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Case study

Microwave self-healing technology as airfield porous asphalt friction course repair and maintenance system

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ABSTRACT

A problem increasingly faced by airport authorities is the maintenance of runways. Due to their large aircraft loadings associated with take-off and landing operations, runways experience surface deterioration. Poor quality runway surfaces cannot be tolerated in such an environment. Maintenance issues must be carried out to maximise safety and minimise the risk of aircraft damage. A recent development has been the introduction of self-healing technologies such as rejuvenator encapsulation, induction and microwave heating to address these issues. This paper summarises a laboratory investigation to determine the effectiveness of microwave self-healing for crack repair of Porous Friction Course (PFC) used for airfields. Four mixtures containing varying percentages of conductive steel fibre were tested. Their relative performance was assessed using the Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS) test methods. The results show that the addition of conductive steel fibre increases initial stiffness and strength of the mix. A combination of micro-wave heating and steel fibre addition to the mix indicates that it is possible to significantly improve asphalt performance by making it self-healing to structural problems such as cracking.

1. Introduction

The two most important materials used in the construction of runway surfaces around the world are either cement or asphalt based. The EAPA [1] reported that out of 126 runways surveyed, 58 were constructed with asphalt, 37 were constructed using concrete and 31 constructed using some other material. Irrespective of the construction method employed, runways need to be constructed with sufficient strength to carry the moving aircraft. Their runways must have adequate wet skid resistance in view of the very high speeds involved. Poor wet skid resistance is a common problem for aged concrete runways. One way of maintaining or renewing operational wet skid resistance in these instances is to overlay the old runway surface with a new porous open-graded surface course known as porous asphalt or friction course (EAPA, 2003). The porous material acts as a drainage layer to reduce surface water adversely affecting aircraft tyre grip on the surfacing in wet weather. However, the high air voids content of these porous asphalt materials i.e. typically around 20%,

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allow water and air to penetrate into the surface course layer. This can accelerate ageing leading to rapid hardening, reduced flexibility and ultimately to aggregate loss and fretting [2].

Self-healing technology [3] offers an alternative method for asphalt airfield runway maintenance. Three main methods have been developed. Rejuvenation is an encapsulated healing agent in the form of a capsule that is added into the asphalt mix during production to restore the original binder properties [4–10]. When micro cracks are initiated within the asphalt layer, they encounter a capsule in the crack propagation path. The fracture energy at the tip of the crack opens the capsule, releasing the healing agent which then diffuses within the asphalt binder to seal the micro crack. It has been reported that rejuvenation may take approximately 20 h [9]. Induction heating and microwave heating involve the addition of electrically conductive fillers such as steel fibres or steel wool to the asphalt mix [3,11–17] during production. Induction heating creates an alternating current which flows through a coil and produces an invisible electromagnetic field around the coil. When this electromagnetic field is induced over a conductive asphalt pavement, it causes the steel fibres within the asphalt mix to heat up. This heats the aged bitumen and softens it, allowing it to flow and repair the micro crack damage. Microwave heating creates high energy wavelengths which react with the conductive fibres in the asphalt. This causes the fibres to heat up which then heats the aged bitumen and softens it, allowing it to flow and repair the micro crack damage. Laboratory studies have shown both methods can repair test specimen damage within 3 min for induction [18,19] and microwave [15,20] heating. The microwave method requires less conductive fibres to achieve the required temperature to heal the damage.

The study reported in this paper investigates the effectiveness of microwave self-healing for the crack repair of Porous Friction Course mixes that would typically be used for airfields. Four mixtures containing varying percentages of conductive steel fibre were evaluated using a testing programme that cracked the test specimens, healed these cracks and evaluated this process using the Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS) test methods. The results showed that conductive steel fibres increase initial stiffness and strength of the mix. The addition of steel fibres significantly improved asphalt healing performance. The results found that Porous Friction Course containing 5% steel fibres outperformed the control mix without fibres and all of the mixtures containing higher contents of the fibre.

2. Materials

2.1. Porous Friction Course mix

The Porous Friction Course (PFC) mix was prepared in accordance with MOD Specification 040. The aggregate was a high skid resistance Silurian greywacke from Northern Ireland. The filler was a combination of crushed Carboniferous limestone filler and hydrated lime to BS EN 459-1. The bitumen was a 160/220 pen as specified by MOD 040. Fig. 1 shows the mix grading curve.

Table 1 summarises the PFC mix constituents and shows their proportions in the mix, both with and without steel fibres. The fibres were added in an amount of 5%, 10% and 15%. Gonźalez et al [21] had demonstrated that 5% is an optimum fibre content within any type of asphalt mix for microwave healing process. Liu [22] had showed that the optimum content of conductive fibre for induction healing of an Porous asphalt mix is 10%. The aggregate grading was kept constant. The addition of steel fibres was used to replace by mass part of the bitumen content.

2.2. Steel fibres

The steel fibre used was Grade 3 coarse-grained Trollull Steel Wool. Fig. 2 illustrates the steel wool fibre used. The fibre diameter was 90 μm. The fibres were cut using scissors to approximately 10 mm in length.

The mixing procedure was amended to avoid conglomeration of steel fibres within the PFC mix. The coarse aggregate, sand, filler, lime and bitumen were mixed first. The steel fibres were then added slowly to the mix. This increased the asphalt mixing period causing the mix to start cooling and reduced its workability. The PFC mix had to be reheated several times to 160 °C. The final mixing of the PFC was performed by hand to ensure that all of the mix constituents were fully and evenly coated by the bitumen.

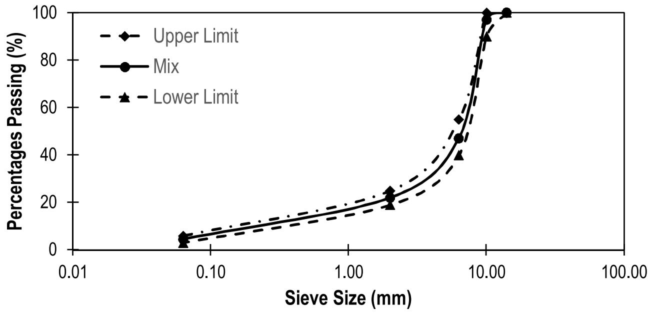

Fig. 1. PFC mix grading.

Table 1
PFC mix composition.

Mix Constituent (mm)	Control	5% Steel fibre	10% Steel fibre	15% Steel fibre
14 to 10	3.0%	3.0%	3.0%	3.0%
10 to 6.3	50.0%	50.0%	50.0%	50.0%
6.3 to 2.0	25.0%	25.0%	25.0%	25.0%
2.0 to 0.063	17.5%	17.5%	17.5%	17.5%
Filler	2.5%	2.5%	2.5%	2.5%
Hydrated lime	2.0%	2.0%	2.0%	2.0%
Bitumen (160/220)	5.5%	5.22%	4.95%	4.67%
Steel fibre	0.0%	0.275%	0.55%	0.825%

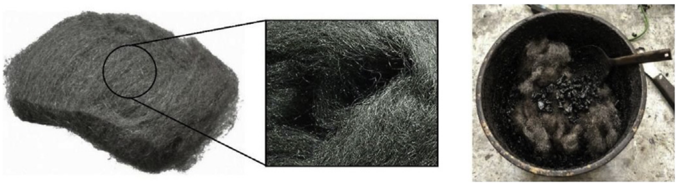

Fig. 2. Trollull Grade 3 steel wool.

2.3. Test specimen compaction

The test specimens were compacted in accordance with IS EN 12697-31:2007 using a SERVOPAC gyratory compactor. Each test specimen got 100 gyrations. They were 100 mm in diameter and approximately 80 mm in thickness. The target air void content was 16% based on a maximum density of 2263 kg/m ^{3}. In total 16 cylindrical specimens, 4 test specimens per mix, were produced per PFC mix. The specimens were cut to 50 mm thickness using a masonry cutting saw for testing.

3. Testing methodology

3.1. PFC Binder Drainage test

The binder drainage test was carried out in accordance with EN12697-18 using the Schellenberg Method. A sample of mixed PFC material was placed in the glass jar and kept at 160 °C for 1 h. Following this the contents of the jar were emptied out and the jar reweighed to calculate the amount of binder left adhered to the insides of the glass jar.

3.2. Indirect Tensile Stiffness Modulus test

The non-destructive Indirect Tensile Stiffness Modulus (ITSM) test was conducted in accordance with EN 12697-26: 2012. This used a Cooper Servo-pneumatic Universal Testing Machine with a pneumatic close loop control system. The specimens were conditioned at 10°C for four hours prior to testing. Two Linear Variable Differential Transformers (LVDT) were used to measure the horizontal deformation. The stiffness value was recorded on two diameters orientated at 90°to each other and an average of these two values reported as the specimen stiffness.

3.3. Indirect Tensile Strength test

The Indirect Tensile Strength (ITS) test was conducted in accordance with EN 12697-23: 2003. This used a Marshall / Indirect Tensile Compression tester. After ITSM testing, the specimens were conditioned in a temperature control chamber at −5 °C for 1 h. The ITS test applies a vertical compressive strip load at a constant loading rate, in this case 50 mm/s, to the cylindrical specimen. The load is distributed over the thickness of the specimen through two loading strips at the top and bottom of the test specimen. The tests were conducted at −5 °C to ensure crack initiation and propagation along the test specimen central loading line. The specimens were loaded until the load value had fallen back to zero or the specimen had fully split into two. Use of the ITS test created two halves of a test specimen that could then be recombined and subjected to micro-wave heating.

3.4. Healing efficiency of PFC mix containing steel fibres

A testing programme was designed to investigate the effect of the conductive steel fibres on the mechanical properties of the PFC mix and evaluate the healing efficiency of the microwave healing system. The programme is as follows:

1 Specimens are first tested for non-destructive ITSM at 10 °C and destructive ITS at −5 °C.
2 After completion of the ITS testing the two halves of the test specimen are recombined. It is then placed into a specially designed cylindrical plastic collar with 100 mm internal diameter and conditioned for 1 h at an ambient temperature of 20 ± 3 °C.
3 The cplastic collar and recombined cracked specimen is then placed in a micro-wave oven and heated for 3 min using the Defrost setting at 300 W.
4 The plastic collar is removed and the specimen is left undisturbed to cool to room temperature 20 ± 3 °C during which the healing process takes place.
5 This testing and healing procedure is repeated twice.

Fig. 3 illustrates the main elements of the test programme. The microwave oven used was a Tesco Solo, Model No: MM08 with 700 W power output. The defrost setting of 300 W for 3 min was found to be the optimum healing condition for the PFC mix. Some sparks were visible during the first healing cycle probably caused by some of the fibres not being fully coated with bitumen. No sparks were observed for the second healing cycle. This is different to that found in literature where the test specimens are healed by heating for 40 s on the highest microwave power setting of 600 W. The study summarised in this paper observed that at this laboratory microwave setting intense sparks and smoke were emitted as the healing began. Subsequent attempts to reduce power had little effect on the samples.

3.5. Thermal imaging

Thermal imaging was carried out to observe heat distribution throughout the test sample due to the microwave based healing process. This used a Micro Epsilon ThermoIMAGER TIM 400. Recording began immediately after the plastic collar was removed from the micro-wave heated specimen. Fig. 4 shows a thermal image of a test specimen 60 s after microwave healing. The image shows temperature distribution across the surface of the test specimen. The average temperature is 61.8 °C ranging from 56 °C at the edges of the test specimen to 66 °C at its centre. Fig. 4 shows that this elevated temperature is relatively evenly distributed across the surface suggesting good steel fibre distribution throughout test specimen and in turn good asphalt mix healing.

4. Results

4.1. PFC Binder Drainage

The principle behind the Binder Drainage test is to quantify the amount of material lost by drainage i.e. material that has adhered to the truck or mixer at the plant. Therefore, it is important to verify what effect the addition of steel fibres would have on Binder Drainage of the PFC mix.

$$\text{The equation used for Binder Drainage } BD = 100 \times \frac{[W5 - W3 - W6]}{[W4 - W3]} \tag{2}$$

Where: BD = the Drained material (%); W_3 = mass of the empty beaker (g); W_4 = mass of the beaker plus batch (g); W_5 = mass of the beaker plus retained material after upturning (g); W_6 = mass of the dried residue retained on the sieve (g)."

The Binder Drainage results are shown in Table 2. The results show that the addition of steel fibres to the PFC mix in concentrations of up to 15% by weight of the bitumen has no / negligible effect on the bitumen and its Binder Drainage.

4.2. PFC mix stiffness

Fig. 5 plots the ITSM test data. This shows a significant improvement in ITSM between the control PFC mix containing no steel fibres and the PFC mix containing 5% steel fibres. The addition of 10% and 15% steel fibres caused a reduction on ITSM values compared to the 5% PFC mixes.

Fig. 6 plots the average ITSM data for the initial testing and then after 2 rehealing periods simulating 2 periods of simulated crack treatment. This shows a gradual linear stiffness decrease for the control mix with a significant

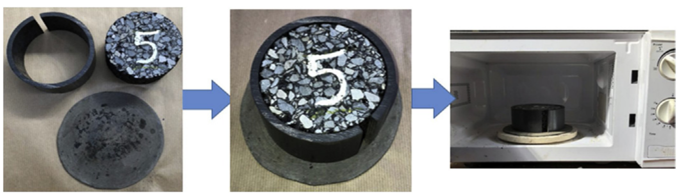

Fig. 3. Microwave healing test system set up.

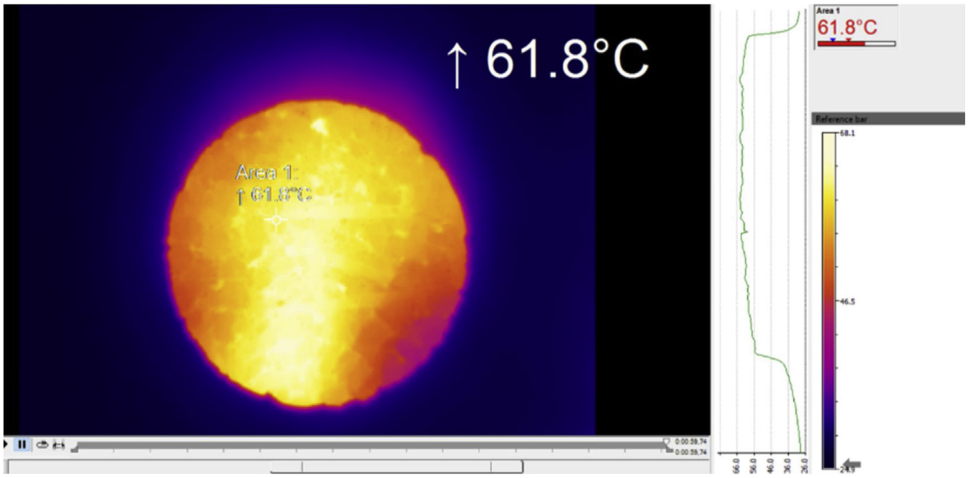

Fig. 4. Example PFC test specimen thermal image 60 s after removal from microwave.

Table 2
Binder Drainage Results.

Mixture	Target Test Temperature (°C)	Actual Temperature (°C)	Average Binder Drainage (%)
Control	160	160	0.1
5% Steel fibre	160	160	0.1
10% Steel fibre	160	159	0.1
15% Steel fibre	160	159	0.1

deterioration in stiffness given by an ISTM ratio of 0.58. The results show that the control samples with no steel fibre have no stiffness recovery. The PFC mixes containing steel fibres show better initial ITSM compared to the control. As the specimens are cracked and healed there is a reduction in stiffness after the first re-healing cycle. The data shows the ITSM to either remain the same or to slightly improve after the second re-healing cycle. After the second re-healing cycle the PFC specimens containing 5% steel fibre have approximately twice the ITSM of the control PFC containing no steel fibre. Whilst this is a simple laboratory investigation the implications of this are significant for maintenance of an airport runway.

4.3. Indirect Tensile Strength

Fig. 7 plots the ITS data. A summary of the average values is given in Table 3. The ITS data show steel fibre addition has a positive effect on ITS. The control PFC group containing no steel fibres had the lowest ITS values throughout testing. The PFC mixes with 5% steel fibres had the best ITS data similar to the ITSM test data. Increasing amounts of steel fibre gave ITS values greater than the control PFC containing no steel fibre. This is due to how the fibres are distributed throughout the mix.

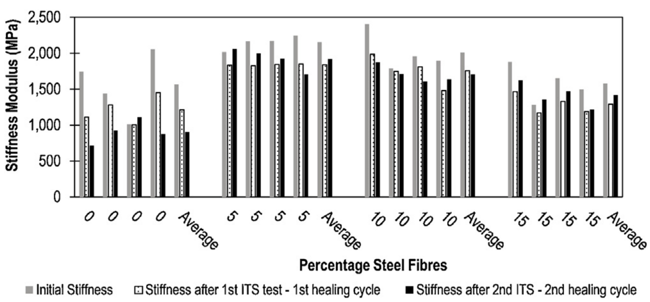

Fig. 5. ITSM data.

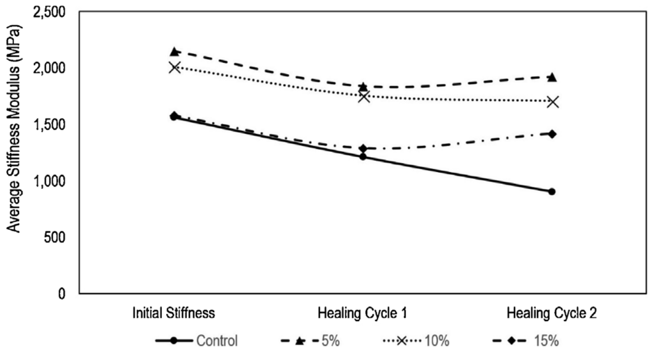

Fig. 6. Averaged ITSM data.

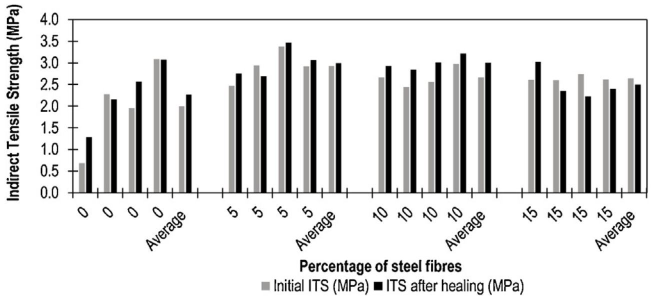

Fig. 7. Average Indirect Tensile Strength before and after healing.

Table 3
Average Indirect Tensile Strength before and after healing.

Steel Fibre Content in PFC Mix (%)	Initial Indirect Tensile Strength (MPa)	Indirect Tensile Strength after healing (MPa)
0	2.00	2.27
5	2.93	3.00
10	2.66	3.03
15	2.64	2.51

4.4. Thermal imaging

Fig. 8 plots the average maximum surface temperature reached immediately after removal from the micro-wave and after 60 s cooling. It shows a strong positive linear correlation between the amount of steel fibres added to the PFC mix and temperature after micro-wave heating with R^2 values of 0.9832 and 0.9524 respectively. For example, after microwave heating PFC specimens with 0% steel fibres reached an average of 55 °C which after 60 s cooling dropped to 45 °C. PFC specimens with 15% fibres reached an average of 81 °C which after 60 s cooling dropped to 73 °C. Fig. 9 illustrates the temperature distribution across the surface of selected PFC specimens 60 s after removal from the microwave. The PFC

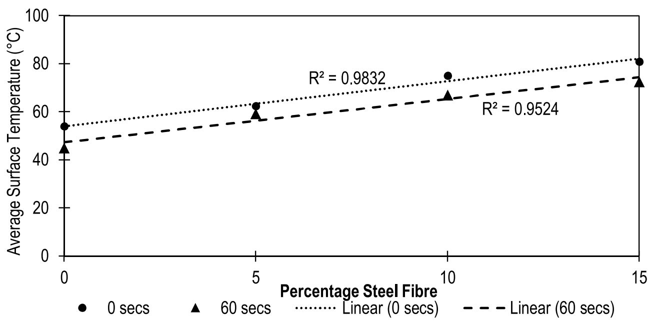

Fig. 8. Average surface temperature vs steel fibre content.

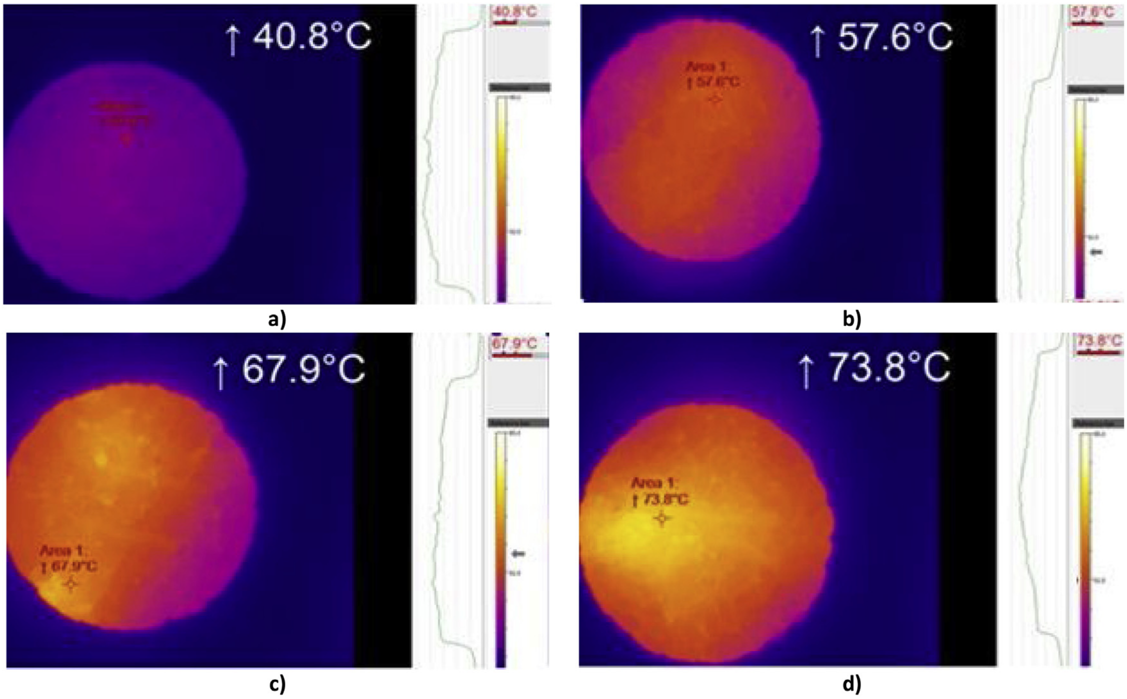

Fig. 9. Thermal images showing maximum surface temperature of PFC specimens containing a) 0%, b) 5%, c) 10% and d) 15% of fibres 60 s of healing.

specimen with no steel fibre is at an average temperature of 40.8 °C. In contrast the PFC with 15% steel fibre is 33 °C hotter. PFC mixes containing steel fibres were found to have better temperature retention, with the 5% mix retaining 95% of its initial temperature after 60 s. 10% and 15% mixes retained 89% and 90% of their initial heat respectively, while the control sample only retained 82% of its initial heat. This heat retention capability is directly attributed to the thermal conductivity of the steel fibres.

4.5. PFC mix microwave healing efficiency

The PFC mix containing 15% fibres did not perform as well as the 5% and 10% PFC mixes. This is probably due to the clustering of steel fibres subsequently superheating the bitumen beyond its flash point.

Fig. 10 shows an example of steel fibre clustering and subsequent steel fibre oxidation in one of the test specimens. The yellow circles show localised areas of bitumen binder damage due to the excessive heating of steel fibre clusters. The red circle depicts an oxidized steel fibre cluster. Larger steel fibre clusters were recorded as having a heat spike of up to 400 °C. Temperatures of this magnitude are above the flash point of the bitumen i.e. approximately 250 °C, and would cause it to instantly vaporize. This is what likely caused the flashes and black fumes that were emitted from the 15% PFC mix during microwave heating. This may have weakened the test specimen structure leading to its poorer test data.

The linear loss in ITSM for the control PFC mixes containing no steel fibre suggest nothing to assist the heating and softening of the bitumen to infill the cracks formed by ITS testing. Consequently, the initial ITS crack and subsequent cracks did not substantially heal during microwave heating i.e. the temperature was not sufficient to be beneficial. This repeated stressing inevitably continued to weaken the PFC mix. This is shown in Fig. 11 which shows PFC specimen #4 containing 0% steel fibres. The image on the left is the test specimen after the second ITS phase. The induced crack is visible. The image on the right shows the crack still to be visible indicating insufficient temperature during healing. The test specimen was heated to 41 °C, as shown in Fig. 9 which is just slightly greater than the bitumen's softening point of 37 °C. Although slightly greater it was not able to sufficiently soften the bitumen to flow and repair the damage closing micro and macrocracks.

The PFC test specimens with 5% steel fibres increased stiffness value after the healing cycles. Fig. 12 shows PFC sample #6 containing 5% steel fibres before and after healing cycle 2. Compared to Fig. 11, the crack is completely healed. The increase in heat has probably reduced binder viscosity allowing it to flow not only into the visible cracks but also into other microcracks within the specimen. This agrees with the major healing mechanism of induction healing being capillary flow [23] and diffusion of the asphalt binder at high temperatures. Fig. 13 shows PFC sample #15 which contains 15% steel fibres. The crack is fully repaired.

Fig. 10. PFC specimen #16 showing localised issues of oxidation and binder damage.

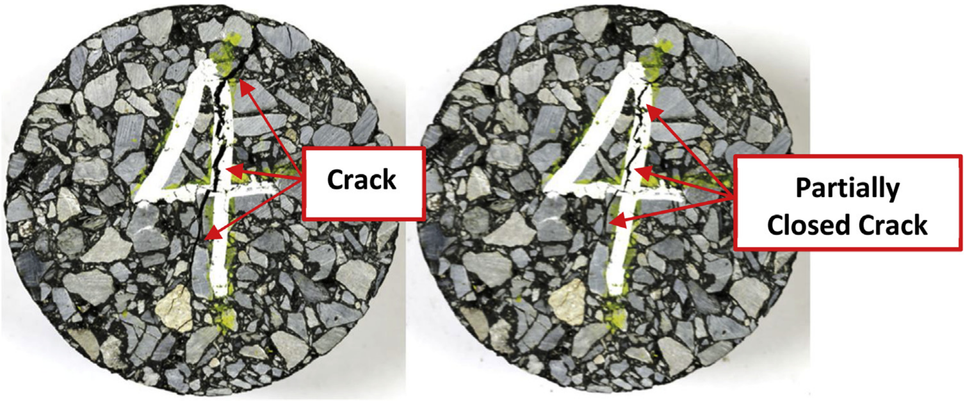

Fig. 11. PFC control specimen #4: Left: before healing and Right: after healing showing partially closed crack.

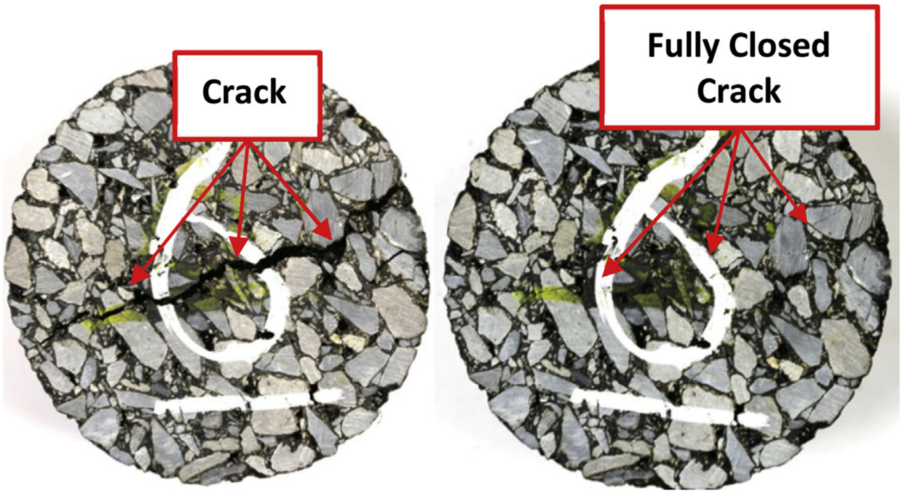

Fig. 12. PFC specimen #6 with 5% steel fibre: Left: before healing and Right: after healing with fully repaired crack.

5. Conclusion

This laboratory study has provided positive evidence that the use of steel fibre and microwave heating is a potential and viable option for airfield asphalt runway repair and maintenance. It has shown that addition of steel fibres and 3 min of microwave healing creates a rapid healing process that offers scope for busy airports faced with real problems of runway closure. PFC mixes containing steel fibres outperformed the control mix with no steel fibres. Even though the PFC mix without steel fibres was able to partially repair its crack damage the mixtures containing fibres managed to achieve full crack closure. The addition of steel fibres reinforced the PFC mix structure improving its stiffness and tensile strength characteristics. Mixtures containing 10% and 15% steel fibres in the mix had lower stiffness and strength recovery after healing in comparison with mixture containing 5% of fibres. This may be due to the clustering of the steel fibre [24] causing high temperate hotspots in the test specimen during the healing process. These localised hotspots may have caused bitumen

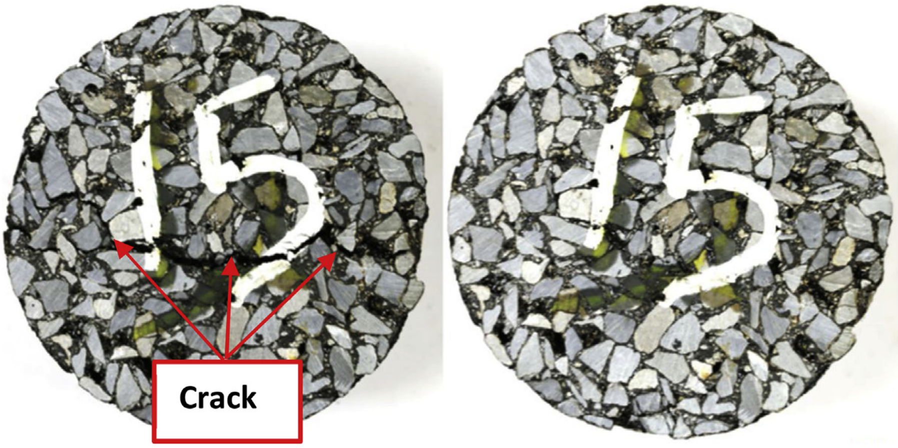

Fig. 13. PFC specimen #15 with 15% steel fibre: Left: before healing and Right: after healing with fully repaired crack.

evaporation thus weakening structural integrity of the test specimen. The laboratory testing concludes that the optimum steel fibre content for the PFC mix is 5% agreeing with previous studies [8,15,21]. It been has found that a lower power heating of 300 W is more suitable for crack healing of the PFC used in this investigation compared to the possible maximum power output of 700 W for the microwave used. This is significant as it shows the importance of this type of laboratory investigation to optimise not only the amount of steel fibre addition but also the amount of energy required to heal cracks in this PFC mix. It may be concluded that this laboratory study clearly shows that the self-healing technology used has significant potential in runway maintenance.

Conflict of interest

The authors declare that there are no conflicts of interst regarding the publication of this paper.

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