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FUTURE ENGINEERING

Effective Concrete Crack Closure Through Innovative Hybrid PET Tendons

The article delves into the enduring challenge of cracking in concrete structures, examining innovative solutions, with particular emphasis on the development and assessment of a novel Tendon (the Side PET Hybrid Tendon (SPHT)). Traditional approaches to crack closure often prove inadequate in terms of both effectiveness and cost efficiency. Through the fusion of Kevlar®, PET, and Kanthal wire, the SPHT exhibits promising abilities in effectively sealing cracks. Laboratory trials showed significant reductions in crack sizes when the tendons were activated, achieving reductions of 60% to 80%. This underscores their potential to greatly enhance the durability of concrete structures. The SPHT presents a feasible remedy for addressing cracking in concrete structures, offering a pathway towards enhanced longevity and diminished maintenance requirements.

Keywords:
Self-healing, crack closure, durability, concrete, shape memory polymer.

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S. Sharifi, V. Novelli, B. Balzano, and S. Pinto, 'Effective Concrete Crack Closure Through Innovative Hybrid PET Tendons', *Proceedings of the Cardiff University School of Engineering Research Conference 2024*, Cardiff, UK, 2024, pp. 47-51.

doi.org/10.18573/conf3.l

INTRODUCTION

Cracking stands as a significant factor in the degradation of concrete, enabling the infiltration of chemicals and potentially resulting in the deterioration of the physical, mechanical, and enduring qualities of concrete constructions [1]. With heightened expectations for extended service life, the persistence of cracks continues to pose a challenge, as they significantly reduce the lifespan of concrete structures [2]. In addressing the issue of cracking in concrete, self-healing technologies emerge as an innovative and promising solution. These advancements hold the potential to enhance the durability and lifespan of infrastructure [3].

Numerous researchers have extensively investigated self-healing concrete, contributing to various aspects and potential applications [4]. These methods primarily include vascular self-healing [5], capsule-based self-healing [6], microbiological self-healing [3], electrodeposition self-healing [7], self-healing via shape memory Materials [8].

One highly effective approach involves employing shape memory materials. These materials demonstrated their capability to seal cracks through the force generated by their shrinkage following activation. Although certain types of shape memory materials, like Shape Memory Alloy (SMA), have displayed a notable capacity to close cracks [9], some researchers have directed their attention to Shape Memory Polymer (SMP) due to the comparatively high cost of SMA materials [10][11].

Among the most promising types of SMP is polyethylene terephthalate (PET), which has demonstrated its capability to seal cracks in plain concrete elements [12]. However, its effectiveness was limited in reinforced concrete and heavy structures due to the relatively low strength of shrinkage [13].

Some researchers have sought to enhance the crack-closing capabilities of PET by incorporating them into prestressed tendons. This approach aims to store prestressed force within the tendons, in this manner enhancing their effectiveness in sealing cracks [10]. Despite efforts, the force stored in the tendons has remained insufficient, highlighting the necessity to enhance their capacity for storing prestressed force. Furthermore, the utilization of PET throughout the entire length of the tendons leads to increased costs, coupled with a significant demand for energy to activate them. It's crucial to highlight that based on the tendons structure, substantial energy is wasted due to inefficient activation methods like oven placement or direct contact with concrete[10] . This not only escalates energy consumption but also poses a risk of harming the concrete structure.

To overcome these disadvantages and limitations, this research explores enhancing the crack closure method used in PET tendons by introducing the Side PET Hybrid Tendon (SPHT). The SPHT consists of an inner core made from Kevlar (a type of aramid fibre) and a piece of PET tube on one side, serving as the sealer. During the manufacturing process, the inner core of a tendon is put into tension and the outer sleeve into compression, such that the tendon is in equilibrium. A Kanthal wire thermal coil has been utilised to supply the necessary heat for activating the tendons after cracking. This coil is embedded within the sealer, ensuring it stays insulated from direct contact with the concrete.

GENERAL CONCEPT

The SPHT tendon consists of inner and outer steel tubes sliding on each other. Inside these tubes, there is a pre-drawn PET tube contain a coil of Kanthal wire (26AWG) acting as a heating generator or activator,. Additionally, it features a pre-stressed core composed of Kevlar® rope, which will be sealed by clamps. The Kevlar® has relatively high strength and low modulus. High strength is necessary for prestressing and reinforcement purposes as it ensures the structural integrity to the tendon, while a low modulus helps minimise prestress losses caused by creep and shrinkage in the mortar or concrete [10]. The components of the tendon are depicted in Fig. 1.

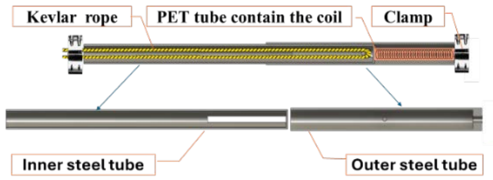

Fig. 1. The components of the tendon.

The pre-stressed core remains constrained by the PET tube until activation occurs. Upon activation, the tension stored within the tendon is released, applying a compressive force on the structure element. This force effectively closes any cracks that develop perpendicular to the axis of the tendon.

The initial phase of manufacturing involves pre-tensioning the inner rob and applying an initial elastic stress. Once the inner cable reaches the desired pre-stress level, the entire system is secured using a commercially available wire clamp. The principle behind the tendon design is shown in Fig. 2.

The tendon will be embedded into the concrete structural element (Fig.3a). Upon the appearance of cracks, the SPHT is activated through heat generated by the coil. This results in the shrinking of PET, thereby releasing the tensile force stored in the Kevlar. Following this, the tendons exert a compressive force on the concrete element through their clamps (Fig.3b). The inclusion of post-tensioning in the beam, combined with the use of stainless steel (304) as inner and outer tube in the tendons, enables both pre- and post-activation unbonded reinforcement. This capability presents the possibility of completely substituting conventional reinforcement within the system.

Fig. 2. Distribution load and image of the tendon.

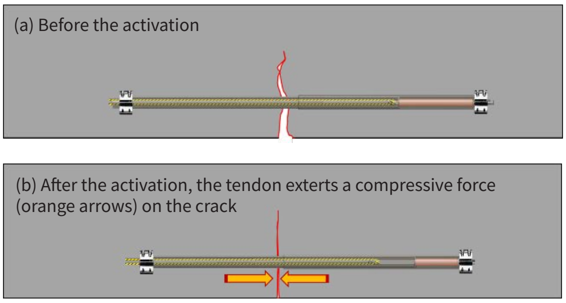

Fig. 3. The concept of crack closure by the tendons.

MATERIALS AND TENDON MANUFACTURE

Concrete mix
The concrete mix comprised Portland cement CEM II A/L 32.5 R (CAS number 65997–15-1), sand (CAS number 14808–100 60–7), 10mm aggregates, and tap water. Cement, sand, and aggregates were mixed in a mass ratio of 1:1.55:2.1, with a w/c ratio of 0.55 by mass. After demoulding (24 hours after casting), the specimens were promptly covered with damp hessian for 6 days following the guidelines of BS EN 12390–2:2019. The choice to use wet hessian instead of a water tank was influenced by safety concerns related to the electrical aspects of the experiment.

The compressive strength exhibited a mean value of 31 MPa with a coefficient of variation of 0.3, whereas the tensile splitting strength showed a mean value of 2.5 MPa with a coefficient of variation of 0.13.

Kevlar® core robe
Kevlar®, an organic fibre categorised within the aramid family, exhibits notable tensile strength. Table 1 provides details on the mechanical properties of the Kevlar that utilised in this investigation.

Tensile Strength MPa	**Young Modulus** MPa	**Density** kg/m3
600	5-7 ×103	1440

Table 1. The mechanical properties of the Kevlar.

Steel tubes
The steel tubes come in two sizes: 16 mm and a 12 mm with a slug, allowing them to slide over each other. The geometric characteristics of the tubes are depicted in Fig. 4.

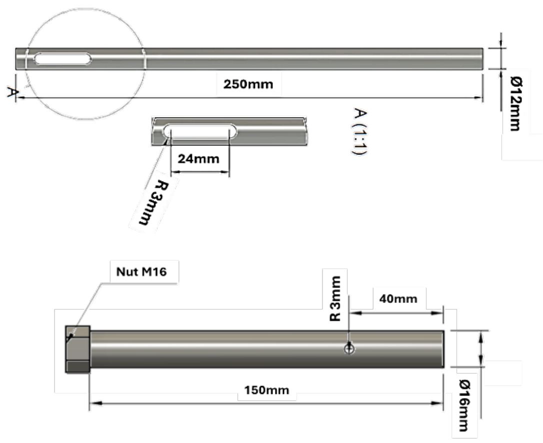

Fig.4. The geometrical properties of the tendon.

PET tubes and coil
The PET tube has a diameter of 10 mm and a length of 80 mm. It houses a Kanthal coil with a length of 60 mm and a coil spacing of 0.2 mm (Fig.5). When an electric current is applied to the coil, it generates heat, activating the PET and causing the tube to shrink.

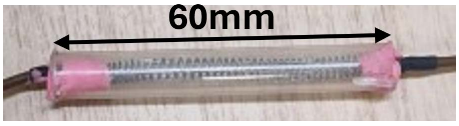

Fig.5. The PET tube and the coil inside it.

The tendons are each 400 mm in length and were cast in pairs at a height of 15 mm from the bottom of the beam. Each tendon stores a force of 2500 N.

LABORATORY EXPERIMENTS

Experiment set up
The tendons' performance was evaluated by embedding them in beams with tendons, along with a control beam (without tendons), all measuring 500x10x10mm. Additionally, four cubes and four cylinders were cast to assess the mix strength. Following curing, notches (0.3 mm wide and 0.5 mm deep) were created in the beams to induce crack formation. Subsequently, the beams were loaded in three-point bending, resulting in the formation of cracks around 0.12 mm wide. Following this, the coils were energised for a period of 1 minute using a power supply providing a voltage of 10 volts and a current of 5 amperes. This resulted in an energy consumption of 3000 joules (calculated as Energy=Power × Time=10 V×5 A×60s). This activation process aimed to generate the necessary heat to activate the PET tubes, as depicted in Fig.6.

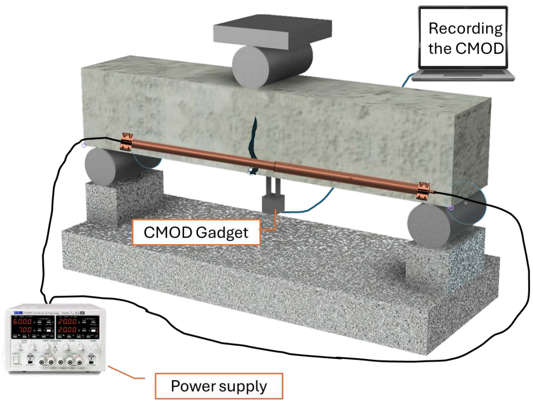

Fig.6. The set up of the experiment.

The size of the crack was continuously monitored using a Crack Mouth Opening Displacement (CMOD) gadget. Additionally, the cracks were photographed both before and after activation using a digital microscope.

RESULTS AND DISCUSSION

Unfortunately, one of the beams did not crack from the notch during formation, rendering the CMOD device unable to measure the crack size and amount of crack closure. Fig.7 illustrates the force-CMOD responses of the test for other two beams. The initial peak in the response signifies the emergence of the first visible crack on the material. Prior to reaching this peak load, the material exhibits a nearly linear behaviour, where increased force leads to a proportional increase in crack opening. Once the max peak load is reached, the force exerted on the material diminishes rapidly. However, in samples containing tendons, the force begins to rise again until a specific limit of crack opening is attained. This phenomenon suggests that the tendons are functioning as unbonded reinforcement.

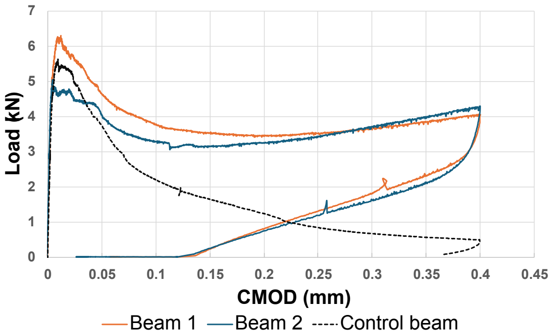

Fig. 7. The force-CMOD diagram.

It occurs due to the tendons generating a hogging moment that counters the sagging moment (bending downwards) applied to the specimens. These opposing forces induced by the tendons cause the overall applied load on the specimen to ascend again following the initial post-peak decline. Once the desired CMOD was achieved, the beams were unloaded, resulting in a reduction in CMOD size. This reduction may be attributed to aggregate interlocking and closure of microcracks [10].

The tendons were activated, and as designed, they successfully reduced crack sizes in beams 1and 2. The crack reduction achieved was 60% for beam 1 and 80% for beam 2 (Fig.7 and 8). These reductions resulted in final CMOD values that are well below the level for significant autogenous (natural) healing to be necessary in the beams.

CONCLUSIONS

In conclusion, the development and evaluation of the SPHT represent a significant advancement in the quest to address cracking in concrete structures. Through a meticulous combination of materials and design, this innovative tendon demonstrates promising capabilities in effectively sealing cracks and enhancing the durability of concrete elements. However one of the beams was lost, the experiment has shown impressive results, with significant reductions in crack sizes achieved upon activation of the tendons. These findings not only underscore the efficacy of the SPHT but also offer potential for its widespread adoption in concrete construction, where durability and longevity are paramount concerns.

Further study could involve the development of tendons capable of storing higher force and transitioning to the ability to use a single tendon instead of a pair.

Conflicts of Interest
The authors declare no conflict of interest.

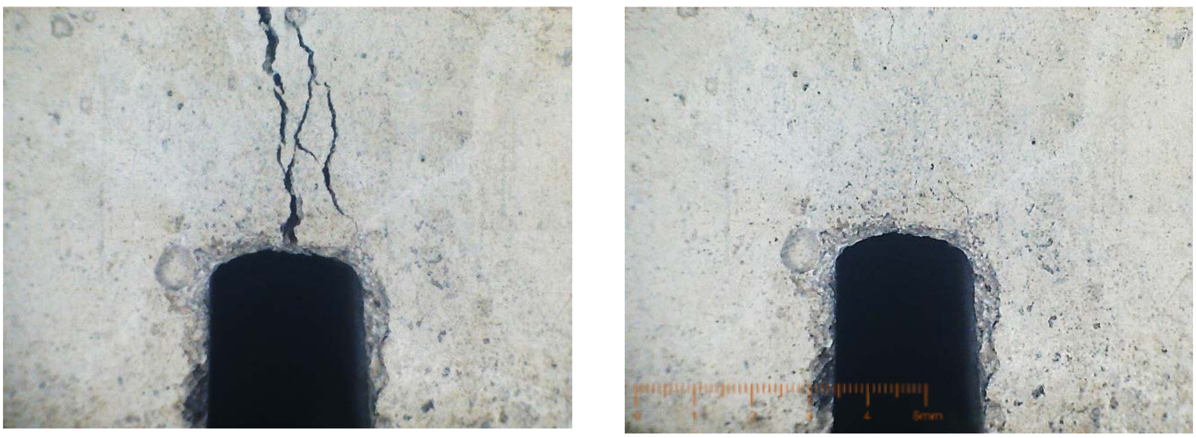

Fig. 8. The crack before (left) and after (right) the activation of the tendons.

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Cynhadledd Ymchwil Peirianneg Caerdydd
Cardiff Engineering Research Conference

E. Spezi and M. Bray (eds.) 2024. *Proceedings of the Cardiff University School of Engineering Research Conference 2024.* Cardiff: Cardiff University Press.
doi.org/10.18573/conf3

Cardiff University School of Engineering Research Conference 2024 was held from 12 to 14 June 2024 at Cardiff University.

The work presented in these proceedings has been peer reviewed and approved by the conference organisers and associated scientific committee to ensure high academic standards have been met.

Cardiff University Press | Gwasg Prifysgol Caerdydd

First published 2024

Cardiff University Press
Cardiff University, Trevithick Library
First Floor, Trevithick Building, Newport Road
Cardiff CF24 3AA

cardiffuniversitypress.org

Editorial design and layout by
Academic Visual Communication

ISBN: 978-1-9116-5351-6 (PDF)