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The fatigue hardening behaviour of cement-based materials

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This paper describes part of a study into the fatigue behaviour of cement-based materials. The mode and mechanism of stable microcracking which occurs during both monotonic and cyclic loading has been examined using a novel re-hydration technique. It is shown that unhydrated particles exposed during fatigue, which are not revealed after monotonic (static) failure, result from an attrition process which takes place subsequent to the passage of the major microcrack fronts. Increases in ultimate static strength after fatigue, which can be produced in specimens tested over a wide range of applied stress, only occur with the presence of "free", or chemically uncombined, water within the cement matrix. Such fatigue hardening is dependent on damage introduced as microcracks in the early part of the fatigue life, and arises essentially from an *in situ*, microstructural self-repair process.

1. Introduction

Concrete design principles are currently well-developed and civil engineers can, in general, design and build safe structures in concrete. This requires comparatively high factors of safety since an appreciation of how failure occurs, as a basis for failure prediction, is far from complete, particularly under variable loading situations.

As interest in cement-based materials develops [1] and trends towards improved structural efficiency result in increased live : dead load ratios in a variety of situations, it is likely that fatigue performance, as with other materials systems, will become of escalating importance in failure assessment. However, at the present time the state of knowledge concerning the accumulation of fatigue damage and the propagation of fatigue cracks in cement-based systems is minimal in comparison with that for metal and alloys, or polymers. This fact is certainly not related to the length of time the problem has been under study, and as far back as 1903 [2] conventional "S–N" curves were used to document the fatigue behaviour of concrete and other cement-based products. Here, the repeated stess or stress amplitude, S (expressed as a percentage of the maximum static strength) is plotted against the number of cycles to failure, N, typically on a semi-log scale.

Concrete does not appear to show a fatigue limit [3–6], i.e. there is no limiting repeated maximum stress below which the fatigue life is infinite, at least to 10^7 cycles. Consequently, "fatigue strength" is usually expressed as the stress level, as a percentage of the (ultimate) static strength, which results in failure after a given number of cyles (usually 10^7). A typically quoted value is 55% [3, 7–9]. Fig. 1 shows characteristic S–N curves derived for the materials used in this investigation.

One of the more interesting effects observed in fatigue of cement-based materials, widely reported in the literature [3, 5–12] and ostensibly having an analogue in metallic systems, is the phenomenon of fatigue hardening. Thus, specimens fatigued at a relatively low stress level frequently exhibit an increase in static strength when tested after fatigue. In metals, such hardening arises from dislocation interactions during cyclic deformation; however, no simple analogy is possible with cement-based materials, and it is the purpose of

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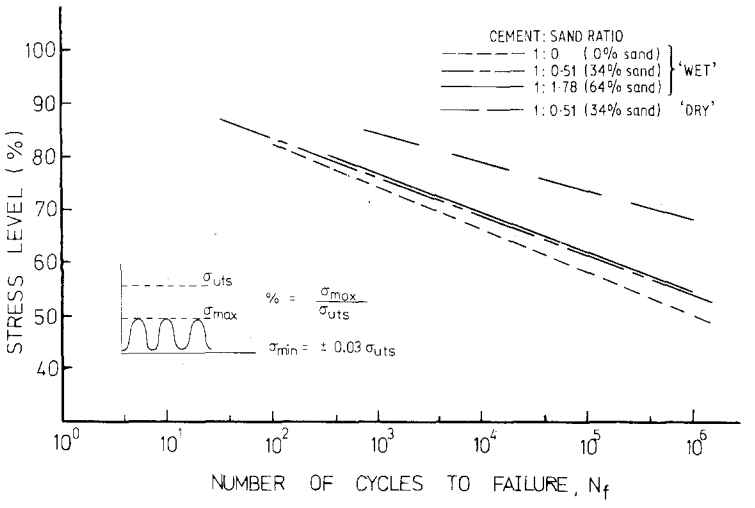

Figure 1 Typical fatigue "*S–N*"diagram for the materials used in the investigation subjected to repeated compressive loading. When the alternating stress is expressed as a percentage of the ultimate static strength, there is little variation between widely differing mixes.

this paper to report on experiments designed to establish the origins of this behaviour in this materials system.

The magnitude of the observed increase in strength may be illustrated by reference to the work of Bennett and Muir [5], who report an average increase of 11% after "run-out" tests (i.e. no failure) to 10^6 cycles at ~55% of the static strength. Such results imply that there is some form of strengthening mechanism operating during low stress level fatigue, and that fatigue failure does not merely arise due to a progressive degradation of the material's structural integrity by damage accumulation, but rather involves two opposing mechanisms, one beneficial to strength and the other destructive.

The ultimate strength of a concrete effectively depends on three factors, namely the strength of the various aggregate additions, the strength of the cement, and the adhesion between the two. The properties of interest of this study, however, are primarily a function of the cement hydrate; the role of aggregate additions appears to be one of providing localized stress concentrations and regions of interfacial weakness without contributing significantly to the underlying mechanisms responsible for failure [6]. Indeed, Antrim [13] and Bennett and Raju [8] have shown that concrete, mortar (cement mixed with sand only) and cement paste alone have virtually identical responses to cyclic loading when expressed as a percentage of their static strengths.

These results have been confirmed for plain cement paste and an increasing amount (34%, 64%) of sand added, Fig. 1 [14]. These data, then, would appear to justify the experimental simplification of restricting investigations to limited aggregate contents, at least in the first instance.

2. Experimental

2.1. Materials

Portland cement, of the so-called "rapid hardening" variety (RHPC), or type III, was used throughout this investigation. The percentage composition by weight was: tricalcium silicate (C_3S*) 49.7%; dicalcium silicate (C_2S) 19.6%; tricalcium aluminate (C_3A) 12.1%; and tetracalcium aluminoferrite (C_4AF) 7.3%. The (Blaine) nominal specific surface area was $5000 \pm 200\,cm^2\,g^{-1}$. As a direct result of the smaller average cement particle size in RHPC, the curing process is accelerated and higher strength is achieved in a comparatively shorter time; thus, the 28-day strength of ordinary Portland cement (OPC) is acheived at around 7 days [15]. This greatly facilitates specimen preparation and testing.

The standard mix included 34 per cent by weight of 600 μm average diameter dry sand, which was required to inhibit shrinkage and drying cracks (for oven-dried samples). The mix proportions used were: water–cement ratio 0.39, sand–cement ratio 0.72. In addition a second mix (0.5 : 1 : 2, water : cement : sand) containing 2% by volume of steel fibres (Duoform, 0.5 mm diameter, 38 mm long) were used for some tests. The components were dry-mixed in a rotary mixer for 1 min, then water was added followed by mixing for a further 5 min; after casting, samples were

*In designating cement compounds, a shortened notation is conventionally used where C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3 and H = H_2O.

vibrated for 20 sec to remove air bubbles. Samples were cast vertically [16, 17] as prisms 180 mm × 60 mm × 60 mm to minimize variations which occur across the sample through settling and moisture migration ("bleeding") when specimens are cast horizontally.

The samples were cured in the moulds at 100% humidity for 24 h at room temperature, after which they were transferred to a water bath, saturated with lime, at 20° C (controlled to within ± 1° C) for 6 days further curing. Such samples, subsequently referred to as "wet", were all tested at age 7 days. "Dry" samples, also cured for 7 days, were air-dried for one day, then oven-dried progressively to 105° C for 6 days to remove the chemically uncombined and evaporable, or "free", water.

2.2. Testing methods

Static and fatigue tests were performed in compression on a 250 kN ESH servohydraulic testing machine. The fatigue tests were conducted under load control at a fixed minimum load of 5 kN, representing a stress of 1.4 MPa. To ensure precise axial alignment and reproducibility of the loading force through the specimen, the samples were capped using a thin layer of epoxy putty and a small covering of semi-rigid plastic [17].

During both static and fatigue tests, elastic and residual (permanent) strains, both longitudinal and lateral, were measured using linear voltage displacement transducers attached to the specimen. In addition, the extent of the damage component, ostensibly due to microcracking, was monitored by ultrasonic pulse transit time (UPTT) measurements, first developed by Jones [18], using transducers fixed to opposite sides of the specimen.

Statistical strength variations between, and even within, batches of concrete are conventionally quite large. Careful quality control of materials and standardized procedures for specimen preparation enabled this to be reduced to less than 5%, but in order to define the 100% stress level, i.e. the static strength, of each batch, either 3 or 4 specimens from 8 were first loaded to failure in a static mode.

Fatigue run-out tests, at stress levels in the range 55 to 60%, were carried out on both wet and dried-out samples at 10 Hz for 10^6 cycles. Following the fatigue test, the samples were tested statically to measure any change in strength over static control samples from the same batch, some of which were tested before, and some just after the post-fatigue test. Other fatigue tests at higher stress levels were interrupted at approximately 0.2 of the fatigue life and tested statically in comparison with controls. The influence of environment, predominantly "drying out" and temperature effects, were examined by carrying out tests in a temperature-controlled water bath.

2.3. Scanning electron microscopy

Specimens for SEM were prepared by interrupting a fatigue test on a wet sample immediately prior to failure, as predicted using UPTT or residual strain measurements, both of which show a rapid increase on the point of failure (Figs. 2a and 2b). The resultant, extensively microcracked sample was readily taken apart, ensuring that fatigue fracture surfaces were not damaged in the final, catastrophic failure. Small specimens from the fracture surface were immediately placed in a vacuum desiccator or re-hydrated in water for times which varied from 1 to 48 h. Preliminary fractographic observations were disappointing in as much as little information could be gained from the surfaces. In order to study in more detail the mode of microcrack propagation through the cement during both cyclic and monotonic loading a technique of "rehydration" of the fracture surface was developed, by which previously hydrated and unhydrated regions could be readily distinguished.

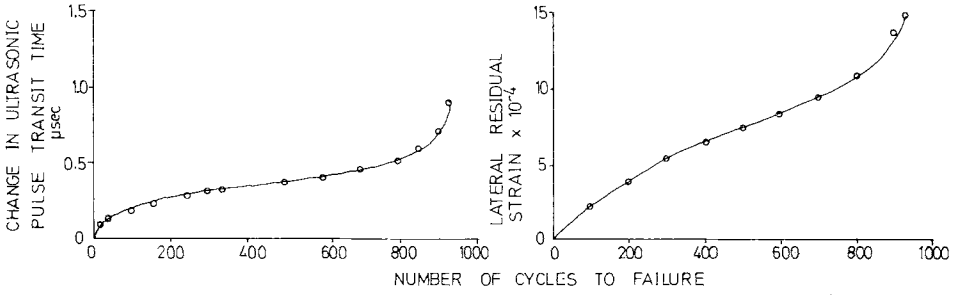

Figure 2 Illustration of the variation of (a) UPTT and (b) residual strain with number of fatigue cycles.

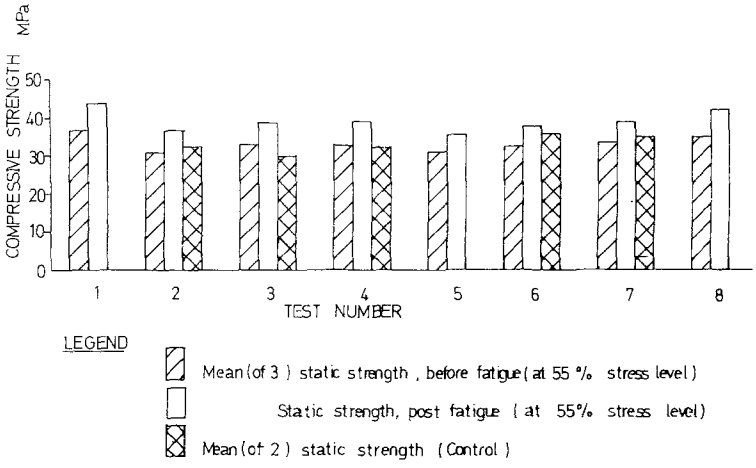

Figure 3 Histogram illustrating the fatigue hardening effect for "wet" specimens. Tests 1 to 4, cement paste plus 34% sand; tests 5 to 8, mortar (sand : cement = 2 : 1) plus 2% by volume Duoform steel fibres.

The procedure adopted was that the samples were exposed to water for a particular re-hydration time: they were then dried in a vacuum to ensure that the re-hydration process had stopped. Although drying can have a disruptive effect on the microstructure, the effect is sufficiently small to enable realistic observations to be made [19]. The specimens were then coated with carbon, followed by a layer of 60/40 gold/palladium, approximately 100 Å thick. The fracture surfaces were subsequently examined using a Cambridge Stereoscan 180 operating at either 20 or 30 kV.

3. Results

3.1. Fatigue hardening

Fig. 3 shows the results obtained for run-out tests on wet samples indicating a hardening effect of approximately 20% following fatigue. Note that included in Fig. 3 are results from samples from the two widely differing mixes used which would seem to confirm that fatigue hardening is a more general phenomenon among cement-based materials.

Results obtained for tests carried out at higher stress levels, and at fractions of the life to failure, are shown in Fig. 4. This data suggests that fatigue hardening is definitely not restricted to long-life/low-stress tests. Strength increases at high alternating stresses can be obtained, provided these tests are not continued beyond a certain limit when progressive damage outweighs the effect of hardening: certainly, the mechanism leading to hardening appears to occur within the first 20% of the life.

For dry specimens, however, there seems to be no such corresponding increase in post-fatigue strength (Fig. 5).

During the experiments it was observed that

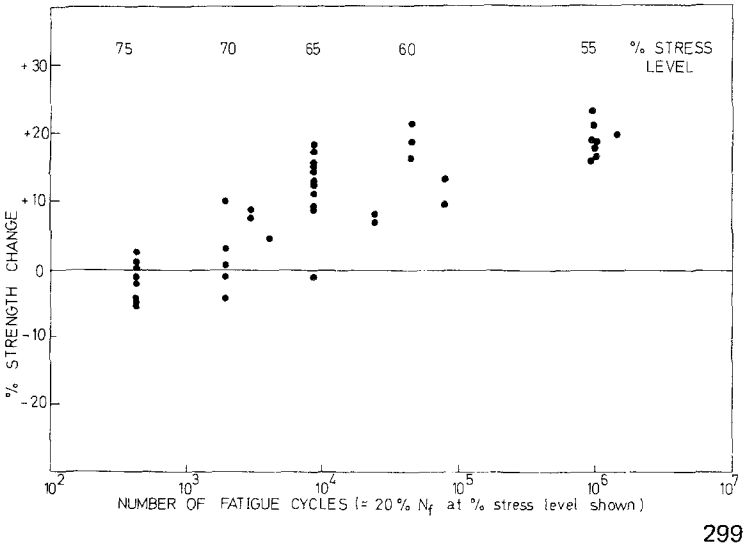

Figure 4 Fatigue hardening as a function of applied stress level ("wet" cement with 34% sand mix). Tests at the stress levels indicated were interrupted at 20 per cent of their anticipated fatigue life, estimated from Fig. 1. Fig. 4 plots the percentage static strength change, = {(post-fatigue static strength − original static strength)/original static strength} × 100, against the respective number of fatigue cycles.

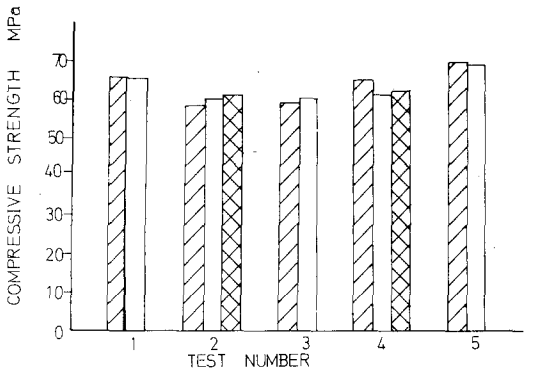

Figure 5 Histogram illustrating the absence of fatigue hardening for "dry" specimens (cement paste plus 34% sand).

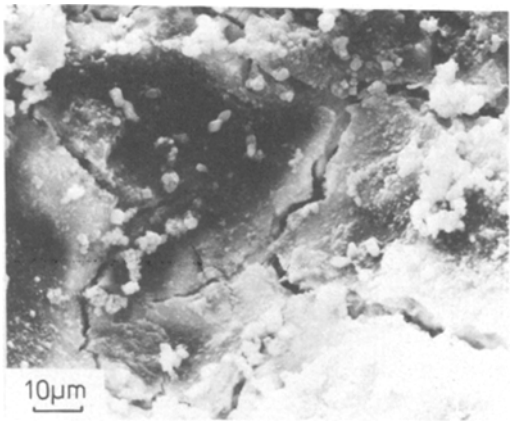

Figure 6 Typical fatigue fracture surface showing extensive microcracking which is significantly more widespread compared with the corresponding static failure.

wet fatigued specimens exhibited a marked temperature rise during cycling (~25° C); the corresponding rise in dry tests is very small.

3.2. Fractography and re-hydration observations

A study of the plain, fractured surfaces showed that fatigue samples exhibited a significantly greater abundance of microcracks than corresponding, statically-failed samples; a typical example of the former is shown in Fig. 6. This observation is confirmed by comparing the increase in UPTT during a static test with that of a typical fatigue test; for ten "wet" tests the mean changes in UPTT were, respectively, 0.25 and 1.0 μsec. Fig. 2 illustrates typical changes in UPTT and residual strain associated with the progressive accumulation of damage which occurs during a fatigue test.

Following a re-hydration treatment the growth of hydration product, in particular needle-like calcium silicate hydrate, from the fatigue surfaces was prolific (Figs. 7 and 8). Static surfaces, by contrast, show much less hydration for the same age (Fig. 9). In broadly quantitative terms based on observations on a number of different surfaces, exposed, un-hydrated product covered approximately 60 to 90% of the fracture surface for the fatigued specimens, compared with only 5 to 10% for statically-failed surfaces, subjected to identical re-hydration treatments.

4. Discussion

4.1. Cement hydration and microstructure

The major reactions occurring during the setting

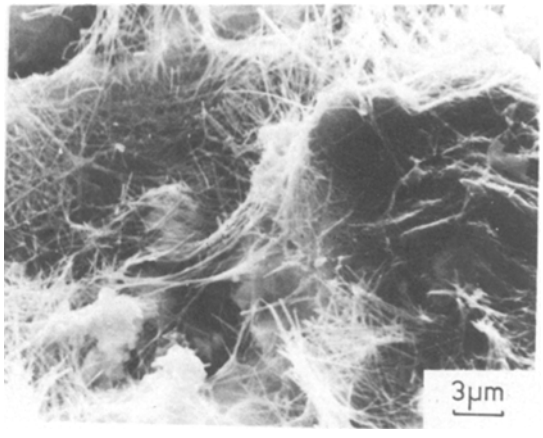

Figure 7 Fatigue fracture surface, re-hydrated for 48 h by exposing the surface to an aqueous environment, showing extensive fibrillar growth of calcium silicate hydrate from unhydrated surfaces produced during the fatigue process.

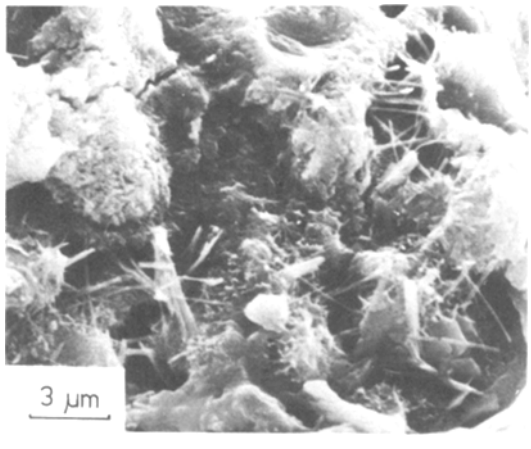

Figure 8 Fatigued and rehydrated for 24 h.

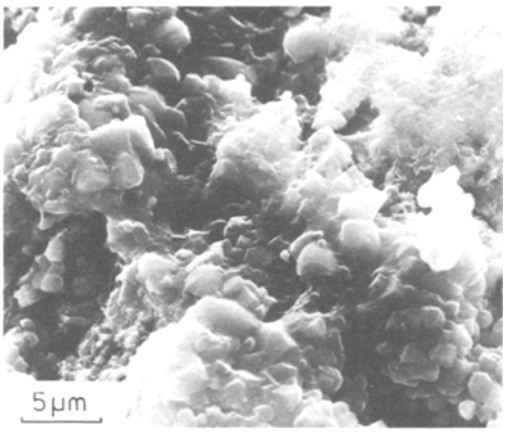

Figure 9 Static fracture surface, monotonically loaded to fracture, and rehydrated for 48 h. Minimal formation of fresh hydrate, indicating that fracture is largely intergranular, i.e. through the interparticle hydrate gel network formed during curing.

and hardening of Portland cement are as follows [20]:

tri, dicalcium silicates (C_2S or C_3S) + H_2O → tricalcium silicate hydrate ($C_3S_2H_3$ or C–S–H) + $Ca(OH)_2$ + heat (~ 20 to 40%)

The other significant hydration reaction is that of C_3A which hydrates in the presence of $Ca(OH)_2$ to calcium aluminate hydrate, C_3AH_6 [21], which is a metastable system changing from a gel to hexagonal platelets to cubic crystals [22].

The understanding of cement chemistry in general and cement hydration in particular is still far from complete despite the significant amount of relevant published literature. The morphology of hydrated C_3S, for example, has been variously described as needles, fibres, cigar-shaped sheets, plates, crumpled sheets or foils, tabulated structures, thin sheets, spicules, spherulitic particles and rosettes [23]. There seems little doubt, however, that hydrated cement consists of a C–S–H gel in which some crystalline phases (e.g. $Ca(OH)_2$) are interspersed. The C–S–H often appears to be of a fibrous nature radiating from individual cement grains which are considered to interlock to form a dense matrix and provide the material's strength, particularly in compression [19, 21]. It appears that the morphology of cement hydration products is very dependent on various factors, including water content [24, 25], age [21], mix proportions [24, 20], carbon dioxide present during curing (leading to carbonates) [26, 24, 27], and temperature [28].

Variations in the composition and structure of C–S–H have led, in the literature, to the distinction between so-called "inner" and "outer" hydration products. Williamson [20] in particular has conducted extensive studies on the hydration of both Portland cement and its respective component phases and the available literature has recently been adequately reviewed by Double *et al.* [19].

When cement is hydrated there is a rapid, initial formation of highly impermeable, gelatinous hydrate coating around the cement grain; the "inner" product is that laid down within this coating, and is generally fine-grained. The "outer" product, often having a characteristic, fibrous structure develops in the originally water-filled void beyond the original grain geometry, at a faster rate than the inner hydrate; hexagonal crystals of $Ca(OH)_2$ also form in the matrix of the C–S–H hydrate gel in the outer hydration product region. In effect, shells of impermeable calcium silicate hydrate gel surround pockets, or kernels, of uncombined cement grains, with the intervening volume filled with needles of hydrating C–S–H radiating outwards in a "hedgehog" fashion from the individual cement grains. Fig. 10 illustrates schematically the sequence of events in the hydration of ordinary Portland cement. The "shell concept", in fact, is not only restricted to C_3S and C_2S, since Brevel [22] mentions in a study of the hydration of C_3A that a tight layer of C_3AH_6 forms around the C_3A grains, impeding further intrusion of liquid, a view noted by Lea [26] and Ramachandran and Feldman [29].

Double *et al.* [19] have recently proposed a viable model for the formation and growth of the needles based on an osmotic mechanism, and draw an analogy with silicate "gardens". The C–S–H fibres which grow radially from the original cement grains appear to be needle-like and hollow [19]. This is a view which has been substantiated by the authors, although it must be noted that composition can substantially affect the needle morphology [30].

4.2. Models for fatigue hardening

Various theories have been proposed to explain fatigue hardening. These include:

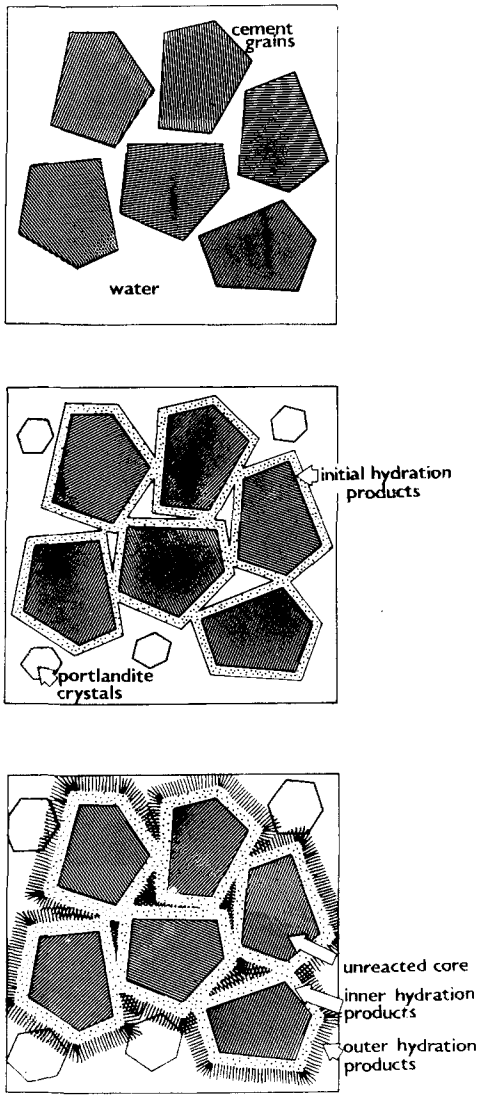

Figure 10 Schematic illustration of the stages involved in the hydration of Portland cement (courtesy of D. D. Double). On adding water a gel coating (the "inner" product) quickly forms around the grains, (b), and hexagonal crystals of calcium hydroxide form as a by-product of the silicate hydration reaction. As the curing process proceeds, (c), fibres or needles (or other hydrate morphologies such as "flowers") develop and interlink to bind the product together.

(i) accelerated curing due to observed temperature increases [5, 8, 9];

(ii) loss of gel moisture under load, or "drying hardening" [7, 8]; and

(iii) redistribution of internal stresses (caused by shrinkage and curing) during fatigue, or "stress annealing" [3, 11, 12].

Taking these in turn, fatigue hardening has been observed in samples at least a year old, where accelerated curing at elevated temperatures could reasonably be expected to have little effect. In addition, tests carried out under constant temperature conditions in the present investigation, using a large capacity water bath as a heat sink, also produced increases in strength comparable to specimens fatigue tested in air.

These latter tests, by providing a continuous supply of free water through the capillary network, also suggest that specimen drying-out during fatigue cannot account for the observed strength increases.

Finally, a "shakedown" mechanism would have some appeal, having as it does a general similarity with such effects occurring in metals. (Although this typically gives rise to fatigue softening by dislocation re-arrangement in a previously highly dislocated, or strain-hardened, structure). However, if this were the major cause of the effect, one would anticipate that the internal stresses set up during the drying process would provide a significantly greater potential for stress redistribution, and therefore fatigue hardening, in "dry" samples. This is not found to be the case (Fig. 5).

The fact that dry tests do not show fatigue hardening indicates that free water plays a significant role in the process. Furthermore, wet samples tested in air produce substantially more heat than dried ones. Bearing in mind, then, the heat evolution associated with the curing process, it would seem that the basis of the hardening phenomenon involves the rapid hydration of previously unhydrated particles.

4.3. Modes of microcrack propagation

It is of considerable interest to determine the mode of fracture in the cement composite, for a given testing situation, i.e. whether cracking occurs through the cement hydrate region, or through the unhydrated cement cores.

The re-hydration technique described in a previous section represents a convenient, rapid and unequivocal way of distinguishing between the two possible alternatives. Thus, fatigue appears to produce a largely "intragranular" mode (exposing fresh, unhydrated surfaces), compared with the primarily "intergranular", or interparticle, fracture observed under static loading (by cracking through hydrate regions).

At this point in time it is not possible to determine unarguably whether fatigue results in a change in fracture mode, or whether the largely intra-

granular surface results from progressive attrition during cycling. The fatigue process itself is likely to involve local stress redistributions, possibly aided by stress-induced migration of water molecules, and this is likely to account, at least in part, for the time dependent (frequency) effects observed in this system [14]. A further contribution to such microcracking during dynamic fatigue could arise from environmentally-induced slow crack growth, or "static fatigue", and there is ample evidence that cement and concrete are susceptible to this (for example, see [31]) in the same way as are other ostensibly brittle materials [32, 33].

In as far as any such mechanism of slow crack growth appears to require some environmentally-active species, (dried samples do not appear to be susceptible [34]), it would seem reasonable to conclude that microcracking, arising due to both static fatigue (within a dynamic fatigue cycle) and to water-facilitated stress redistribution, would therefore predominate in the hydrate gel regions having access to free water. Furthermore, variations in local stress which do arise and lead to stable cracking during static loading [35], would also tend to be restricted to the intergranular regions, where static crack growth predominates.

It seems reasonable to conclude, therefore, that the intergranular, exposed unhydrated cement fracture surfaces produced by fatigue in compression in samples of the age under test (equivalent to 28 day OPC) result from an attrition process, after passage of the main microcrack fronts through predominantly intergranular or hydrate gel regions. It cannot be specified at this stage whether this involves progressive grinding away of the relatively soft hydrate coatings surrounding each unhydrated particle, or an abrasion process, the stresses due to which induce intraparticle cracking. It should be noted that osmotic pressure, which gives rise to tubular fibre formation [19] as mentioned earlier in Section 4.1, may well assist in the penetration of the impermeable shells during attrition.

4.4. Mechanism of fatigue hardening

Experiments described in preceeding sections indicate that the fatigue process results in the exposure of significant numbers of unhydrated cement particle cores. If sufficient "free", i.e. chemically uncombined, water is available (normally present in capillaries, interlayer spaces and micropores) it will combine with freshly exposed unhydrated material to form new hydration product. The reaction is strongly exothermic, contributing to the increased temperature of the sample under test. The hydration is likely to be rapid because of the finely divided nature of the fractured, unhydrated cement particles, and the fine, C–S–H needles can readily bridge the cracks, typically 0.5 to 5 μm wide (Figs. 8, 11a and b).

The point must be raised as to why such a microstructural repair process should result in a material that has a strength exceeding that of the original product. The answer would appear to lie in part with the effect that such "repair" has on the total pore volume within the matrix. It is well known that porosity is a major factor affecting the strength of cement products (for example, see Jambor [36]), and for a wide range of water–cement ratios the compressive strength increases inversely with the porosity. Thus during fatigue, by reducing the total volume of water-filled, or

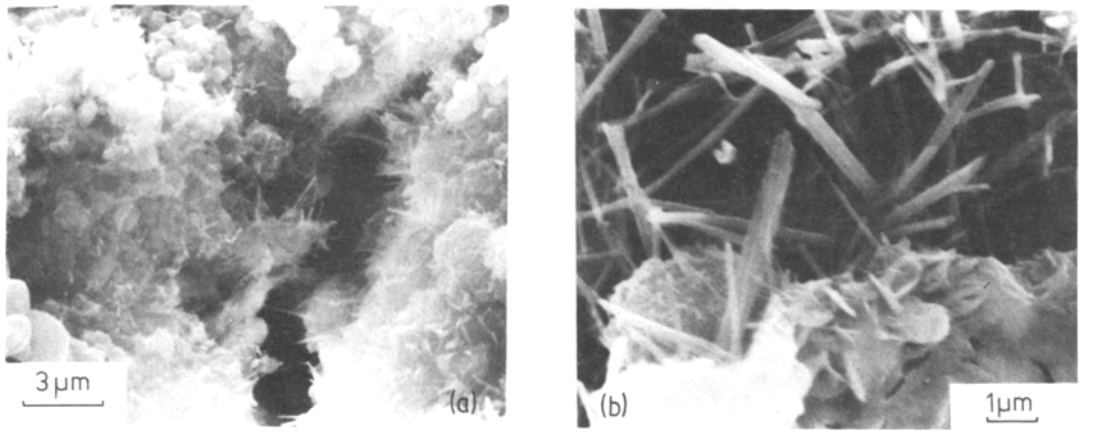

Figure 11 Fatigue fracture surfaces rehydrated for (a) 7 h, and (b) 24 h illustrating hydrate bridging of microcracks as the basis of the "microstructural repair" process (see also Fig. 8).

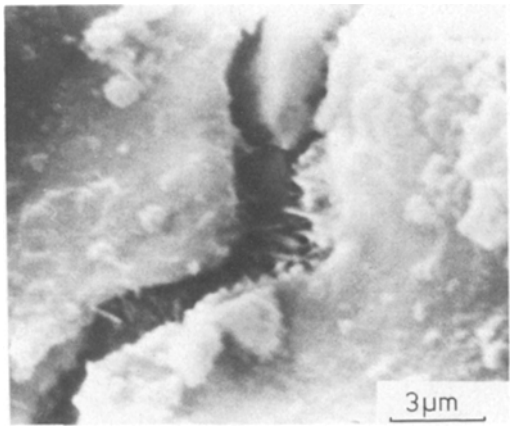

Figure 12 Fatigued and rehydrated for 1 h only: C–S–H needles form in the microcracks after very short times, provided free water is available.

partially filled, pores through the hydration of previously unreacted cement, a resultant increase in strength would be expected. In addition, it is likely that microcracking will have taken place preferentially in regions of higher local stress, and in doing so relieve the stress concentration, at least to a certain extent. In subsequent bridging of these microcracks, the repair process will also cause a local strength increase by effectively removing the pre-damage stress concentration.

Studies have shown that needles of calcium silicate hydrate appear in the fatigue crack after as little as 1 h of rehydration (Fig. 12); re-hydration and therefore strengthening can begin to take place from the point when cracks first form, and certainly throughout the test. Longer re-hydration periods result in more extensive growth of hydration products: Figs. 11a, b and 7 are fatigued and re-hydrated at 7, 24 and 48 h respectively. These observations are consistent with the results shown in Fig. 4: damage introduced in the first few cycles, or at any rate in the first stage of the fatigue life ($<0.2N_f$), is repaired by hydration, either during the test or while the specimen is left to stand, and bigger increases over the static control samples are observed the longer the period which has elapsed after damage has occurred.

One assumption fundamental to this relatively simple mechanism is that hydration, and therefore fatigue hardening, can continue uninhibited during fatigue cycling, i.e. the microcracks, once formed, remain sufficiently open to allow the growth of fresh hydrate. This, at first, seems unrealistic when one considers the loading/unloading nature of the fatigue cycle.

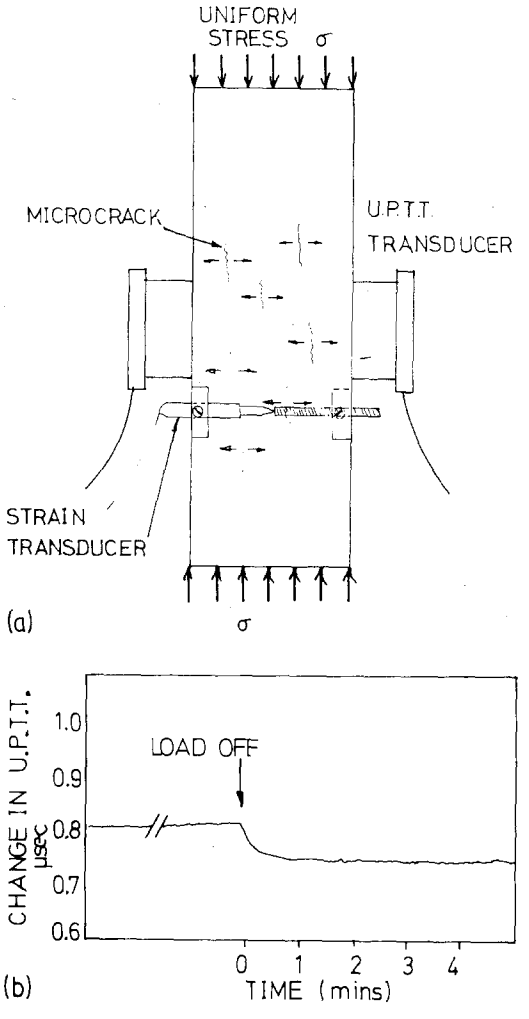

Figure 13 (a) Schematic illustration of the development of longitudinal microcracking in a compression specimen. (b) Change in UPTT on unloading a specimen during fatigue, showing only partial recovery, suggesting that most microcracks, once formed, remained at least partially open throughout the fatigue cycle.

The applied longitudinal compressive stress results in lateral tensile stresses within the sample, opening up (approximately) vertical microcracks (Fig. 13a), which might reasonably be expected to close during the unloading portion of the cycle. However, measurements of the UPTT and residual (permanent) lateral strain during a fatigue test show that there is a progressive, and quite similar, increase in both parameters (Fig. 2). (Note the acoustic emission studies [35, 37] confirm that change in UPTT, although less sensitive than AE, is indeed a measure of the extent of microcracking within a test sample.) Similarly, simply unloading during a fatigue test does not produce any significant recovery of the UPTT, Fig. 13b: were the

cracks to close completely, it would be expected that the UPTT would revert to its original value at the start of the test. It can therefore reasonably be concluded that microcracks formed during fatigue remain open, or at least partially open, at all points of the loading cycle, facilitating the formation and growth of fresh hydrate and therefore fatigue hardening.

An immediate implication of the observations described and interpreted in the preceeding paragraphs is that, provided a wet environment is available, *in situ* microstructural self-repair can take place in any cement or concrete structure. In addition, fatigue loading results in increased strengths (and therefore, for example, improved long-term creep resistance), provided a certain fraction of the fatigue life is not exceeded.

5. Conclusions

(1) The fracture morphology of cement-based products has been studied using a re-hydration technique and scanning electron microscopy. Static fracture results in a largely intergranular fracture path, i.e. through the hydrate gel regions. Fatigue, on the other hand, produces extensive regions of exposed, unhydrated cement particles.

(2) Consideration of the mode and origins of stable microcracking during fatigue suggest that such unhydrated particles are exposed by an attrition process which takes place subsequent to the passage of the main microcrack fronts.

(3) Strength increases following fatigue can be observed in tests carried out over a range of applied stress levels, and result directly from damage introduced in the form of microcracks in the early part of the life. Tests at high stress levels will only show such fatigue hardening if stopped within about the first 20% of the estimated fatigue life.

(4) Fatigue hardening requires the presence of free, i.e. chemically uncombined, water within the matrix; samples dried at 105° C do not exhibit the effect. The likely mechanism involves microstructural repair and the hydration of freshly exposed, previously unhydrated surfaces in fatigue microcracks, with strength increases resulting from a decrease in the overall porosity of the composite, in conjuction with reductions in localized stress concentrations.

(5) Compression fatigue in cement-based materials produces microcracks which remain open even at the minimum of the loading cycle, and therefore facilitate microstructural repair.

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