INDICES FOR PREDICTION OF REPAIR MORTAR PERFORMANCE

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ABSTRACT

Recent literature addressing identification of parameters, the control of which is essential in ensuring minimal cracking in cementitious repair mortars applied over hardened concrete, appears convergent towards unanimity on the role of indices such as free drying shrinkage ε_{sh}, tensile creep strain ε_{cr}, tensile strength f_t and tensile modulus of elasticity E_t in the evolution of the dominant tensile stress in the repair layer due to substrate restraint.

This paper focusses on kinematic basics of restraint deformation in shrinkage and creep, the identification of a more complete list of indices governing stress buildup, the interaction of new generation admixtures and relevant indices and an overview of an ongoing research program that uses a combined numerical-experimental strategy to predict the in-situ performance of a patch repair system.

KEYWORDS

Patch repair; drying shrinkage; tensile creep; restrained shrinkage stresses; moisture diffusivity; finite element modeling; performance indices; failure modes.

INTRODUCTION

Repair mortars applied to hardened concrete substrates have a tendency to shrink on drying. As a result of restraint provided by the substrate at the interface and/or the periphery for an enclosed patch repair, drying shrinkage cannot proceed freely. This results in the development of various stress components, the interaction of which can lead to premature failure of the patch. The potential failure modes include vertical cracking due to direct tension, horizontal cracking due to transverse or peeling tensile stresses and delamination due to interface shear stresses (Rahman et al., 1997a).

The problem is further compounded if the repaired structure is subjected to an aggressive environment, with cracks providing free access for intrusion by chloride ions. Thus, it becomes imperative that in order for a patch repair to retain its integrity and to protect the reinforcement in the substrate, the nucleus of the performance criterion should be minimum or crack free repair layer.

In order to attain such an ambitious performance specification in field conditions, the complex gamut of events governing the stress buildup has to be uncloaked. Further, the role of various material parameters or indices in the stress buildup has to be identified, allowing for the rational development of specifications for patch repair.

Restrained Stress Fields

A simplistic one-dimensional kinematical model is shown in Fig. 1 that allows for a pedagogical discourse on the development of a restrained stress field in a patch repair. Fig. 1(a) shows the location of an unstressed element as line *AB*. If the repair layer was free to shrink, a shortening of δ_{sh} would occur in it. However, it is not free since it is bonded to an already hardened substrate. In order to ensure compatibility of deformation, the repair mortar would be subjected to a tensile elastic strain δ^{r}_{el} with the substrate being subjected to a compressive elastic strain δ^{sub}_{el}. The position of *AB* after the restrained shrinkage deformation is *A'B'*, with repair mortar being in a state of tension and the substrate in compression.

In the second stage of evolution, the primary stress field due to restrained shrinkage triggers an onset of restrained creep deformations (Fig. 1(b)). If the repair mortar was not restrained, there would be a δ^{r}_{creep} deformation in it due to the tensile creep characteristics of the repair material, with a corresponding δ^{s}_{creep} due to compression in the substrate (this component could be taken to be zero for the hardened substrate). Since the two components have to deform in a compatible manner, the repair layer sustains an elastic compressive strain and the substrate a tensile elastic strain in order to bring the final profile of *AB* to *A''B''*. It is noted that the stress field due to restrained creep is of an opposite sense to that of restrained shrinkage - in effect helping to relax the repair layer.

In addition to the direct tension (σ_x) in the repair, interlaminar shear stresses τ_{xy} are set up due to gradients of σ_x and peeling stresses σ_y by virtue of gross equilibrium considerations (Rahman et al., 1997b).

Key Indices

The simplified mechanism depicting development of stress fields due to restrained shrinkage and creep leads to the identification of certain repair mortar indices playing a central role in its performance. The complete list appended by indices governing time rate of evolution of stresses includes:

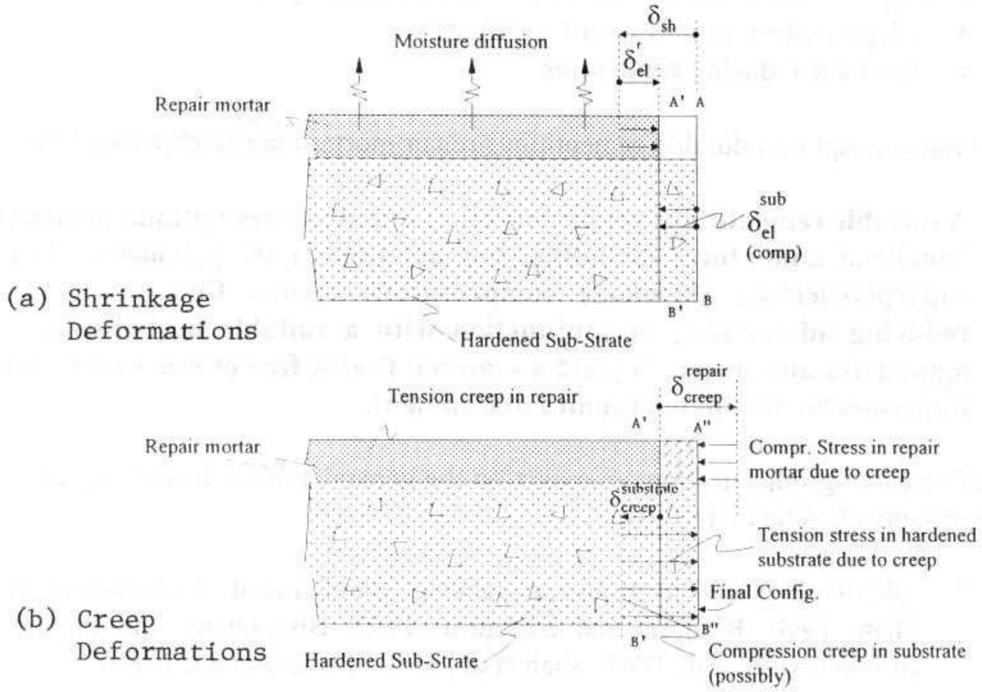

Fig. 1. Restrained shrinkage and creep in patch repair

* free drying shrinkage ε_{sh}
* free tensile creep strain ε_{cr}
* coefficient of moisture diffusivity D
* surface transfer coefficient f
* tensile elastic modulus E_t
* tensile strength f_t
* interface bond or cohesion c

In view of a tremendous market potential, the race for development of a perfect cementitious repair mortar is proceeding at tremendous pace in commercial and in academic research laboratories around the world. It was in late 1995 that Pinelle in an elegant presentation commented that the prediction of cracking tendency of repair mortars had hithertofore remained a puzzle, although progress had been made beyond the myth that compressive strength was the key associated index. Focussing on some of the relevant indices, Pinelle (1995) demonstrated the beneficial influence of polymers on the performance of repair mortars, noting that both an acrylic polymer and a blend of vinyl acetate/butyl acrylate reduced the development of restrained stresses.

The development of a durable repair mortar, using a criterion of minimum cracking coupled with impermeable or dense internal structure, has led to a number of superior new generation products, utilizing various admixtures including:

- incorporation of polymers
- silica fume
- superplasticizers in powder or liquid form

- single or double acting shrinkage compensating agents
- polypropylene, cellulose, or steel fibers
- shrinkage reducing admixtures

The overall concept of a durable cementitious repair mortar may be elucidated as:

> **A durable cementitious repair mortar is one that uses optimal proportions of beneficial admixtures including, but not limited to, polymers, silica fume, superplasticizers, shrinkage compensating agents, fibers and shrinkage reducing admixtures, in conjunction with a suitable host mix of cement, aggregates and water, to yield a material that is free of cracks and relatively impermeable in a patch repair environment.**

Work of research groups making an impact on the general area of durable repair materials may be broadly classified into:

* role of admixtures in shrinkage cracking (Banthia et al., 1996; Grzybowski and Shah, 1990; Khajuria and Balaguru, 1992; Bissonnette and Pigeon, 1995; Bloom and Bentur, 1995; Shah et al., 1998; Paillere et al., 1989)

* simple mechanistic models for prediction of uniform tension in repair layer (Pinelle, 1995; Ignatiev and Chatterji, 1992)

* finite element models for evolution of direct tension, peeling and interfacial shear (Rahman et al., 1997a, 1997b; Asad et al., 1995, 1997)

INTERPLAY OF ADMIXTURES AND INDICES ε_{sh}, ε_{cr}

The role of admixtures in shrinkage associated cracking has focussed on evolution of drying shrinkage (ε_{sh}) and tensile creep (ε_{cr}) curves, substantiated by evidence of 'tendency towards cracking' by simulation of restraint shrinkage using:

* ring specimen (Carlson and Reading, 1988)
* linear specimen with movable and fixed grip (Paillere et al., 1989)
* plate type specimen with orthogonal restraint (Khajuria and Balaguru, 1992)
* scaled down patch systems (Banthia et al., 1996; Asad et al., 1997)
* Sika-Banziger mold (Banziger, 1997).

Using a miniaturized version of a patch repair system subjected to accelerated drying to induce cracking, the influence of fibers on controlling shrinkage cracking has been reported by Banthia et al. (1996). As anticipated, steel and polypropylene fibers are shown to be effective in reducing crack widths and in allowing multiple fine cracking to occur. Increased volumes of fibers are shown to reduce number of cracks.

Bissonnette and Pigeon (1995) have reported on the tensile creep characteristics of concretes modified by silica fume and by fibers. The authors conclude that silica fume enhances tensile creep as well as drying shrinkage, but the effect is relatively small. It is worth noting that the silica fume replacement was 7% by weight of cement. Inasmuch as most admixtures influence not only the creep strain but also the drying shrinkage characteristics, the authors make an astute observation:

> ***A higher creep (strain) to shrinkage (strain) ratio will improve the resistance of thin concrete repairs to cracking.***

Thus, one could define the evolution with time of the ratio of specific creep to shrinkage and use this index as a key predictor in the performance of repair mortars.

In addition, increase of tensile creep with increasing w/c and decrease with increase of loading is confirmed by Bissonnette and Pigeon (1995). Further, fibers are show increase creep in tension.

Bloom and Bentur (1995) present an interesting treatise on the free and restrained shrinkage of concrete in early stages with and without silica fume. Using high levels of silica fume (15% by weight of cement), they found that the presence of silica fume increased free plastic shrinkage of the concrete and led to earlier cracking in comparison to similar low w/c concrete with no silica fume. This is attributed to accelerated setting in the presence of silica fume.

Wiegrink et al. (1996) have demonstrated earlier cracking and increased evolution of crack widths with increased silica fume replacement. The authors cite a significant reduction in specific creep with increased silica fume content as the prime variable influencing degradation in crack response. This revelation is an interesting dichotomous scenario: silica fume is known to render the concrete structure impermeable, but is simultaneously affecting the crack resistance properties negatively.

An exciting new admixture that results in shrinkage reduction [SRA] has been reported by Balogh (1996) in the form of a propylene glycol derivative that is added to the concrete mix water. Shah et al. (1998) report a 50 percent reduction in drying shrinkage with a 2 percent addition of SRA by weight of cement.

Single- and double-acting shrinkage compensating agents are now used in most new generation commercial repair mortars. These agents trigger an expansion of the mortar in the plastic and early hardening stages, providing an initial compressive stress in the restrained patch layer.

Mechanistic Models Predicting Uniform Tension

Ignatiev and Chatterji (1992) and Pinelle (1995) have presented mechanistic models which predict the development of uniform tension in a patch repair layer, treating the patch as a composite material-indeterminate system subject to uniform straining. These models illustrate the role of certain key indices including ε_{sh}, ε_{cr}, f_t and E_t on the performance of a patch repair layer. The models serve as valuable tools for an estimate of a bound on patch layer tension, but do not account for the interaction of moisture loss and shrinkage and the development of other stress components (peeling and interfacial shear) that control failure modes distinct from vertical cracking of repair layer.

Finite Element Models

Inasmuch as shrinkage occurs due to loss of moisture which itself is a time dependent boundary value problem, the finite element methodology has been used to great advantage (Rahman et al., 1997a, 1997b; Asad et al., 1995, 1997). The model separates the process into a moisture diffusion problem which feeds input into a stress analysis module, the two being linked by a phenomenologically obtained invariant moisture loss-shrinkage strain relationship. Finite element simulation not only uses indices identified in the first generation mechanistic models [ε_{sh}, ε_{cr}, f_t, E_t] but also the coefficient of moisture diffusivity (D) and surface transfer coefficient (f), parameters governing the moisture loss process. In addition, the model can be adjusted to account for influence of variations in environmental humidity, temperature and wind speed on moisture loss and the resulting restrained stress fields.

RESEARCH PROGRAM

Now that the pieces of the puzzle governing the tendency towards cracking under restrained shrinkage are falling into place, it is only a matter of time before repair engineers would have access to specification guidelines ensuring durable repair. In order to attain this target, research programs both in the Department of Civil Engineering and the Research Institute at King Fahd University of Petroleum & Minerals are currently in progress, addressing various facets of the durability of repair materials.

One component of the program in the Department of Civil Engineering (1993) has focussed on performance evaluation of major commercial products available in the Kingdom. Such an evaluation requires an elaborate format initiated by product selection, laboratory investigations for measurement and evolution of key material indices, numerical models for solution of interactive moisture diffusion-restrained shrinkage stress fields and field performance of prototype composite patch repair specimens. Fig. 2 is a schematic detailing various features of the research program completed or in progress, culminating in the articulation of a suitable set of specification guidelines ensuring a minimum crack repair.

In order to make the results of the research inquiry of consequence to the repair industry, certain generic products most commonly marketed and used have been adopted for an in-depth study. A broad classification of cementitious repair products in demand includes:

1. Cementitious repair products modified for shrinkage compensation with pulverized plasticizers.

2. Polymer modified cementitious products with polymer powders of various generic classes like acrylic, SBR, vinyl acetate, etc. The polymer powder enhances flexibility, adhesion to substrate and provides improved water tightness. These products also include shrinkage compensatory agents.

3. Polymer and silica fume modified cementitious products. The latent reactive silica fume improves durability, imparts strength and provides a dense matrix for preventing the ingress of chlorides and sulfates.

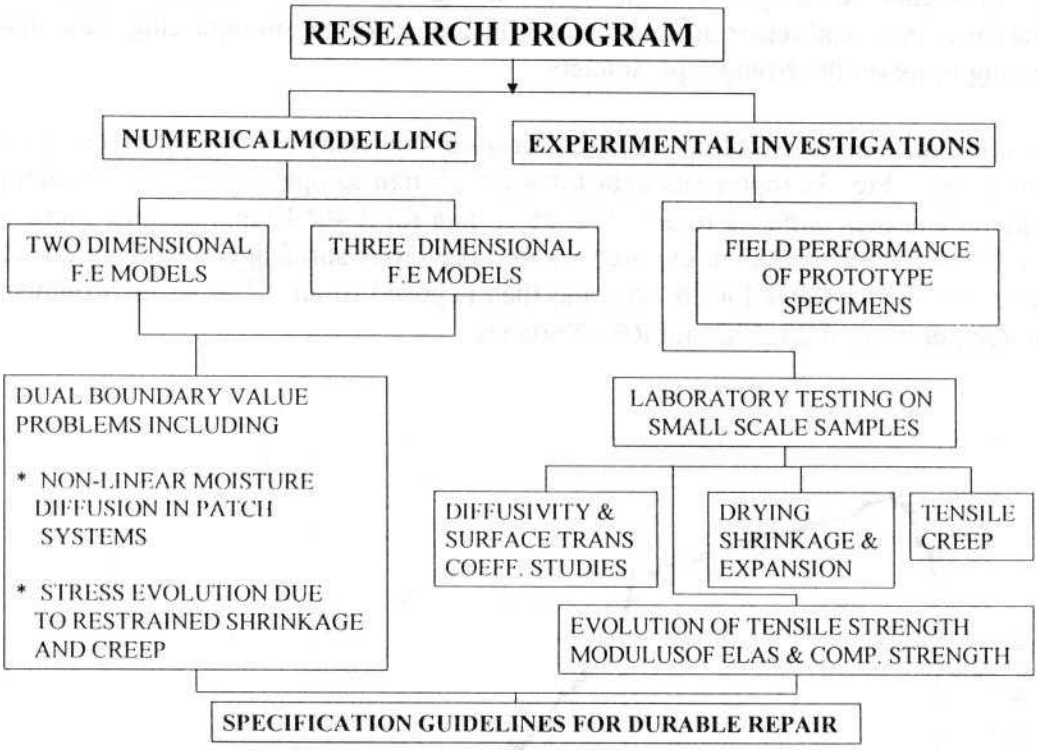

Fig. 2. Schematic of research program

4. Fiber reinforced cementitious products with/without polymers and with/without silica fumes. The polymeric fibers impart crack control and improved crack distribution and in some products, microfibers are added to impart flowability to the mix.

5. The fluid microconcrete with fluidifiers imparts free flowability to the mix. It is generally self compacting, self bonding and shrinkage compensated.

The repair products generally have shrinkage compensation in dual state; the plastic and hardened state to counteract high shrinkage strain due to the rich cement mix.

For the purpose of ongoing research at KFUPM, the following commercially available materials have been selected:

1. CM : Cementitious repair mortar with shrinkage compensation
2. PMC : Polymer modified cementitious repair mortar
3. FMC : Fluid microconcrete with two stage shrinkage compensation
4. FRM : Fiber reinforced cementitious mortar

The minimum indices (necessary but not sufficient) required for an estimate of the cracking tendency of a repair layer include ε_{sh}, ε_{cr}, E_t and f_t. Based on the simplifying assumption of a rigid substrate, the direct tension in the repair layer may be approximated by

$$\sigma \sim E_t\,(\varepsilon_{sh} - \varepsilon_{cr})$$

which must then be compared to the tensile strength f_t. At present, manufacturer's data sheets for commercial repair products do not include information regarding these indices - focussing more on the strength parameters.

Shown in Fig. 3 are a set of ε_{sh}–t curves for a commercially available, polymer modified mortar PMC. Fig. 3a represents data for a 25*25 mm sample, sealed on demolding for 200 hours and then exposed to air. Fig. 3b is data for a 40*40 mm sample, immersed in water for 200 hours and then exposed to air. Fig. 3c is shrinkage data for a 25*25 mm specimen, cured in water for 28 days and then exposed to air. The air environment was room temperature of 20±2°C and RH of 60±5%.

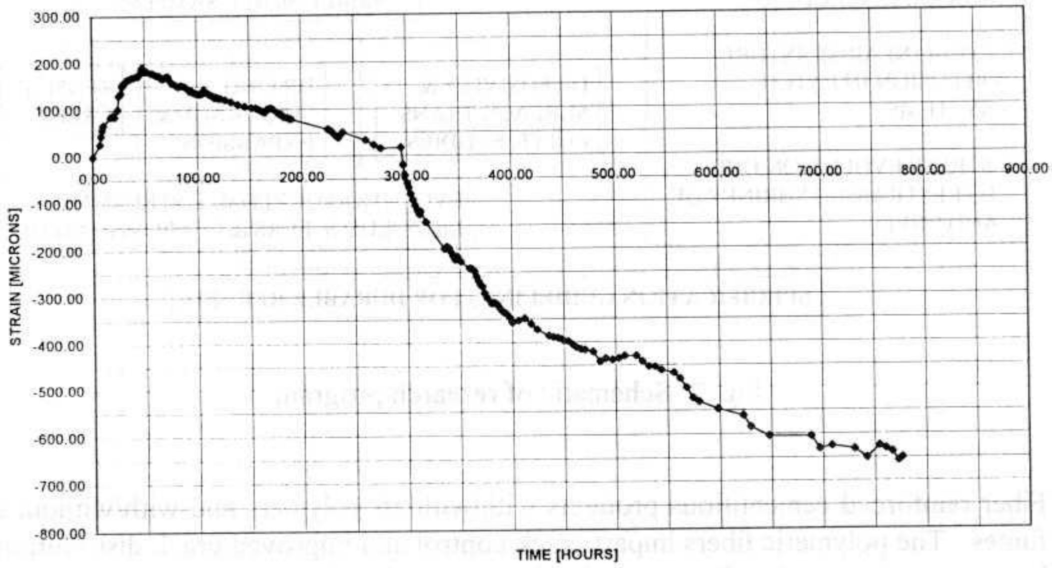

Fig. 3a. ε_{sh} vs. t for material PMC (25*25 mm)

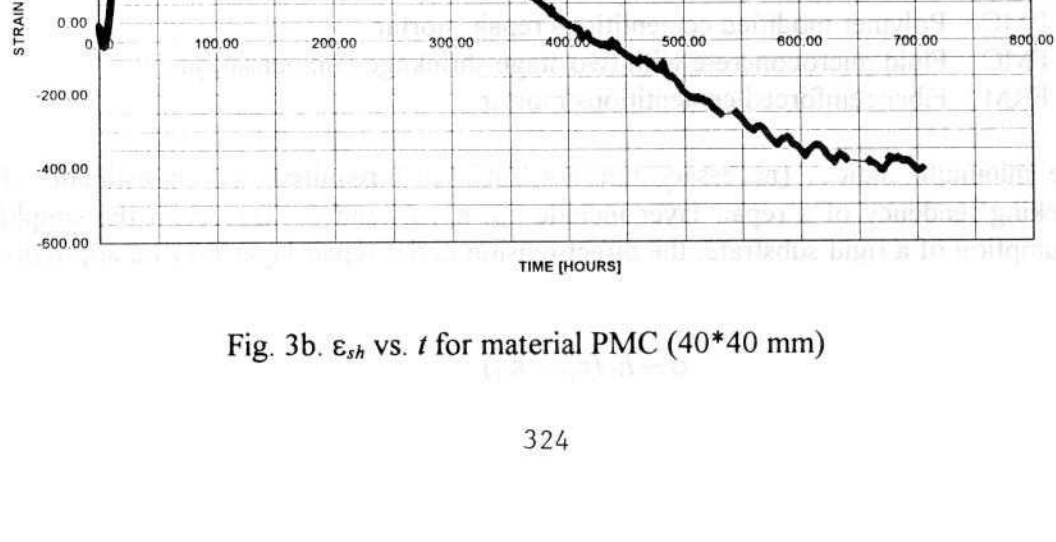

Fig. 3b. ε_{sh} vs. t for material PMC (40*40 mm)

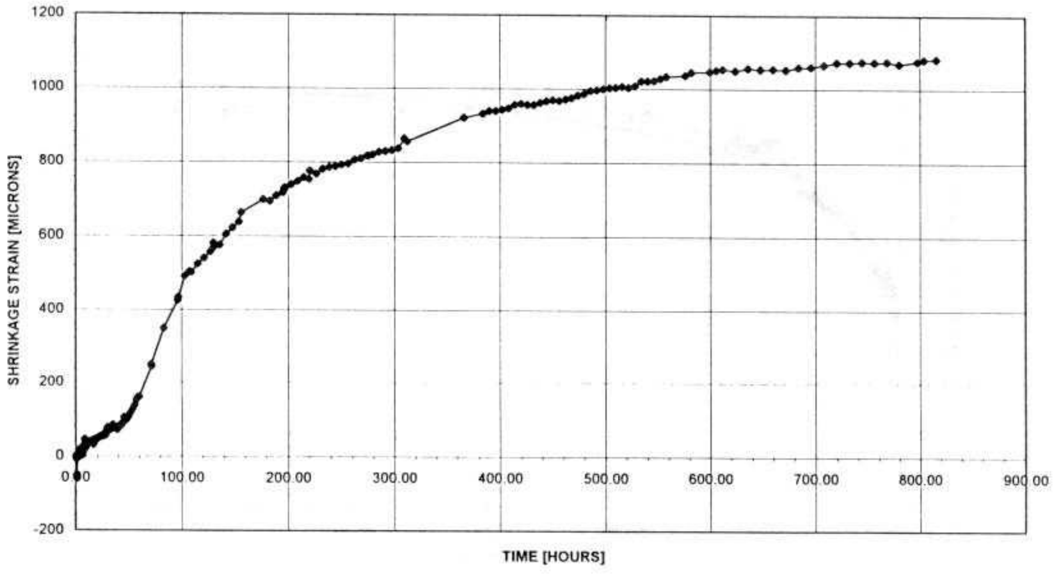

Fig. 3c. ε_{sh} vs. t for material PMC (expansion ignored)

The results of Figs. 3a and 3b show an initial expansion, which is a manifestation of shrinkage compensation. This expansion was measured by embedded gages. No attempt was made to measure the expansion in the data of Fig. 3c. The data as presented in these three figures shows a source of common error in shrinkage measurements ~ the reporting of gross shrinkage in contrast to net shrinkage values. For example, Fig. 3a shows a net shrinkage of 650 μs at 750 hours whereas Fig. 3c shows a gross shrinkage of 1050 μs at the same time.

Manufacturer's data must specify environmental conditions at which ε_{sh} is measured, in addition to conditions of initial cure and existence of initial expansion. Similarly, shrinkage performance criteria should be stated in terms of either gross ε_{sh} or net ε_{sh}.

Fig. 4 is the evolution of a typical specific tensile creep curve (ε_{cr} per unit stress) determined for material FRM. Plate 1 shows a series of creep testing frames specially designed to conduct this test. In order to compute the total creep, a simultaneous test has to be conducted on an unstressed specimen in order to obtain the shrinkage strain which must then be deducted from the measured total strain of the stressed sample to yield the creep. The two components of creep, basic and drying, can also separated by monitoring autogeneous shrinkage i.e. shrinkage of specimens under sealed conditions.

Figs. 5 and 6 show the evolution of tensile strength f_t and tensile modulus of elasticity E_t for material PMC.

It is of interest to note that the evolution of properties with time are essentially of the form

$$\text{Property }(t) = \frac{t^c}{A + Bt^c} * \text{Property }(t = \text{end interval})$$

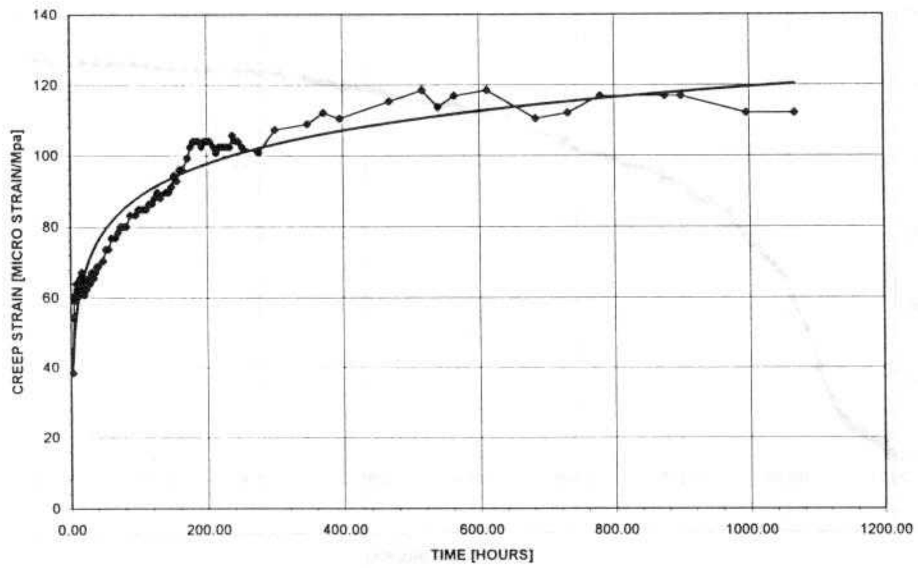

Fig. 4. Specific tensile creep ε_{cr} vs. t for material FRM

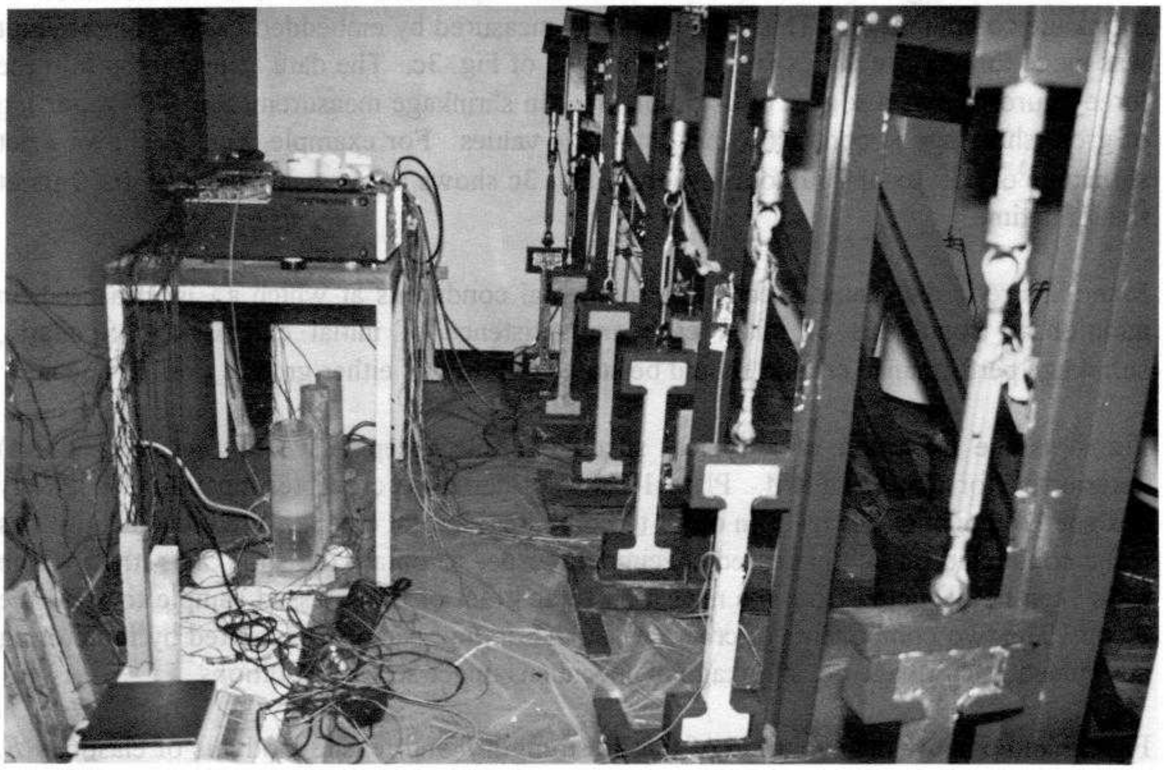

Plate 1. Tensile creep testing frames

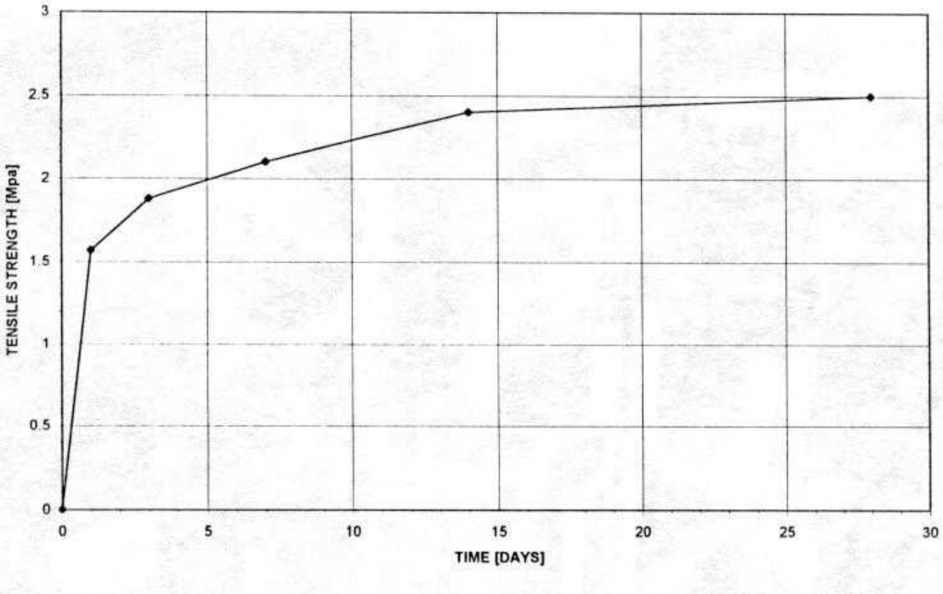

Fig. 5. Evolution of tensile strength for PMC

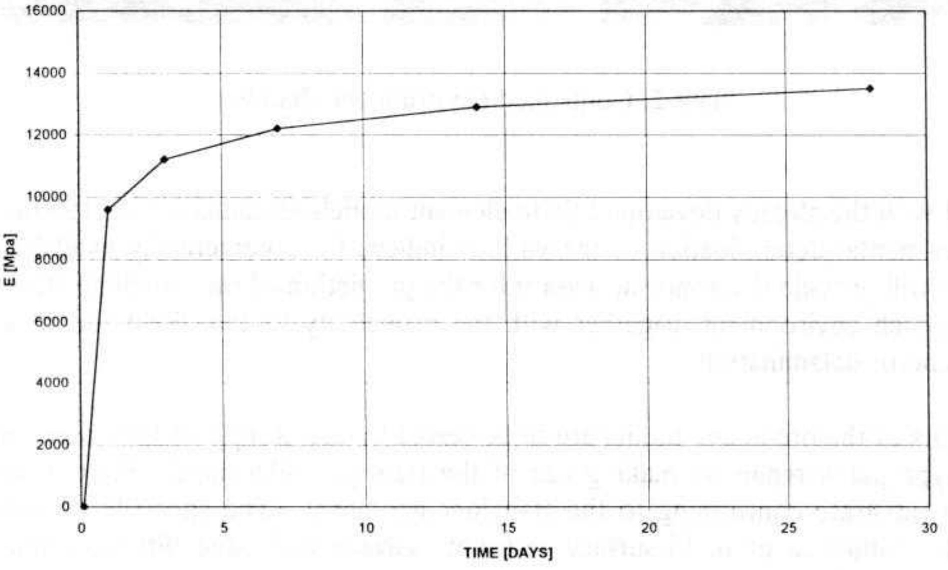

Fig. 6. Evolution of tensile modulus of elasticity for PMC

where A, B and c are experimentally determined constants.

In order to paint the complete picture, indices vital to the rate of moisture loss (diffusivity D and surface transfer coefficient f) have to be also determined. Samples are presently being tested in a specially assembled controlled environment chamber (Plate 2) that allows for diffusivity measurements of samples of varying initial cure period and to monitor the influence of wind speed on transfer coefficient f. In addition, the chamber can be adjusted for a desired temperature and RH.

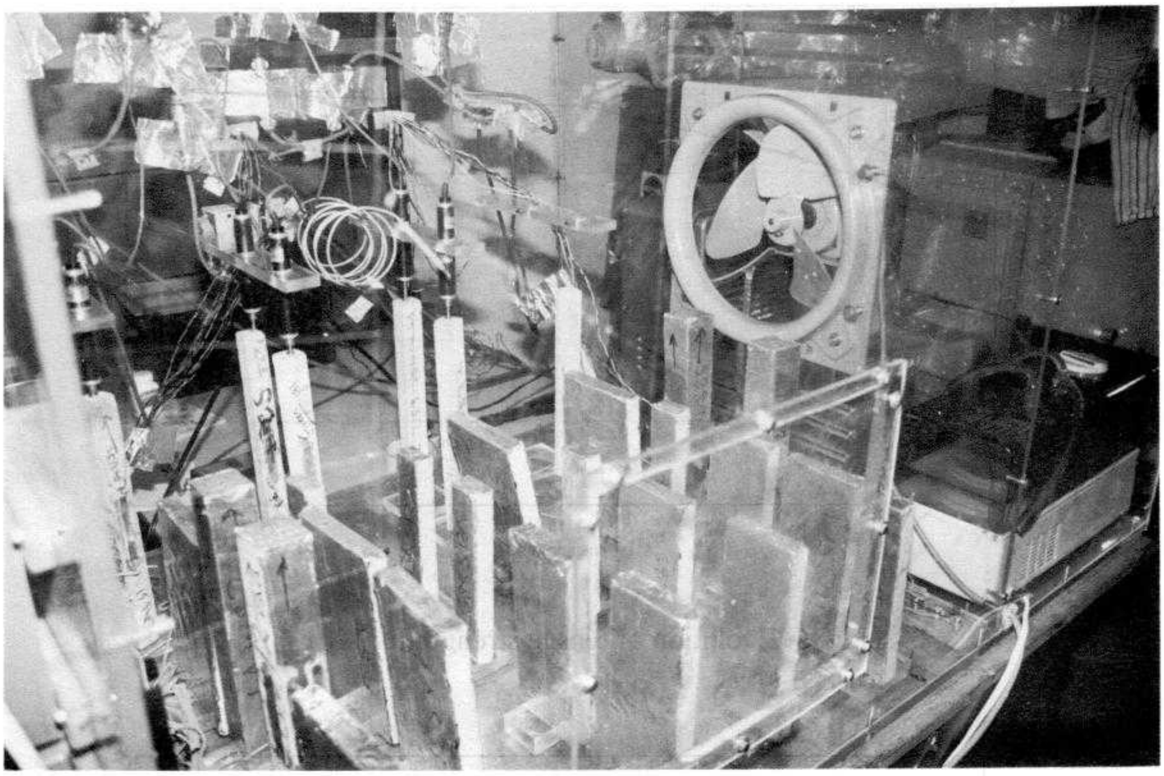

Plate 2. Controlled environment chamber

Coupled with the already developed finite element models (Rahman et al., 1997a, 1997b), the experimental determination of the various indices for commercially available generic products will provide the armor necessary for the prediction of the complete stress field in a given patch environment, together with the probability of the likelihood of cracking, peeling and/or delamination.

The results of the predictive model are to be tested by monitoring of field performance of a prototype patch repair by making use of the Banziger-Sika mold. Plate 3 shows the concrete substrate conforming to the Banziger geometry. The specially designed mold allows for influence of multi-surface restraint, surface and edge diffusion and varying repair layer depth.

CONCLUSIONS

It has been shown that in order for repair engineers to obtain a first-level approximation for tendency of patch repairs to crack, manufacturers of commercial repair products must append their data sheets to include information on material indices including ε_{sh}, ε_{cr}, E_t and f_t.

For circumstances warranting a more precise determination of tendency of repair to be susceptible to peeling and delamination failure, in addition to cracking under direct tension, data for diffusivity D, surface transfer coefficient f and interface bond c should also be provided in order to drive a finite element simulative model.

Plate 3. Concrete substrates for Banziger-Sika mold

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