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A new system for crack closure of cementitious materials using shrinkable polymers

Anthony Jefferson [a,*], Christopher Joseph [a], Robert Lark [a], Ben Isaacs [a], Simon Dunn [a], Brendon Weager [b]

[a] *Cardiff School of Engineering, Cardiff University, CF24 3AA, UK*
[b] *NetComposites, Chesterfield, S41 9QG, UK*

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ABSTRACT

This paper presents details of an original crack-closure system for cementitious materials using shrinkable polymer tendons. The system involves the incorporation of unbonded pre-oriented polymer tendons in cementitious beams. Crack closure is achieved by thermally activating the shrinkage mechanism of the restrained polymer tendons after the cement-based material has undergone initial curing.

The feasibility of the system is demonstrated in a series of small scale experiments on pre-cracked prismatic mortar specimens. The results from these tests show that, upon activation, the polymer tendon completely closes the preformed macro-cracks and imparts a significant stress across the crack faces.

The potential of the system to enhance the natural autogenous crack healing process and generally improve the durability of concrete structures is addressed.

1. Introduction

Almost half of the £80 × 10^9 spent on construction work in the UK per annum is allocated to repair and maintenance of existing structures [1], a large proportion of which is associated with concrete structures. Even allowing for certain historical problems with construction practice, the large annual expenditure on refurbishing and replacing concrete structures points strongly towards the need for more durable cement-based material systems. This, combined with the recognised need to improve the sustainability of concrete construction [2,3], means that there is now an important requirement to develop more durable, efficient and sustainable concrete structures.

The durability of concrete is often compromised by the ingress of saline water, acid rain and carbon dioxide into cracks formed by early age shrinkage and/or mechanical loading. In order to minimise these deleterious actions, reinforced concrete (RC) structures are generally designed such that maximum crack widths are limited to between 0.1 and 0.4 mm (depending upon the application) under long-term serviceability loading [4]. By contrast, conventional pre- and post-tensioned structures are generally designed to be uncracked under serviceability loading. However, despite these design constraints and other code provisions aimed at ensuring durability, there have been problems in the relatively recent past with the durability of concrete structures [3]. Whilst some of these problems may have had other root causes, such as poor grouting of post-tensioned tendon ducts, once cracking has occurred any such problems are exacerbated.

Pre-stressed structures, which are designed to be uncracked, should be inherently more durable than RC structures, but the application of the pre-stress by pre or post-tensioned steel tendons is relatively costly and requires expensive anchors and jacking operations.

Previous investigations have explored the use of shape memory alloy (SMA) bars to replace traditional pre-stressing tendons [5,6]. Whilst these materials have been shown to be effective at providing pre-stress in concrete elements, their relatively high cost makes their use unviable for all but the most specialised of applications.

In the present approach, low-cost shrinkable polymer tendons, which have the ability to shorten or shrink when heated above a transition temperature, are incorporated into the cementitious material. The tendons are anchored and thus impart a compressive stress into the host material when the shrinkage mechanism is activated.

There has been considerable interest recently in Shape Memory Polymer (SMP) materials, both in academic and commercial domains [7–9], but whilst such materials could in principle form post-tensioning tendons, many of these materials develop relatively low stresses (e.g. 2–8 MPa) when undergoing shrinkage under restrained conditions. By contrast, certain drawn (pre-oriented) semi-cystalline polymers such as polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET) have the potential to develop higher restrained shrinkage stresses (e.g. 20–80 MPa) [10,11]. In such materials, the process of drawing at an elevated temperature aligns and stretches the previously random long chain molecules. The aligned molecular configuration is then frozen upon cooling but can be released by reheating above a transition temperature. This leads to a significant shrinkage potential with restrained shrinkage stresses as high as 80 MPa having been measured in PET filaments [10].

* Corresponding author.
E-mail address: JeffersonAD@cardiff.ac.uk (A. Jefferson).
URLs: http://www.cardiff.ac.uk (A. Jefferson), http://www.cardiff.ac.uk (C. Joseph), http://www.cardiff.ac.uk (R. Lark), http://www.cardiff.ac.uk (B. Isaacs), http://www.cardiff.ac.uk (S. Dunn), http://www.netcomposites.com (B. Weager).

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In the present work, tendons formed from shrinkable PET were employed in a series of experimental tests on small scale mortar beams which were pre-cracked and then subjected to heating in order to activate the shrinkage mechanism within the polymer tendons.

The basic premise of the system is that the durability of concrete structures would be greatly enhanced by the incorporation of low-cost tendons which would allow early age cracks to be closed and a state of compression created in the cementitious matrix by remote activation. It is envisaged that in later versions of the system, activation will be achieved via an electrical supply. It is emphasised that the authors do not believe that shrinkable polymer tendons can replace conventional pre-stressing tendons, for which typical peak stresses at jacking are in the region of 1300 MPa.

This new material system is subject to a pending patent application [12].

In the present work, the only pre-stressing and reinforcing elements in the mortar beams are the polymer tendons, but it is envisaged that the system could be used as a crack-closure system for both reinforced and otherwise unreinforced structural components.

2. Concept of material system

The basic concept of the material system is illustrated in Fig. 1, and may be summarised as follows:

1. Cracking occurs in the cementitious material due to early age shrinkage, thermal effects and/or mechanical loading.
2. The shrinkage mechanism in the anchored embedded polymer tendon (or tendons) is activated by heating, which results in crack closure and compressive stresses being developed across the closed crack faces.

The closure of cracks can enhance the natural autogenous healing process [13] and in general such closure serves to enhance the durability of the structural component.

The tendons used in this investigation were unbonded. Fully bonded tendons were tested in some trial experiments but it was found that the very high local strains that occur in fully bonded tendons as they cross open cracks cause the tendons to yield and thereby nullify the polymer shrinkage mechanism. However, in unbonded tendons, which were anchored only at the ends of the specimen, the effective increase in total strain in the tendon due to crack openings was found to be relatively small and thus no plastic yielding occurred and the shrinkage potential remained available for crack closure.

3. Polymer materials

A set of essential criteria were identified as part of the process of selecting candidate materials for the tendons, which are summarised in the following;

- Shrinkage activation temperature <100 °C but >60 °C, on the one hand to avoid damaging the cementitious material but on the other to avoid activation by either heat of hydration or by heat from the outside environment on warm days.
- Minimum restrained shrinkage stress in the tendon to be >20 MPa.
- Adequate resistance to the alkaline environment of the cementitious matrix (i.e. pH 12).
- Maximum long-term relaxation loss of pre-stress of 30%.

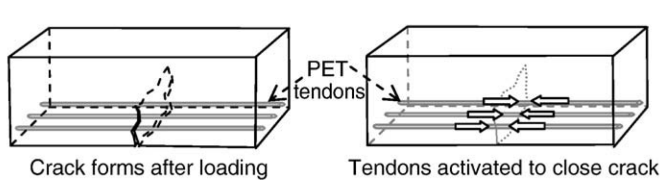

Fig. 1. Schematic illustration of concept for new composite material system.

The minimum value specified for the restrained shrinkage stress in the polymer was guided by the consideration that the system should be able to close cracks and put a crack into a compression of at least 1 MPa. This benchmark value was chosen since it is twice the value of 0.5 MPa identified in reference [13] as that required to enhance autogenous self-healing.

Assuming that Euler beam theory applies, the strain produced in the cementitious material is negligible in comparison with the free shrinkage potential strain of the polymer (which is several hundred percent), and that the area of concrete removed by the tendon is negligible; then the extreme fibre stress (σ_c) produced in a rectangular cementitious section of width b and depth h by a tendon of cross-sectional area ρbh at an eccentricity ηh with a restrained shrinkage stress (σ_p) is given by:

$$\sigma_c = \rho\sigma_p(1 + 6\eta). \tag{1}$$

Noting that

$$\rho = \frac{A_p}{bh};\ \eta = \frac{e}{h};\ \text{in which}$$

$$A_p = \text{cross}-\text{sectional area of the polymer and } e = \text{eccentricity}.$$

Thus, if the tendons have an area equal to 2% of the cementitious beam gross cross-section and are placed at an eccentricity of $h/4$, a tendon shrinkage stress of 20 MPa is required to produce an extreme fibre pre-stress of 1 MPa. It is noted that, whilst the trial system uses tendons located at the neutral axis for reasons dictated by the scale of the specimens, in the final system it is envisaged that tendons/grids will be positioned eccentrically.

This paper does not address the long-term behaviour of the system, which is the subject of ongoing work. Therefore not all of the criteria have been proven at this stage. Long-term relates to the design life-time of a structure and thus would be typically of between 50 and 120 years depending upon the application.

As discussed in the Introduction to this paper, the most promising materials identified were semi-crystalline polymers. A series of 'screening' tests were undertaken using a tensile loading rig with inbuilt oven to explore a range of candidate materials, the details of which are provided in Table 1. The tests were performed on specimens 280 mm in length with the oven temperature being raised from ambient (25 °C) at a rate of 1 °C per minute until failure.

Table 1
Candidate materials.

Name	Polymer	Description	Form	Area[a] (mm^2)	Supplier
PP PURE	PP	Oriented PP tape coextruded with PP-PE copolymer	Tape	0.126	Lankhorst
PP Armordon	PP	Oriented PP tape coextruded with PP-PE copolymer	Tape	0.224	Don & Low
PP Lotrak	PP	Oriented PP tape	Tape	0.10	Don & Low
PE Certran	PE	Melt spun PE continuous filament yarn	Yarn	0.061	University of Leeds
PP Multiprof	PP	Oriented PP tape coextruded with heat sealing layer, fibrillated	Fibrillated Tape	0.24	Lankhorst
PET Shrinktite	PET	Oriented PET tape	Tape	0.10	Aerovac

[a] Area = original cross-sectional area of specimen.

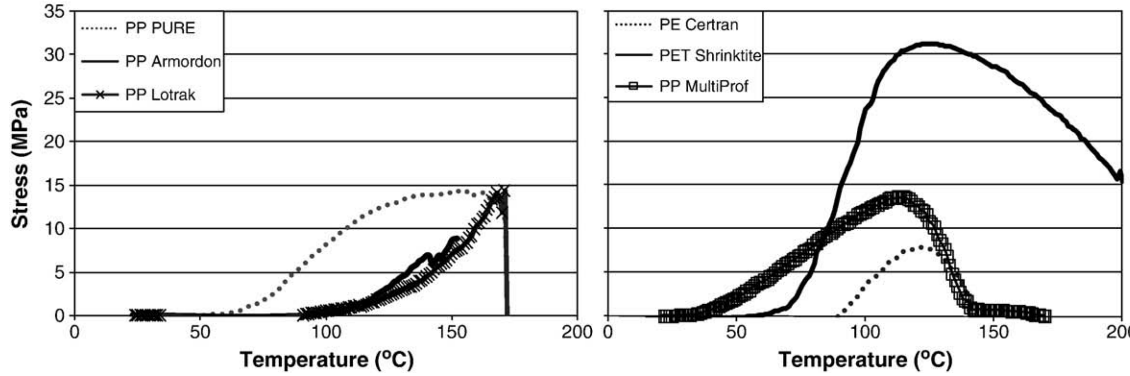

Fig. 2. Results from polymer screening tests.

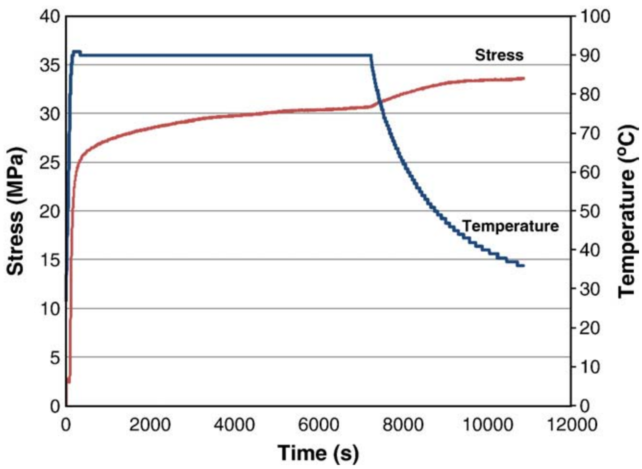

Fig. 3. Restrained heating tests on PET strips.

The results, in terms of shrinkage stress versus temperature, are provided in Fig. 2.

The most promising material was the PET Shrinktite, which developed a peak stress of more than 31.5 MPa in the screening tests. None of the other materials tested reached the basic criterion stress of 20 MPa. Further, more accurate, tests were then conducted on this material which is readily available in the form of 32 mm wide 0.046 mm thick tape. From this tape, sections of width 6 mm, thickness 3.45 mm and length 450 mm were formed by laying 75 strips into a specially prepared jig and then applying heat locally at the ends to bond the strips together. Trials were then conducted to explore if sufficient shrinkage stress could be reached with heating up to 90 °C, a value chosen to be a little below the 100 °C at which damage to the cementitious material is expected. Each test was undertaken three times and the average peak stress reached was 33.5 MPa with a coefficient of variation (CoV) of 2.05%. A representative graph from one of the tests is shown in Fig. 3, which shows that heating at 90 °C for half an hour followed by cooling to ambient temperature produced the peak stress. A similar, but longer term, test conducted over 9 days showed a stress loss of less than 1%, which gave a first indication that long-term relaxation losses would be acceptable, assuming that the polymer material behaved in a characteristic manner with exponential decay in relaxation losses [14]. It is noted that long-term relaxation tests are planned in order to further explore this important issue.

4. Experimental details

The concept outlined in Section 2 was tested using a series of three-point bend experiments conducted on small scale, hollow, prismatic mortar beams, the testing arrangement for which is illustrated in Fig. 4.

It was found from trials that the small scale of specimens and nature of the layered tendons meant that the easiest way to achieve well anchored unbonded tendons was to use hollow beams in which the tendons were placed and anchored after casting and curing.

The tendons comprised 75 individual strips of PET tape (each strip being 6 mm × 0.046 mm) which had been bonded together at the ends. The anchorage system for these tendons, which comprised clamping plates and a plug of melted material as illustrated in Fig. 4, limited slip to a degree which was insignificant in comparison with the shrinkage potential of the polymer. This anchorage system was thoroughly tested in trials on isolated tendons prior to the testing of the beams.

The procedure used to ensure that the tendons were consistently loose at the start of the tests was as follows. With the tendon in

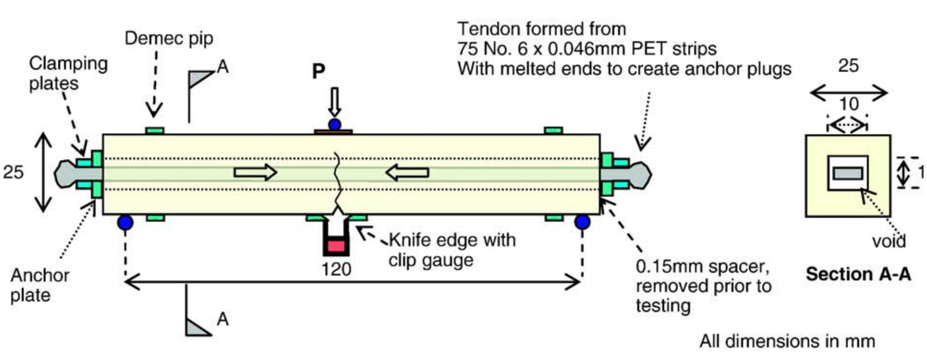

Fig. 4. Testing configuration.

Table 2
Summary of specimen details.

Group		Stage 1	Stage 2		Stage 3
	PET tendon inserted prior to day 4 test	Day 4 3-point bend test	Heated at 90 °C for 18 h	PET tendon removed prior to day 8 test	Day 8 3-point bend test
3 control beams, tested on day 4 (Ctrl1)	No	Yes, to failure	N/A	N/A	N/A
3 control beams, tested on day 8 (Ctrl2)	No	No	Yes	N/A	Yes, to failure
3 post-tensioned beams with PET tendon throughout (from day 4) (PET)	Yes	Yes, to 0.3 mm $CMOD_{CG}$[a]	Yes	No	Yes, to failure
3 post-tensioned beams with PET tendon removed after activation (PETr)	Yes	Yes, to 0.3 mm $CMOD_{CG}$[a]	Yes	Yes	Yes, to failure

[a] 1: Day 1 is taken as the day of casting. 2: An opening of 0.3 mm measured by the clip gauge 4 mm below the underside of the specimen equates approximately to an opening 0.22 mm measured by the DIC equipment at 1.75 mm above the base of the specimen at the end of the softening branch in the unpre-stressed stages. 3: $CMOD_{CG}$ = Crack Mouth Opening Displacement by clip gauge.

Table 3
Measured material properties.

	E kN/mm^2	E_p kN/mm^2	f_{cu} N/mm^2	$f_{t\ (Stage\ 1)}$ N/mm^2	$f_{t\ (stage3)}$ N/mm^2	G_f N/mm
Mean	24.8	6.0	23	2.0	0.09	0.025
CoV %	*1.6*	*2.5*	*8.3*	*7.3*	*10.6*	*11.7*

E = Young's modulus of mortar, E_p = Young's modulus of PET, f_{cu} = cube strength of mortar, f_t = tensile strength of mortar, and G_f = fracture energy.

position through the void, one end of the tendon was anchored. The beam was held vertically and a 1 kg weight was hung on the tendon after which a 0.15 mm spacer was inserted between the anchor plate and the clamping plates, prior to the latter being tightened. Heat was then applied to the excess PET beyond the end of the anchor plates using a soldering iron in order to form a mechanical anchor plug. The 0.15 mm spacer was removed prior to testing.

The cross-sectional area of the tendons was 20.7 mm^2, which is 3.9% of the cross-sectional area of the un-notched mortar beam.

After preparation, the tests were conducted in three stages: Stage 1 being loading to form a crack, Stage 2 being heating to activate PET shrinkage and Stage 3 being reloading. In Stage 2 (at an age of 4 days) the specimens, with tendon in place (except for controls), were removed from the loading rig, placed in an oven and heated for 18 h.

Twelve 145 mm × 25 mm × 25 mm specimens were cast and these were divided into 4 groups of 3 beams. 3 of these had the tendons in place throughout all stages (PET_a to PET_c); 3 had tendons in place in Stages 1 and 2 only (PETr_a to PETr_c) and 6 control beams had no tendons, of which 3 were tested at the end of Stage 1 (Ctrl1_a to Ctrl1_c) and the remainder tested at the end of Stage 3 (Ctrl2_a to Ctrl2_c). The testing stages and parameters for each group of tests are summarised in Table 2. In addition, material tests were conducted on the mortar to determine the compressive strength, fracture energy, tensile strength and Young's modulus. The mean values and coefficients of variance (CoV) from these tests are given in Table 3.

All mortar beams were cast using a mix which comprised Water: Cement:Sand contents of 306 kg/m^3:510 kg/m^3:1530 kg/m^3 respectively, (or 0.6:1:3 by weight).

The materials used in the mix were Portland-fly ash cement, designation CEM II/V-V32.5 R, supplied Lafarge Aberthaw, which contains 7% fly ash. 0/4 mm concrete sand, dredged from Nasia, Swansea compliant with EN12610, except that this sand was passed through a 1 mm sieve prior to mixing. Mixing was undertaken in a CreteAngle® Multiflow Pan Type Mixer Model 'S'.

The specimens were compacted on a vibrating table and the mortar was placed in three layers, the first of which provided a bed for a polystyrene former, the second being to the upper surface of the former and the last layer to the top surface of the mould.

The polystyrene former was used to create an axial void, and this former was removed during demoulding on day 2. Immediately after casting, the beams were then covered in wet hessian and wrapped in cling film. The tendon was inserted on day 4 immediately prior to Stage 1 testing.

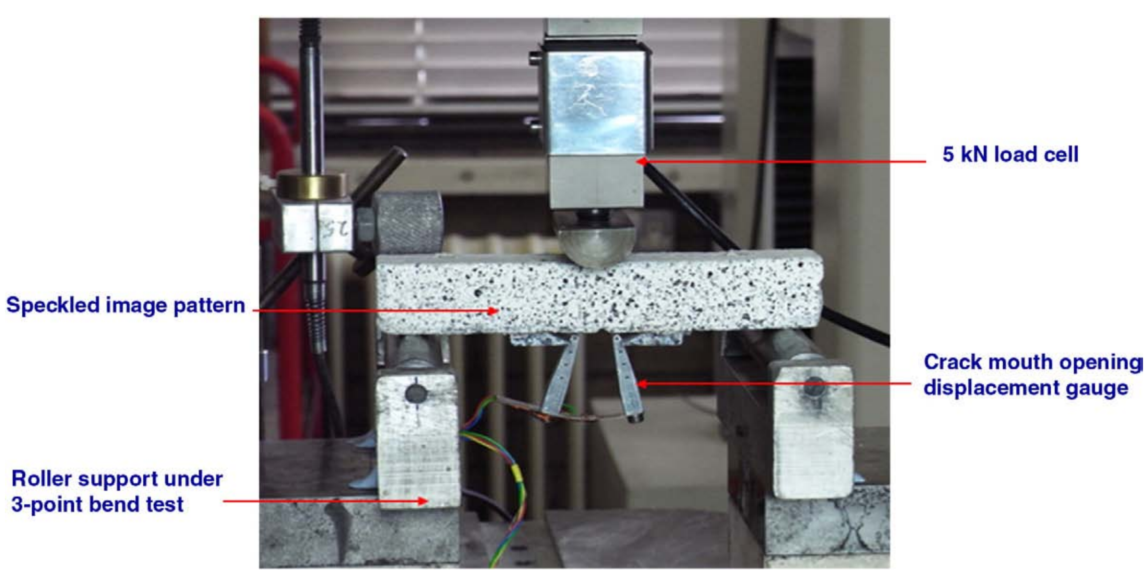

Fig. 5. Three-point bending testing arrangement.

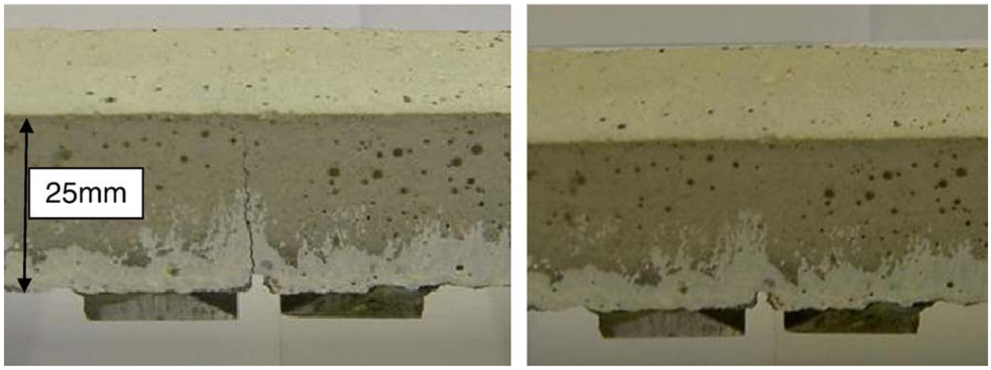

Fig. 6. Specimen from Group PET (left) cracked after Stage 1 loading (right) with crack closed after polymer activation (Stage 3).

A photograph of the loading rig used is given in Fig. 5. A light weight clip gauge (CG), located between knife edge plates glued to the underside of the beams, monitored the Crack Mouth Opening Displacement (CMOD) during the experiment. The load is controlled via feedback from a machine stroke displacement transducer which allows the softening behaviour to be captured.

Full 2D displacement and strain information was captured for one of the side faces of each beam using a digital image correlation (DIC) system which employed two cameras tracking a speckled image on the side of the specimens [15,16]. The actual system used was the "vic 3D system" supplied LIMESS which has an accuracy of 1 μm for displacements for the chosen grid size of 120 mm × 25 mm [15].

The CMOD was thus measured independently using two methods (i) with the clip gauge and (ii) with the DIC system. The former was automatically plotted during the experiment and was thus used to detect the unloading point. The latter (DIC) was obtained by post-processing images after the experiment was completed. The DIC CMOD ($CMOD_{DIC}$) values were measured across the 3 mm deep pre-fabricated notches in the mortar specimens at a height of 1.8 mm above the underside of the beams, whilst the CG CMOD ($CMOD_{CG}$) was measured across the knife edges approximately 4 mm below the bottom of the specimen.

Control group 1 was used to ensure that the response of the specimens with loose tendons was the same as that for specimens without tendons. Control group 2, which was subject to the same heating regime as the specimens with tendons, was used to assess the effect of the heating and additional curing time on the strength of the specimens. The group with tendons removed prior to Stage 3 was used to assess the degree of autogenous crack healing.

5. Results and discussion

The primary aim of the test series was to assess the ability of the activated tendons to close cracks and put the specimens into a state of axial compression.

Full crack closure is illustrated by the photograph of a Group PET specimen in Fig. 6, which shows the specimen at the end of Stage 1 testing, after loading and unloading, and at the end of Stage 2 following tendon activation by heating. It may be seen that the crack is no longer visible after tendon activation.

The clip gauge readings were, allowing for the different depths at which the crack mouth opening was measured, consistent with the results from the DIC, however the DIC measurements were taken directly on the surface of the specimen and exhibited less 'noise'. Thus, the latter were chosen for the presentation of the results in Figs. 7–10.

Good consistency was achieved between the individual tests from each group, as illustrated in Fig. 7. This shows the Stage 1 tests for the PET and Ctrl1 groups, for which the peak load range was 193 to 223 N.

The specimens with loose PET tendons were unloaded when the $CMOD_{CG}$ reading reached approximately 0.3 mm. This point is based on the clip gauge value because this was available during the experiment. The value is equivalent to approximately 0.22 mm for the CMOD_DIC measurements.

Comparison between PET and Ctrl1 data shows that, as intended, the loose PET tendons had an insignificant effect upon the response of beams during Stage 1. It is noted that the small differences between the PET and CTRL specimens may be seen in the circled area in Fig. 7.

The effects of the polymer post-tensioning after transition are illustrated in Figs. 8 and 9; with Fig. 8 showing the response of a representative test from the PET Group for testing Stages 1 and 3, and Fig. 9 showing the same comparison for the PETr Group in which the polymer was released immediately prior to the final test. The data

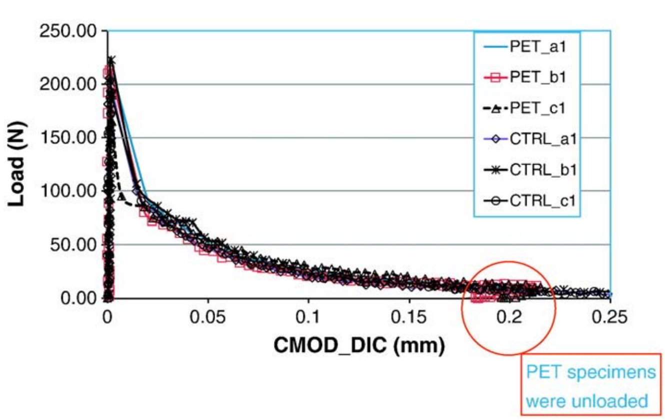

Fig. 7. Stage 1 Load-CMOD results.

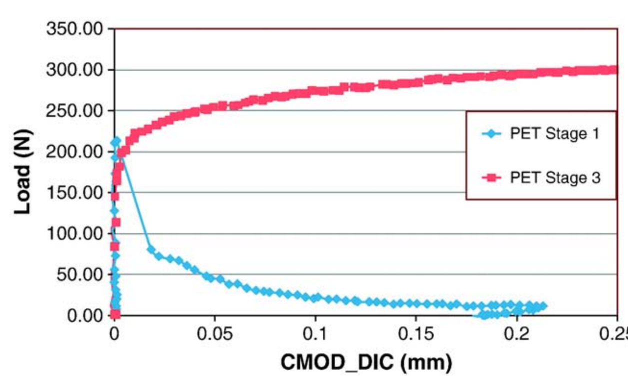

Fig. 8. PET Stages 1 and 3.

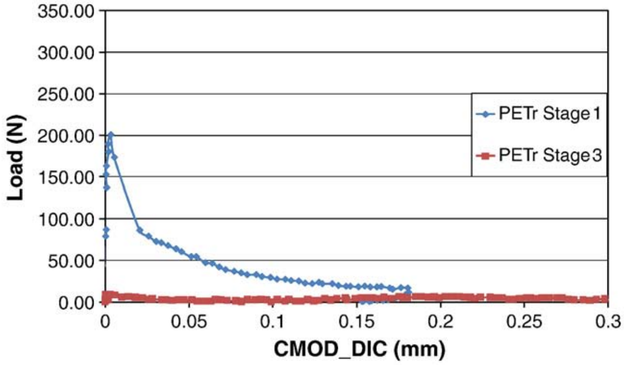

Fig. 9. PETr Stages 1 and 3.

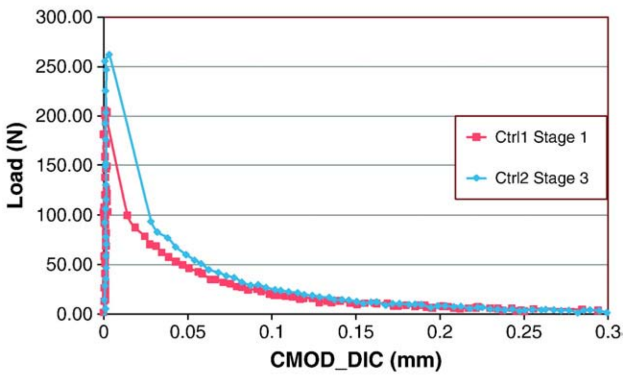

Fig. 10. Control specimens. Without heating (Stage 1) and with heating and further curing (Stage 3).

indicate that the post-tensioning was such as to maintain the crack in an effectively fully closed state up to a load of 150 N, and a predominantly closed condition ($CMOD_{DIC} < 0.005$ mm) up to 200 N. These loads are associated with nominal average pre-stresses in the mortar (at the central notched section) of 1.5 MPa and 2 MPa respectively. Fig. 8 shows the response of a representative PET test for Stages 1 and 3. The load at the end of the test was 300 N and this corresponded to a CMOD of 0.25 mm. The CoV of the load at this CMOD in the three tests in this Group was 2.6%.

The softening responses shown in Fig. 7 show a greater apparent 'ductility' than would normally be expected for a fully cured mortar of the composition of that used here. However, all of the tests reported used mortar at a relatively early age and it has been found by others [17] that early age cementitious materials exhibit a greater crack opening at the end of a softening curve than do their fully cured counterparts.

Fig. 6 shows the crack extending to the upper surface over half of the width of the specimen and thus, in this case, a negligible load was carried by the concrete at the end of Stage 1. In the other specimens, cracks were not visible on the upper surface after Stage 1 testing and the small area of uncracked concrete near the upper surface was believed to be responsible for the small residual loads in the control tests at the end of Stage 1, which were between 4% and 8% of the peak load, with all but one specimen in the range 4% to 6%. In all cases the specimens needed to be treated very carefully after Stage 1 because of their very low residual strengths, however in none of the cases reported, did the specimens completely separate into halves at the end of Stage 1 loading.

Fig. 9 also illustrates that no measurable crack healing occurred. A follow-on study has been undertaken to explore the effects of using different Stage 2 curing regimes on the healing process. This follow-on work focuses on autogenous healing and will be the subject of a forthcoming publication.

The effect of the heating upon the mortar was isolated by testing control specimens at Stages 1 and 3. Representative data from these tests are shown in Fig. 10 which indicates that the combined effect of heating and the additional four days of curing resulted in an increase in peak load and associated tensile strength of approximately 25%.

Finally, one of the essential criteria listed in Section 2 was long-term stability of the polymer in an alkaline environment. Whilst long-term tests are needed, the work to date has shown that no degradation occurred in the polymer over the duration of these short term tests. The findings of others who have explored degradation of PET fibres in cement-based materials are mixed, with some suggesting little degradation [18] and others suggesting significant degradation [19].

6. Conclusions and closing remarks

The results of the experimental programme presented in this paper show that the concept of post-tensioning mortar beams using oriented shrinkable polymer tendons is viable for crack closure and low-level pre-stressing.

The most effective material for the tendons, as judged from a series of screening tests, is PET Shrinktite. This material has a shrinkage potential of approximately 34 MPa under restrained conditions when heated to a temperature of 90 °C and allowed to cool. This temperature is such as to cause negligible damage to a cementitious material.

The three stage experimental procedure showed that: (i) the fracture softening response of the unreinforced notched beams is the same whether or not pre-activated polymer tendons are present; (ii) the effect of polymer activation is to close preformed cracks and apply a pre-stress of between 1.5 and 2 MPa; (iii) no significant crack healing is achieved with dry activation and curing, and; (iv) the effect of heating and additional curing from day 4 to 8 increases the strength of the mortar by approximately 25%.

Research on the system is ongoing and future publications will present results from a parametric study on the effect of Stage 2 curing regimes on autogenous healing, and from a detailed numerical study of the system with a new time dependent material model for the shrinkable polymer.

Acknowledgements

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