DELAYED CONCRETE PRESTRESSING WITH SHAPE MEMORY POLYMER TENDONS.

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Abstract

Issues that govern the durability of concrete include the ingress of saline water, carbon dioxide and acid rain. The main path for this ingress is via cracks that are formed by early age shrinkage or mechanical loading. The closure of such cracks would improve the durability of concrete. The feasibility of closing cracks by using oriented shape memory polymers (SMP) on small scale hollow mortar specimens has been previously demonstrated and the autogeneous crack healing effects have been investigated. This paper presents details of an experimental and numerical study of delayed pre-stressing and crack closure system in larger concrete beams.

The system involves embedded SMP tendons in a concrete beam that are heat activated to induce restrained stresses in the tendons thus pre-stressing a concrete element and closing cracks. Experimental results and qualitative evidence of the system's performance in pre-cracked concrete prisms are presented. The effects of autogeneous crack healing in concrete are quantified through repeated loading cycles.

Keywords: Concrete, Crack closure, Durability, Shape memory polymers

1 Introduction

1.1 Durability and damage in concrete

It is generally accepted that the design-life of concrete structures is decreased by the development of micro-cracks and the ingress of water, carbon dioxide and chloride ions into these cracks. This may cause carbonation, sulphate-related degradation of the concrete and potentially could corrode conventional reinforcement, such corrosion can be mitigated by the use of stainless steel reinforcement, but at a cost premium. The gradual process of concrete degradation results in the requirement for regular repair and maintenance work on concrete structures, with large associated costs. Cracking in unmodified concrete is virtually unavoidable, and is generally caused by thermal effects, early-age shrinkage, mechanical loading, freeze-thaw effects or a combination of these factors (De Rooij & al. 2013, Isaacs & al. 2013)

1.2 Avoiding concrete cracking through prestressing

Steel prestressing, either as pre or post-tensioning, may be used to either limit or entirely avoid concrete cracking due to tensile stresses by placing a calculated compressive stress into the concrete member (ACI-ASCE 1999). However, prestressed concrete is significantly more expensive than conventional reinforced concrete due to the initial material and equipment costs for installation (Syal & Goel 2008). There are also increased risks when demolishing or altering a prestressed structure due to the high stresses used, typically around 1300 MPa during jacking (Jefferson & al. 2010).

A crack closure system using delayed prestressing with shape memory polymers (SMPs) is proposed. The stress generated by the polymer is much lower than conventional steel prestressing and is therefore safer during installation and demolition. It is also expected to be far cheaper due to the materials used and the avoidance of heavy plant.

1.3 Crack closure in concrete using SMP

SMPs are materials which respond to external stimuli by altering their physical shapes. The most common stimulus used to provoke this change is direct heat, leading to a shape change of the polymer. This form of SMP is known as thermoresponsive, and the ability of the material to undergo this shape change is referred to as the shape memory effect (SME) (Xie 2011). If the SMP is restrained during the shape change a stress will be generated within the material (Dunn & al. 2011).

Proof of concept experiments carried out by Jefferson & al. (2010) and Isaacs & al. (2013) used drawn Polyethylene Terephthalate (PET) tape to close cracks in prismatic hollow mortar beam specimens, making use of the restrained shrinkage stress activated by heating. Conclusions from these studies were that activation of the tendons closed the cracks and applied a pre-stress of between 1.5 – 2 MPa on the mortar beam specimens therefore enhancing the autogenous healing within mortar. This is based in part on the premise that, evidenced by Heide & Schlangen (2007), the presence of a compressive stress on crack faces submerged in water enhances the autogenous healing observed within concrete samples.

However, these experiments were undertaken at a small scale within a laboratory setting, and made use of mortar beams rather than the type of structural concrete that would be used in major construction projects. As the system is ultimately envisaged to form part of infrastructure assets, further experiments were planned to incorporate structural mix designs using larger samples to assess the feasibility of the system within construction.

1.4 Crack closure numerical model

A numerical model developed by Dunn & al. (2011) and Hazelwood & al. (2013) describes the short and long term behaviour of shape memory polymer tendons. Recent improvements to the model allow it to predict long-term crack behaviour of a concrete beam placed in axial compression by a shape memory polymer tendon. The experiments described within this paper are to be used to further validate the model by direct comparison of results.

1.5 Aims of the paper

This paper provides details of experiments aimed at upscaling the SMP crack closure system proposed by Jefferson & al. (2010), Dunn & al. (2011) and Isaacs & al. (2013) as part of the Materials for Life programme involving Cardiff, Bath and Cambridge Universities.

An experimental series investigating the autogenous healing of load induced cracks in structural concrete when subjected to compression using shape memory PET tendons is currently underway, with some early results presented here.

2 Experimental details

2.1 Concrete composition

The composition of the concrete used in the reported tests is given in Table 1. This contained CEM II V-B 32.5R cement, crushed limestone 4/10 mm coarse aggregate, 0/4 mm sea dredged sand from Bristol channel as fine aggregate, 0/2 mm crushed limestone dust and Adomast Adoflow Extra plasticiser. It was designed to achieve S3 (100-150mm) slump class and a target compressive strength of 53 MPa (C35/45). Specimens were cast in moulds coated with release agent and de-moulded after 24 hours. Afterwards cured in water at 20±3 °C until the age of testing as detailed in Section 2.4.

Table 1
Concrete composition

Cement (kg/m^3)	**w/c ratio**	**Coarse aggregate** (kg/m^3)	**Fine aggregate** (kg/m^3)	**Limestone dust** (kg/m^3)	**Water** (kg/m^3)	**Admixture** (l/m^3)
400	0.48	990	648	162	192	1.3

2.2 Specimen details

Nine 500x100x100 mm concrete prisms and nine 100 mm cubes were cast. Three of these prisms (PETr) were cast with a 10x40 mm void at 30 mm eccentricity from the centreline to allow the external anchoring of shape memory tendon. Three prisms (PET) contained cast-in SMP tendon at 30 mm eccentricity from the centreline and three prisms (Control) did not have any modifications. Cross-sections of the prism specimens at mid-point are shown in Fig. 1.

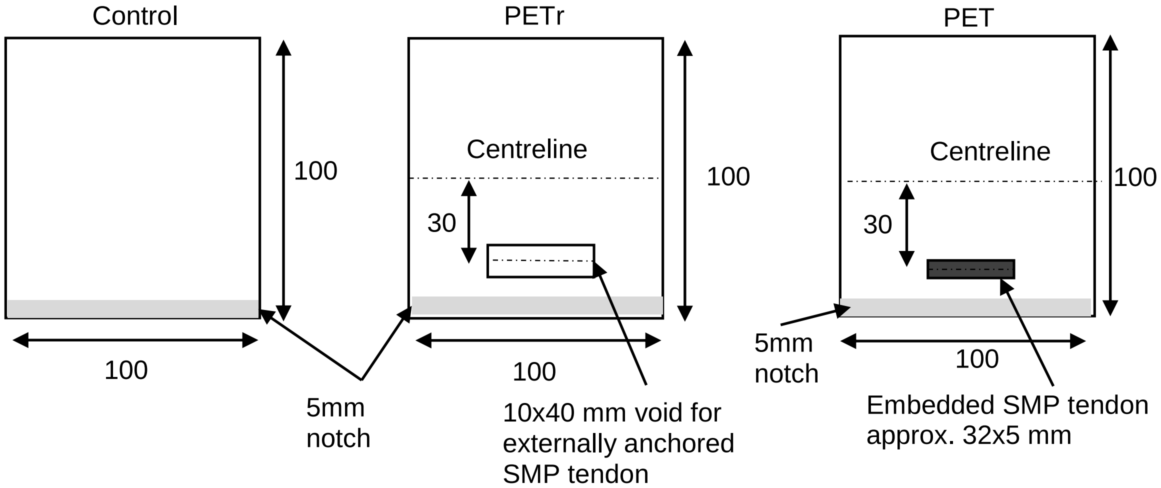

Fig. 1 Cross-sections at mid-point of the concrete prisms, dimensions given in mm

2.3 SMP tendon details

The SMP tendons were made up of 100 commercially available oriented PET strips that were 0.046 mm thick and 32 mm wide. In restrained conditions when heated to 90°C the SMP produced shrinkage stress of 24 N/mm^2 that in turn pre-stresses the bottom face of the specimens with 1 MPa compression and encourages closure of cracks. Fig. 2 shows the SMP tendon with external anchorage where the ends of the strips are melted to prevent any potential slippage during activation.

Fig. 2 SMP tendon with external anchorage for PETr prisms

2. 4 Loading and testing setup

The loading setup is shown in Fig. 3. Concrete prisms were notched with a 5 mm wide and 5 mm deep notch at the centre of the bottom face. Knife edges were attached either side of the notch for crack mouth opening displacement (CMOD) measurement. On the 7th day all prisms were loaded in three point bending until a 0.5 mm CMOD was reached and then unloaded thereby allowing the cracks to reach their stable (unloaded) condition. Images of the created cracks were taken after unloading with a Veho Discovery VMS-001 USB microscope. Afterwards the prisms were heated in an oven at 90±5 °C for 24 hours in order to activate the SMP tendons. Following this, the prisms were cooled to room temperature, microscope images were taken of the cracks and the prisms were returned to a water tank to cure for further 28 days. On the 35th day the SMP tendons were removed from the prisms, which were designated PETr specimens. Microscope images were taken of the cracks and all prisms were re-loaded in three point bending setup until 0.5mm CMOD was reached.

Three cubes were tested for compressive strength on the 7th day, three were subjected to the same curing and heating cycle as the prisms and tested for compressive strength on the 35th day and three were only cured in water and then tested for compressive strength on the 35th day.

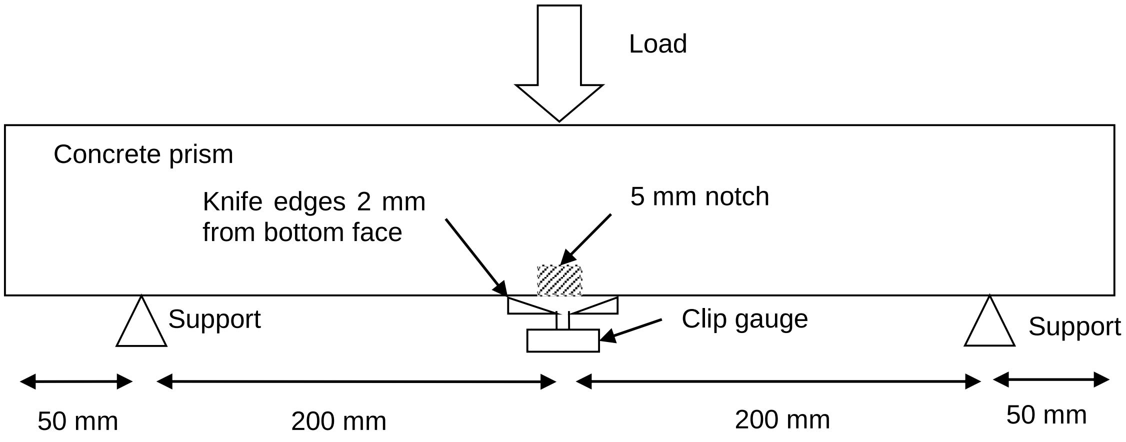

Fig. 3 Loading setup for concrete prisms

3 Results and discussion

Fig. 4 and 5 show typical crack width changes in the concrete prisms during the study and these are representative of all results observed. In the Control specimens the crack widths did not change during the heating stage as indicated by images A and B in Fig. 4. Minor reductions in the crack widths due to white precipitation on the crack faces were observed after the immersion of the prisms in water for 28 days but the cracks were still clearly visible as shown in image C in Fig. 4; whereas the PET and PETr prisms with SMP tendons had a significantly reduced crack widths after the heating stage. The average reduction in crack widths in PET and PETr specimens after the SMP tendon activation as measured by optical microscopy was 74%. This demonstrated that the SMP tendon activation was successful and the crack closure system works on scaled-up concrete beams. Image C in Fig. 5 shows that after immersion in water for 28 days following the first loading the cracks were not visible and the average crack reduction for specimens with SMP tendons was 93% as measured by optical microscopy. This is attributed to the autogenous healing of concrete as the cracks in PET and PETr prisms were reduced to a size that can be healed with this mechanism.

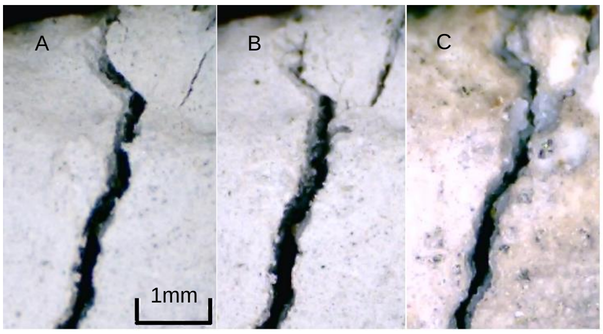

Fig. 4 Typical crack width changes in Control specimens. A - after cracking on 7th day, B – after heating in oven on the 8th day, C – after immersion in water for 28 days on the 35th day.

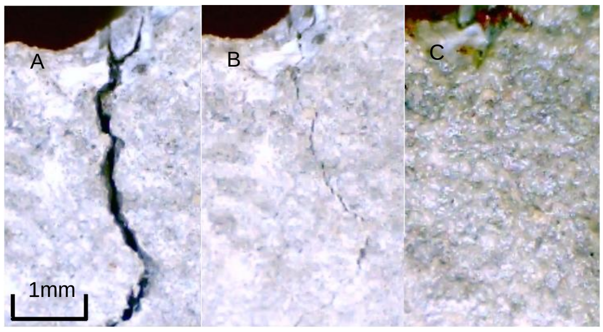

Fig. 5 Typical crack width changes in PET/PETr specimens. A - after cracking on 7th day, B – after heating in oven on the 8th day, C – after immersion in water for 28 days on the 35th day.

Fig. 6 to 8 show typical load-CMOD response curves for the concrete prisms during the initial loading on the 7th day and the final loading on the 35th day. These are representative of the results observed during the study. No strength recovery was observed in Control prisms in the final loading stage whereas PETr prisms, from which the SMP tendons were removed prior to the final loading, exhibited definite peak loads confirming the improved autogenous healing of cracks in concrete due to the SMP system. The average load recovery of three PETr prisms on the 35th day, when calculated as shown in Fig. 9, was 13% whereas for Control beams the average was 1%. The load recovery values for PETr specimens are much lower than those observed by Isaacs & al. (2013) in which the average recovery value was 79%; however, they used mortar specimens that were cracked to smaller crack widths and tested at an earlier age than in the present experiments. The PET prisms with internally anchored and activated SMP tendons in the final loading stage showed that the SMP tendons act as an elastic reinforcement – after the initial peak of the Load-CMOD curve, which corresponds to the cracking of the concrete, the tension in the prism is resisted only by the polymer as indicated by almost linear response afterwards. Fig. 8 shows the re-loading curve up to 0.5 mm CMOD, however, the specimens were reloaded up to 1 mm CMOD and at that point the crack traversed the entire cross-section of the concrete and the two pieces of the prism were held together by the SMP tendon alone. This was considered to be a failed specimen and thus the unloading part of the curve is not shown.

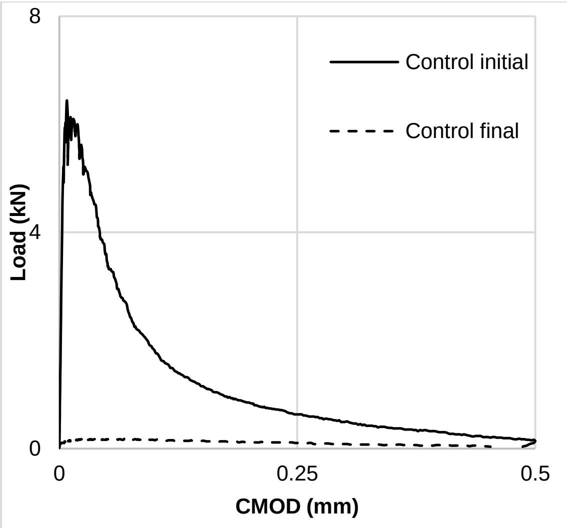

Fig. 6 Typical load v. CMOD response from Control prisms.

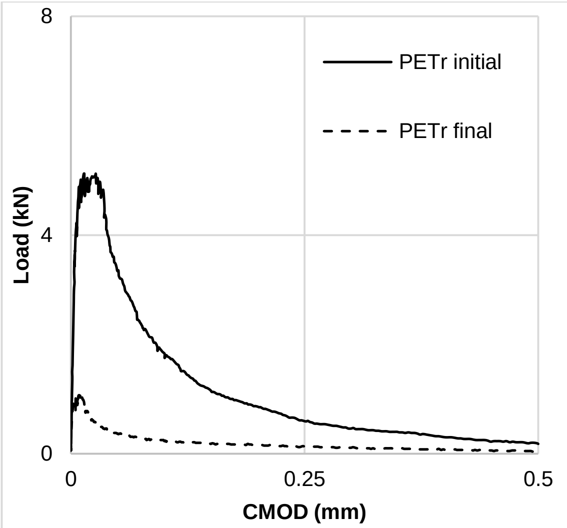

Fig. 7 Typical load v. CMOD response from PETr prisms.

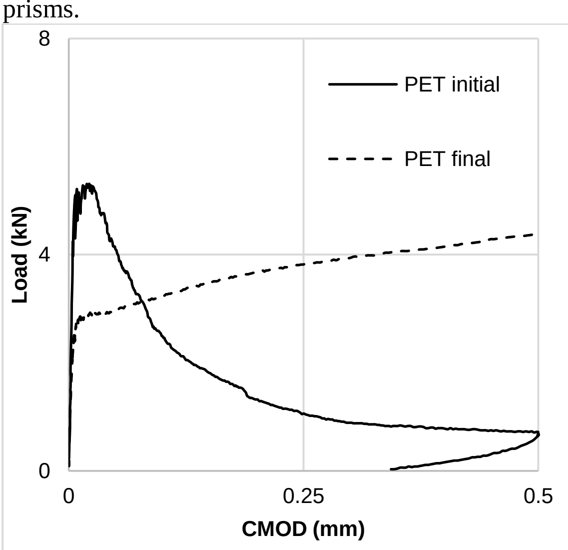

Fig. 8 Typical load v. CMOD response PET prisms.

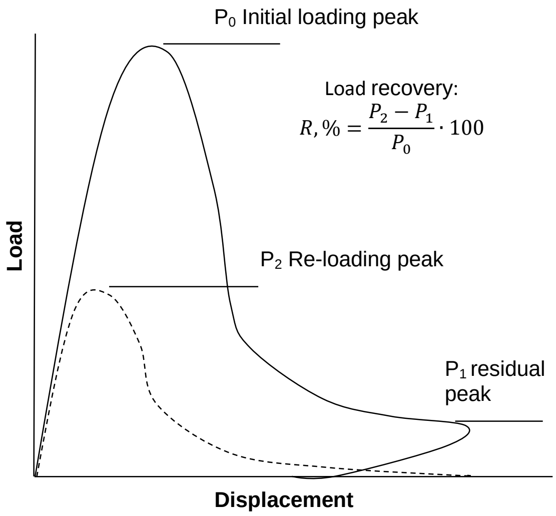

Fig. 9 Load recovery calculation diagram.

4 Conclusions

The proposed delayed concrete pre-stressing system using SMP tendons has been demonstrated to close, or significantly reduce crack widths, in structural concrete prisms that have been cracked to 0.5 mm

CMOD. On average a 74% crack width reduction was achieved after SMP tendon activation and this rose to 93% when specimens were placed in water after cracking and tendon activation. Furthermore, the results indicate that the proposed system enhances the autogenous healing of concrete as 13% load recovery after 28 day healing was observed for PETr prisms as opposed by 1% shown by Control specimens. The load recovery was lower than that observed in small mortar specimens and could be due to the lower volume of cement paste in concrete. The crack width reduction and enhanced autogenous healing is encouraging and the system will be developed further with an improved tendon activation method.

Acknowledgements

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