20 mm wall thickness is given in Fig. 1 below. The test procedure is shown in Fig. 2.

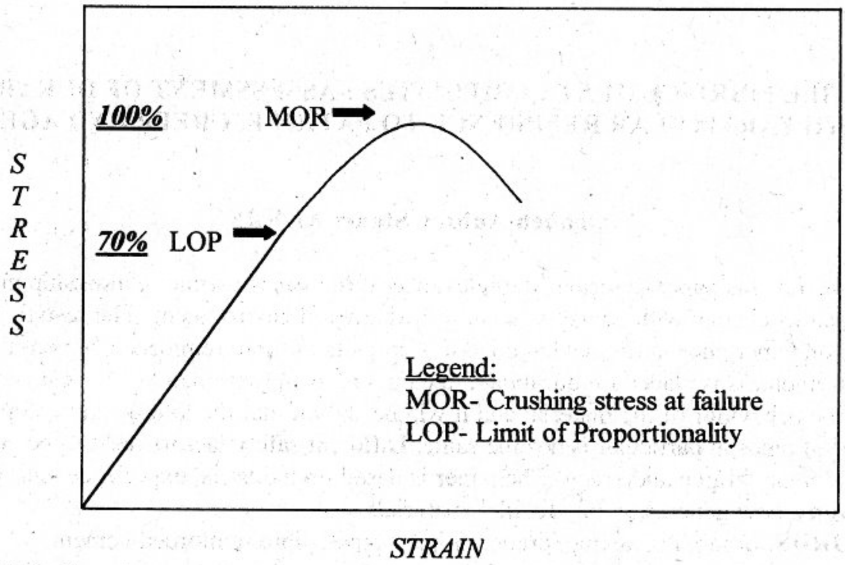

Fig 1

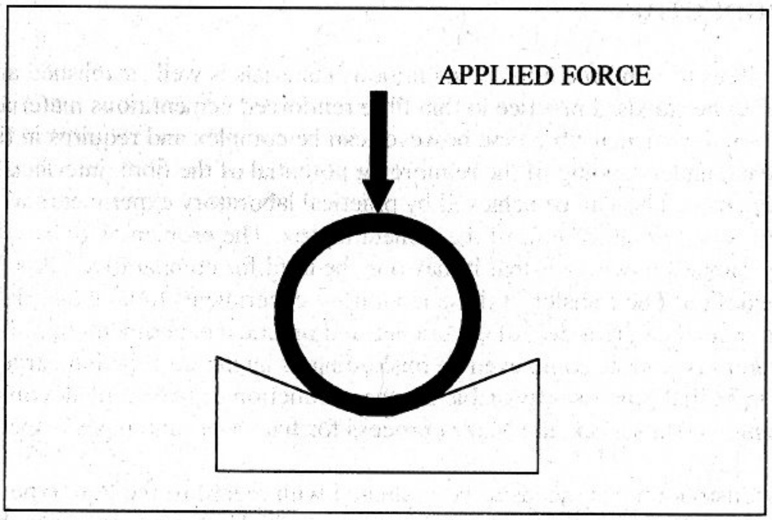

Fig 2

The pipe has a "pseudo ductile" type of failure. This type of failure has been reported previously [1].

It is generally accepted in the literature that the first crack in cement fibre composites occurs at LOP and with increased load, fibre pullout, fibre fracture and separation of the fibre matrix interfacial bond occurs. This has been observed using Scanning Electron Microscope studies [1], [2].

The fresh fibre cement composites display pseudo ductile behaviour, which can be an advantage in many fields of application. It was soon realized however that fibre cement properties change with time and the ageing properties of the materials is an important factor to consider for long term durability predictions, in particular when utilizing the ductile property of the material.

The fresh fibre cement composites contain much un-hydrated cement clinker with a good bond between fibres and matrix. The cement matrix is rather porous, on account of the generally low degree of hydration: spaces between clinker grains tend to be filled with low density cement paste. The degree of hydration is enhanced by natural weathering, and the matrix begins to show evidence of more re-crystallization. Nevertheless, many of the larger-scale micro structural features broadly resemble those of fresh material. Ageing changes the size and shape of the pores and the total porosity decreases. This has been described in the literature [3].

In the case of pipes buried underground the ageing process can be very complex. The outer wall of the pipe undergoes a different degree of ageing to the inner wall. Depending on the soil surrounding the pipe, the hydration and carbonation of the outer wall will have a different degree of ageing to the inner wall. In most cases however it appears that the inner wall of the pipe has the more advanced hydration due to the more wet environment inside the pipe. Within three to four years of ageing in an underground environment, the difference in degree of hydration between the outer and inner wall of the pipe can be as much as 30 %. This differential ageing results in internal stress fields which are built up between the inner and outer walls of the pipe. If they become too large and eventually greater than the tensile strength of the pipe material, failure will occur. In a fresh pipe the stress build up can be released by micro cracking and self healing (exposed un-hydrated cement clinker in contact with water forms new cement hydration products). In an aged pipe however, because of the decreased "ductility", the stress build up can occur without self healing and the failure mode of the aged pipe can be catastrophic. This type of failure can be costly for example pipes buried under high rise building. For this reason it is important to understand the change in "ductile" behaviour of the pipe with age and in turn predict the long term properties. In addition to the change in ductility due to ageing, pipes also experience creep due to soil pressure and fatigue due to live traffic loads. These aspects will be discussed in the next section.

3. ASSESSMENT OF THE CREEP MECHANISM

A creep test was conducted on a 600 mm (wall thickness 20 mm) diameter pipe using dead weights. The loading procedure was performed according to standard practice with varied dead loads representing a percentage of the ultimate crushing load to failure. The test set-up for the short term crushing test and long term creep tests were identical (as represented in the Fig. 2).

In this case dead loads where applied at 40 %, 50 %, 60 % and 70 % of the ultimate load to failure. It should be pointed out that it is not the intention to report here on the extrapolation of the creep curves for the prediction of service life. The emphasis is rather placed on failure and/or creep behaviour as a function of time versus loading regime and used for the interpretation of the creep mechanism and material property behaviour.

The load versus creep curves are given below in Fig. 3

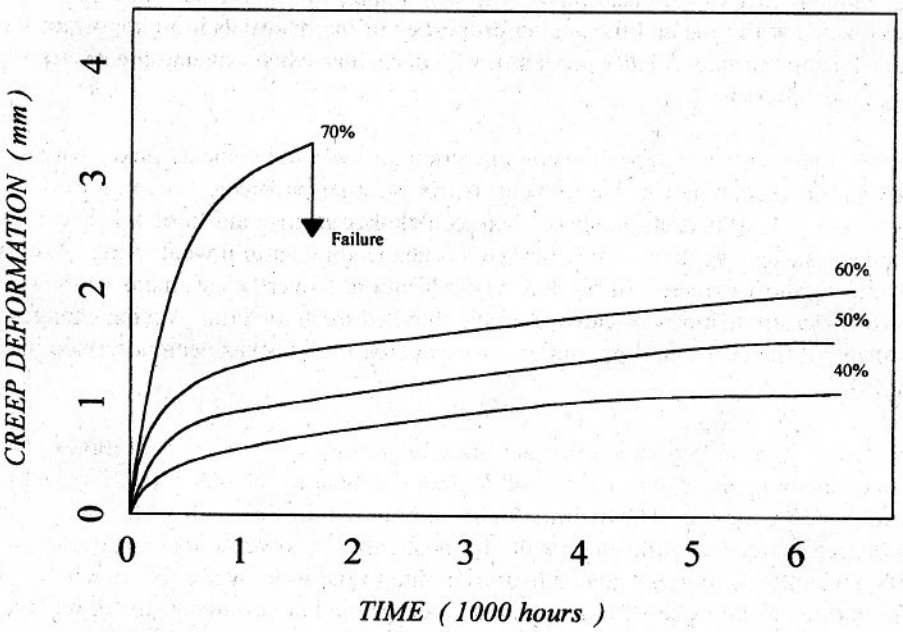

Fig 3

The creep behaviour of the pipes (given in Fig. 3) indicate that failure occurred at loads of up to 70 % of the ultimate load to failure. This corresponds to the load at LOP (see Fig. 1 from a short term crushing test), which is where first cracking occurs. Loads below 70 % of the ultimate load to failure, show creep deformation without failure after 250 days.

It is suggested here that two mechanisms of creep are evident in fibre reinforced cement composites. These are:

1) Creep due to crack propagation occurring at loads equal to or a greater than LOP
2) Creep deformation related to stress relaxation of the material

The former results in failure within relatively short periods at time and is strongly related to the mechanical and creep properties of the fibres bridging the cracks, the interfacial bond and crack propagation. The latter is more complex as it is related to the microstructure of the cement paste, the crystalline phase of the calcium silicate hydrates, porosity, water content in the pores, the interfacial bond, the fibre properties, etc.

Tests and observations have led to the following general conclusions concerning the magnitude of creep in fibre cement based composites:

- Creep depends directly upon the imposed stress: for stresses above 70 % of the ultimate material strength, the relation is non linear crack propagation; for stresses at or below 60 % progressive deformation occurs
- Creep is influenced by external humidity and is higher in water saturated specimens

The relevance of these results with respect to the actual stresses on pipe underground will be discussed later in this paper.

4. ASSESSMENT OF THE FATIGUE MECHANISM

Fatigue of a material is progressive fracture, which consists of cumulative damage resulting from variable or cyclic loading. The word fatigue is used, for such situations where there is no stabilisation but rather a gradual increase in damage. In cement based brittle materials, cracks spread out from a system of initial micro-cracks and multiply under relatively low loads. The opening and propagation of micro-cracks determine the materials' behaviour under sustained and cyclic loads.

The fatigue strength of materials means the maximum value of stress, which may be supported indefinitely and is indicated in relation to the static strength under single, short-term, loading. Usually, and for practical applications, it is assumed that the maximum load supported during 1 million to 2 million cycles may be considered as the fatigue strength of the material. The strength under cyclic loads in brittle materials is mostly represented as decreasing with time. For fibre reinforced cement based materials, however, it is believed that the fatigue behaviour is different to that of brittle materials.

The present state of knowledge of the fatigue strength of brittle matrix composites under various loads is not very large. The main reason is that the testing of elements under fatigue is particularly long and expensive and observation of the structures does not furnish all the information necessary for such an assessment. Basic phenomena in gradual degradation of the material structure are strongly related to many external influences and until now only approximate predictions are possible.

In cement based composites, however, the cracks are controlled by elements of their internal structure, aggregate grains and reinforcing fibres. Micro-cracks of various dimensions exist from very low loads. They propagate and multiple cracks appear caused by an additional input of the external energy. The load is supported initially by the matrix and later by reinforcement. Usually, the stress at local concentrations (tips of initial cracks, inclusions) exceeds the tensile matrix strength. For this reason cracks propagate at each load cycle even if the mean stress values in a cross section are relatively low. By this accumulation of damage, the strength and stiffness of the composite material decreases.

The damage to the material is also recognised under cyclic load as a set of permanent micro structural changes caused in a material by physical or chemical actions. These changes in the materials' structure may have various forms, e.g.:

- Matrix cracks
- Fibre fracture
- Fibre matrix debonding

Practical tests using similar testing equipment to the creep tests (see Fig. 2) for fibre cement pipes revealed that at loads above 50 % of the ultimate crushing strength, failure occurred after 200'000 cycles, whereas at loads below 50 % fatigue hardening occurred and after 2 million cycles the pipes even became stronger.

From the short term crushing test described earlier in this paper, the first crack (LOP) occurred at 70 % of the ultimate crushing strength, whereas in a fatigue test significant cracking leading to failure occurs at 50 % stress levels.

Therefore, the fatigue behaviour in a cement fibre composite may be separated into two types of material properties:

1) Fatigue micro cracking leading to ultimate failure
2) Fatigue micro cracking leading to strength increases in the material (fatigue hardening)

The mechanism proposed for fatigue hardening is: Micro cracking in the material exposing new un-hydrated cement clinker grains. In the presence of water contained in the pores, hydration of the newly exposed clinker occurs and the C-S-H fills the micro cracks resulting in crack healing. Conditions for fatigue hardening are: Micro cracks exposing un-hydrated clinker and water for re-hydration to occur. Fatigue hardening can result in up to 15 % increase in ultimate loads to failure of pipes after 2 million cycles under water.

5. FIELD TESTS: A CASE STUDY OF BURIED PIPES

Laboratory measurements are always good for predictive purposes, however in order to gain a good idea of how a pipe will function in the "real" situation, it is important to conduct a series of measurements in the field as well. A case study was carried out on a 600 mm (wall thickness 20 mm) diameter pipe which was buried in a trench in Switzerland close to a limestone quarry. The added advantage for this case study was that the pipe was subjected to earth loads and traffic loads resulting from the trucks driving back and forth from the quarry. The pipe deflections and stress were measured with special gauges mounted inside the pipe and attached to recorders placed in a manhole adjacent to the pipe being monitored. At the same time the frequency of the truck traffic was recorded.

The pipe was buried with a standard earth/gravel fill, 1 meter below the surface of the ground and laid on a concrete block. The change in internal diameter was measured directly after the pipe was buried and during the entire test period. The ultimate ring bending strength of a pipe from the same production, was measured at 40 N/mm^2 and it was assumed that the buried pipe would have very similar strength values.

The maximum ring bending stress, measured at the crown of the pipe directly after installation was 5 N/mm^2· This represents 12 % of the ultimate ring bending stress. The associated deflection measured was 0.5 mm. It is obvious from this field test that the soil support on the sides of the pipe played a very important role in absorption of stresses from the soil/gravel above the pipe. After 6 months and approximately 1500 truck passes, the maximum ring bending stress measured at the crown was subsequently reduced to 3 N/mm^2 (approx. 8 % of the ultimate ring bending stress). The associated deflection was 0.1 mm. The most plausible explanation for this is: due to compaction or settlement of the earth/gravel above and around the pipe caused by the live truck loads, the imposed stresses on the pipes could be more efficiently transferred to its surroundings, lowering the stress on the pipe itself.

Comparing these results with theoretical calculations from the ATV-Working sheet A127 [4] these measurements are very realistic for a rigid class pipe. Therefore this case study may be used together with the laboratory measurements in order to draw conclusions with regard to long term creep and fatigue behaviour of this particular cement fibre reinforced pipe.

6. SUMMARY AND CONCLUSIONS

a) The measurement of the mechanical properties of a fibre cement composite material (in this case a pipe) measured after initial curing are important guidelines for the assessment of the product in service.

b) Just as important however, is the understanding of the ageing behaviour which includes cement "post" hydration, change in the fibre-matrix interfacial bond and possible changes in the fibre itself.

c) Potentially ductile cement composites do become more brittle with age and the degree of this embrittlement is required for the service life prediction of the product in service.

d) The embrittlement with age may be related to the increase in fibre-matrix interfacial bond and the matrix "hardening" with age.

e) Differential ageing in pipes underground causes inherent stress gradients to build up between the inner and outer pipe wall which could result in failure if these become larger than the ultimate tensile strength of the material.

f) A fresh (28 day old) pipe subjected to a standard crushing test has a first crack stress (LOP) at 70 % of the ultimate stress to failure.

g) If the pipe is subjected to sustained loading such as earth loads which are equal to or greater than the 70 % stress load, the pipe will creep with time by means of progressive crack propagations. Below 70 % stress levels, the pipe will creep not necessarily by crack propagation but by material property creep related to water in the pores and matrix, interfacial bond and other factors.

h) The assessment of fatigue behaviour of a cement based composite material is different from creep as micro cracks occur at and above 50 % of the ultimate failure load and under cyclic loading these micro cracks do not heal. On the contrary they propagate leading to premature failure of the product. Below 50% of the ultimate load to failure fatigue "hardening" takes place; the product subjected to 2 million cycles had higher ultimate strength values than before the fatigue test. It has been suggested that fatigue hardening under these conditions is related to micro cracking in the cement matrix exposing un-hydrated clinker which with subsequent hydration heals the crack.

i) A case study where a pipe was monitored in the field, exposed to earth and live truck loads revealed that pipes buried underground would be subjected to stresses well below the design ultimate loads and in reality stresses of up to 12 % of the ultimate load can be expected. This would suggest that the pipe would always operate in the so called linear-elastic zone and that creep deflections will not necessary lead to failure.

j) As the pipe ages underground the product material will increase in stiffness which will then lead to even lower deflections. As the soil around the pipe compacts due to live loading, the stress on the pipe is reduced even further.

In conclusion it is clear that a good understanding of the mechanisms of ageing, creep and fatigue behaviour of the product are essential for long term service life predictions and without all three it would be impossible to make these predictions.

ACKNOWLEDGEMENT

The author is much indebted to ETERNIT AG, Niederurnen, Switzerland for permission to publish these results and my word of thanks go to Mr. A. Holte and Mr. H. Schaffner for their support in this matter.

REFERENCES

[1] Akers, S.A.S., Crawford, D., Schultes, K. and Gerneka. D.A., "Micro mechanical studies of fresh and weathered Fibre Cement composites Part 1: Dry testing", The International Journal of Cement and Lightweight Concrete., Vol. 11, Number 2, May, 1989, pp.117-124.

[2] Bentur, A., and Akers, S.A.S., "The microstructure and ageing of Cellulose Fibre reinforced cement composites cured in a normal environment", The International Journal of Cement and Lightweight Concrete, Vol. 11, Number 2, May, 1989, pp.99-110.

[3] Pirie, B.J., Glasser, F.P., Schmitt-Henco, C., Akers, S.A.S., Durability Studies and characterisation of the Matrix and Fibre-Cement Interface of Asbestos-Free Fibre-Cement Products," Cement and Concrete Composites., Vol. 12, Sept., 1990, pp.233-244.

[4] ATV-Arbeitsblatt A 127, "Richtlinie für die statische Berechnung von Entwässerungskanälen und Leitungen", Dec., 1984, St. Augustin: Gesellschaft zur Förderung der Abwassertechnik e.V. (GFA)