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ENHANCED CONCRETE CRACK CLOSURE WITH HYDRID SHAPE MEMORY POLYMER TENDONS

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Abstract: Concrete is one of the most used building materials. It behaves well in compression. but it cracks when subjected to tensile stresses. These cracks may consequently compromise the durability of the whole structural element, i.e. acting as preferential paths for water percolation inside the structure, leading to further problems, such as, corrosion of the steel reinforcement bars. Shape memory polymers (SMP) have been used in the past in the design of a novel system aiming to reduce the size (or possibly close) these cracks. Polyethylene terephthalate (PET) was the SMP which showed the best potential for this aim. During production, it is subjected to a drawing process at high temperature, aligning 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. PET tendons were embedded within the structural element. Being restrained, the PET tendons developed a compressive stress when activated, thereby promoting crack-closure. The tendons made of PET showed very promising results. However, the stress developed by the restrained tendons remained quite low. In this work a preliminary study of a novel hybrid tendon is presented. The tendons are made by combining the natural behaviour of the PET with a pre-stressed inner core. The new system has the potential to increase the stress developed by the tendons, hence further improving the crack-closure, and to provide reliable post-activation reinforcement.

1 INTRODUCTION

Concrete continues to be one of the most important building materials, despite its unavoidable tendency to crack. Its strength and versatility make it a strong and long-lasting option for numerous construction settings worldwide [1]. Concrete can deal very well with compression but, due to its low tensile strength, it will crack when subjected to tension stresses [2]. Cracks formed on the concrete surface may compromise the durability of the whole structural element, i.e. they could act as preferential paths for water to percolate inside the structure leading to further problems such as corrosion of the steel bars[3]. Repairs and maintenance still constitute a big burden on the whole-life cost of concrete structures [4].

One approach that has been developed to reduce the size of (or even fully close) the cracks, is to include novel shape memory polymers (SMP) tendons within the concrete structures. A very promising SMP material chosen is pre-oriented polyethylene terephthalate (PET)[5].

Polyethylene terephthalate (PET) is a thermoresponsive shape memory polymer. During production, the polymer is subjected to a drawing process at an elevated temperature, aligning and stretching 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[5][6]. Upon activation, these SMP tendons apply a compressive force to close the cracks and in turn promote autogenous healing and increase the durability of concrete structures. Initial work employed the direct shrinkage capability of the PET but, despite initial success, the stresses generated were relatively limited [6].

This work presents the results from a preliminary study on a new hybrid tendon system, which had the aim of increasing the crack-closure stress. The new hybrid system consists of two elements: the first is an outer cylinder made of pre-drawn PET; the second consists of a pre-stressed element that forms the core of the hybrid tendon. The pre-stressed core is restrained by the outer PET cylinder until the latter is activated, at which point the pre-load in the core and the shrinkage potential of the cylinder are released such that they apply a compressive crack-closure force to the structural element in which they are embedded.

The preliminary results show an increase of stress generation which significantly enhances the crack-closure capability.

2 GENERAL CONCEPT

Jefferson et al. (2010) introduced a crack-closure system for cementitious materials using shrinkable polymers. The system consisted of tendons made of PET. The tendons were anchored at discrete points such that they were restrained within a structural element. Upon activation, via heating, a restrained shrinkage stress is generated, which in turn imparts a compressive force to the matrix and thereby closes any open cracks. Autogenous healing then occurs and is enhanced by the cracks being put into this compressive state [7].

Although very promising preliminary results were obtained, the stress developed by the tendons upon activation remained limited, i.e. few tens of MPa [5].

This work aims to enhance the stress developed by the tendons by combining the shape memory effect of the PET together with a second pre-stressed element. Figure 1 shows the concept of the novel crack-closure system designed for the purpose of this study.

The tendon has two main components: an inner core (initially in tension) and a PET "sleeve" (initially in compression).

The first stage consisted in the pre-tensioning of the tension element (Figure 1a) which is tensioned elastically. Once the inner core reached the desired pre- stress T, then the whole system was "sealed". At this point the external force was released on the inner core when the system has returned to equilibrium. The PET sleeve is now in compression. (Figure 1b).

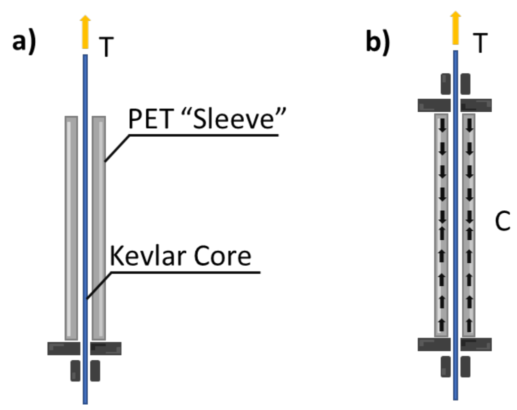

Figure 1. General concept of the hybrid tendon.

The system, now in equilibrium, is embedded in the structural element.

The hybrid tendon is activated when cracking occurs (Figure 2a). Upon activation, the sleeve shrinks and releases the force stored in the inner core (Figure 2b).

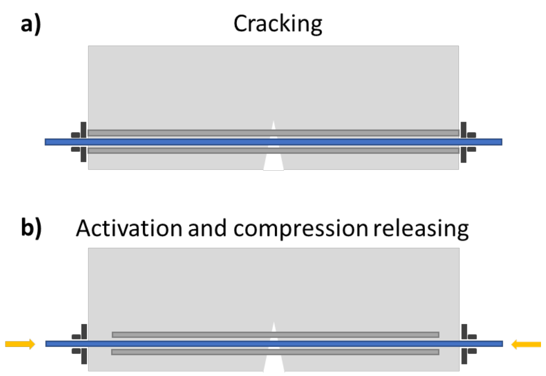

Figure 2 Activation of the hybrid tendon and its effect of the cracked beam.

3 MATERIALS

3.1 PET "sleeve"

Figure 3 shows the typical cross section of the hybrid tendon. The geometrical properties of the PET sleeve are reported in Table 1.

The activation temperature for the PET chosen for this preliminary study is about 100° C, reaching the maximum shrinkage between 120-130° C.

The length of each sleeve is 255 mm. Figure 3 shows the typical cross section of the tendon.

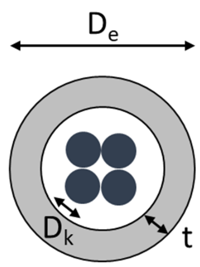

Figure 3 Hybrid tendon cross section

The external Diameter D_e and the wall thickness of the sleeve shown in Figure 3 are reported in Table 1.

Table 1: Tendon's geometry.

D_e	t	D_k
mm	*mm*	*mm*
8.6	1.5	2.4

By way of an indication, Figure 4 shows the potential behaviour of the PET once activated. Six 50mm length PET tubes were activated by placing them in an oven at 130 °C. The length recovery is certainly considerable (i.e. 8-15 %).

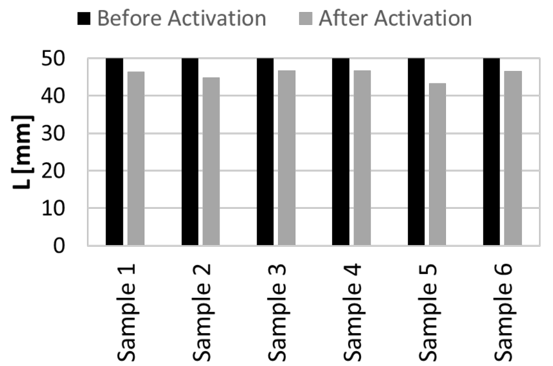

Figure 4 Comparison of length of six PET samples before and after the activation.

The mechanical properties of the PET sleeve are reported in Table 2

Table 2: PET mechanical properties.

Tensile Strength	Young Modulus	Density
MPa	*MPa*	*kg/m³*
100	6000	1380

3.2 Kevlar inner core

The core of the tendons was made by combining 4 Kevlar ropes with nominal diameter D_k of 2.3mm as reported in Table 1.

The mechanical properties of the Kevlar rope are reported in Table 3.

Table 3: Kevlar rope mechanical properties.

Tensile Strength	Young Modulus	Density
MPa	*MPa*	*kg/m³*
600	5-7 x10^3	1440

The ropes were inserted in the PET sleeve and then mounted on a load cell. The Kevlar inner core was then pre-stressed and clamped using stop-cable fittings, which are commercially available. The core was then stressed in order to achieve a prestress of 700 N stored in each tendon.

4 LABORATORY EXPERIMENTS

4.1 Preparation of the specimens

For the purpose of this preliminary study, mortar beams with dimensions 75x75x255mm were tested. Figure 5 shows the typical cross section of the mortar specimen with the embedded hybrid tendons.

Two tendons were embedded in the mortar beam at a distance *c* from the bottom and the lateral side of the beam.

The geometrical properties of the cross section are reported in Table 4.

Table 4 Geometry of the hybrid tendon's cross section.

b	h	c
mm	*mm*	*mm*
75	75	17

The mortar paste was prepared at a water to cement ratio of 0.6. After the tendons were positioned in the wooden mould, the mortar paste was poured in three layers. A small vibration was imposed between a layer and the other in order to facilitate the compaction of the mortar.

As previously described, each tendon would store a pre-stress of 700N for a total of 1400 N for each mortar beam.

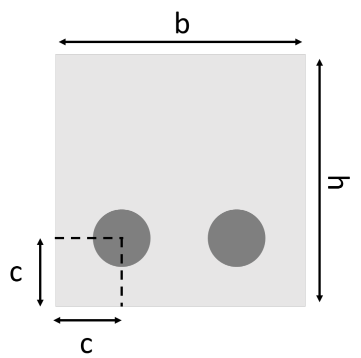

Figure 5 Cross section of the mortar beam with embedded hybrid tendons.

After 24 hours the mortar beam was then removed from the mould and covered in wet hessian and wrapped in cling film. The specimen was cured for 7 days.

4.3 Testing

After curing, the specimen was tested in three-point bending. Prior the test, the specimen was notched in order to accommodate the knife edge plates glued to the underside of the beam. A light weight clip gauge was located between the plates to monitor the Crack Mouth Opening Displacement (CMOD) during the experiment. The load was controlled via feedback from a machine stroke displacement transducer which allows the softening behaviour to be captured.

Figure 6 shows the Force-CMOD graph recorded during the test. This shows that the specimen exhibited a quasi-linear behaviour until a peak (which corresponds to the point where the mortar began cracking), after which the load decayed with increasing deformation.

The test was stopped at a CMOD value of 0.4 mm. The aim was to induce a considerable damage in the specimen in order to test the reliability of the hybrid tendons as crack-closure system.

At this point, the specimen was unloaded. It is worth noticing that the CMOD showed a non-zero value when the load was completely removed. This is due to the nonlinear behaviour of the fractured mortar [8]. For this reason, the complete closure of the crack must be forced by applying a compressive load.

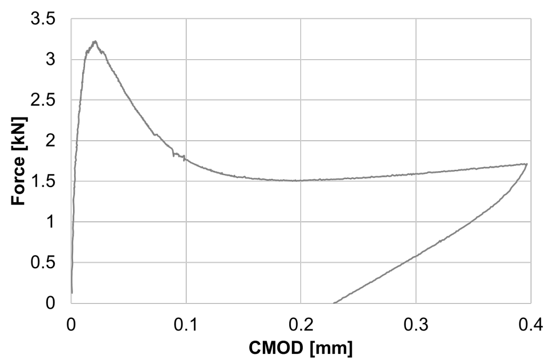

Figure 6 Force-CMOD diagram recorded during the 3-point bending test for the mortar specimen.

After the test, the crack in the specimen was measured. The beam was, then, placed in the oven at a temperature of 130° C for 45 mins. After the tendon was activated, the crack width was measured again in order to evaluate if the stress stored in the tendons was released hence reducing the crack width.

4.4 Results

The crack width before and after the activation was measured by combining a magnifying camera together with a CAD software. Figure 7 shows the comparison between the crack aperture before and after the polymer activation.

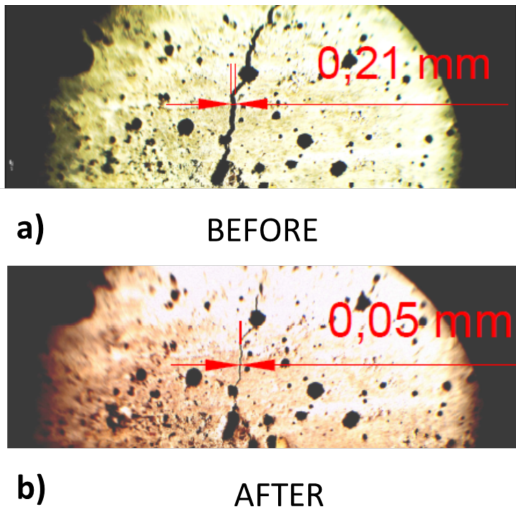

Figure 7 Measurement of the crack width before and after the activation of the hybrid tendons.

It is evident that the stress stored in the tendons was successfully released, once the polymer was activated in the oven. Crack closure was about 24%, which is a very encouraging result.

5 CONCLUSION

This paper presented the design of an innovative crack closure system. The system was developed by combining the shape memory properties of the Polyethylene Terephthalate (PET) with a pre-stressed Kevlar rope. The idea was to produce a hybrid tendon capable to store a pre-stress and then release it when needed by activating the SMP.

The results of the preliminary experimental tests showed that the pre-stress stored in the tendons was successfully released to the mortar beam. Furthermore, the internal Kevlar core provides reliable post-activation reinforcement.

The study is, however, still at its initial stage but research on this hybrid system is on-going.

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