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ABSTRACT

This paper studied the induction heating and healing capacity of asphalt mortar by adding electrically conductive additives (e.g. iron powder and steel fibers), and examined the influence of different combinations of them on the mechanical response of asphalt mortars. Induction heating technique is this innovative asphalt pavement maintenance method that is applied to the conductive asphalt concrete mixtures in order to prevent the formation of macro-cracks by increasing locally the temperature of asphalt mixtures. It was found that increasing steel fiber content within the asphalt mortar the tensile strength and the fatigue life increased respectively. It was also proved that the conductive asphalt mortars with iron powder appeared improved mechanical response when steel fibers were added. Furthermore, it was observed that asphalt mortars containing a combination of additives – steel fibers and iron powder - demonstrate a better induction heating efficiency than mortars including only steel fibers. Finally, the induction healing capacity of conductive asphalt mortars is determined.

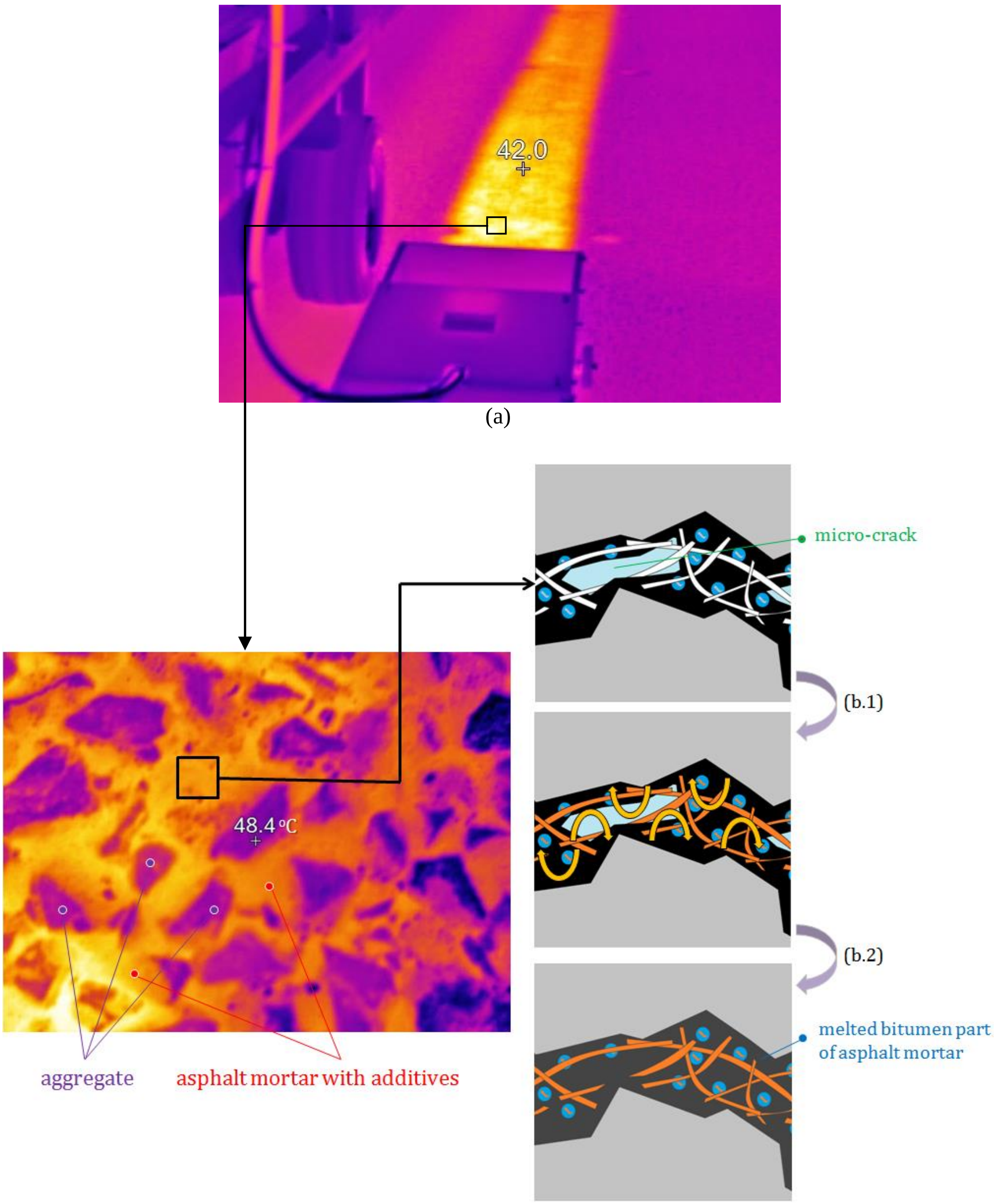
INTRODUCTION

Asphalt concrete mixtures are the most common types of pavement surface materials applied in transportation infrastructures and consist of asphalt binder, aggregate particles and air voids. These mixtures are temperature-dependent materials with self healing capability because they can restore stiffness and strength (*1*-*3*). Because of the importance of reducing the energy consumption and the corresponding emissions of CO_2, many investigations of new materials with enhanced functionalities have taken place recently. Moreover, the necessity of developing more durable and sustainable pavement structures has led the pavement industry to search for new ways of solving construction and rehabilitation issues. Hence, the employment of state of the art techniques, for construction or maintenance is becoming more and more important.

Regarding asphalt pavement maintenance, there are various techniques that can be used to restore the mechanical characteristics of mixtures during their lifespan (*4*-*6*). Induction heating technique is one of the promising techniques to prolong the service life of asphalt pavements. Field trials are already available and a very exciting example is the Dutch motorway A58 near Vlissingen, see Figure 1.a. This technique requires new mixtures with conductive additives in order to make them suitable for induction heating. Particularly, the alternating magnetic field induces eddy currents in the additives and consequently heats them according to the principles of Joule's law. The generated heat in the additives increases locally the temperature of the asphalt mixture, through the temperature rise the bitumen is melting, the micro-cracks are healed, see Figure 1.b, and the mechanical properties of the pavement are recovered. This approach of introducing induction heating with main purpose to activate the self-healing capacity of porous asphalt is named induction healing.

Previous research indicated that asphalt mixtures, with the addition of conductive additives, such as steel fibers, can be heated in a very short time by using the induction heating technology (*7*-*12*). However, the distribution of steel fibers within mixtures appears to have a direct relation with the volumetric and mechanical properties (*13*-*20*) of asphalt mixtures and it was observed that the characteristics of steel fibers – diameter and length - are affected by the mixing and compaction processes (*11*). It is very important to develop conductive asphalt mixtures with well dispersed conductive particles to provide sufficient isotropic properties to the materials. For this reason, filler-sized conductive additives can be added into asphalt mixtures as alternatives to study the influence of different combinations of additives on the mechanical response of asphalt mixtures and the induction heating and healing efficiency and the mechanical response of asphalt mixtures.

During the induction heating, the asphalt mortar part of asphalt concrete with conductive additives is heated locally without heating the stone aggregates. Thus, asphalt mortar with additives is selected to be investigated in this research. The effect of different volumes of steel fibers and iron powder on the electrical and thermal properties is evaluated by using a digital multimeter and a thermal sensor (CTherm Analyzer), respectively. After the electro-thermal investigation, the tensile strength and fatigue performance of conductive asphalt mortars are studied. As mentioned above, although the reinforcing impact of steel fibers on mechanical properties of asphalt mixtures has been studied extensively, still limited research was ensued to appraise the performance of asphalt mortars with different conductive additives. Furthermore, the induction heating and healing capacity of conductive asphalt mortars is examined as well. The objective of this paper is to study experimentally the structural and non-structural performance of induction heated asphalt mortars since it is the crucial part of asphalt concrete that suffers more damage and contains the conductive additives for induction heating.



(b)

FIGURE 1 Infrared image (a) during induction heating of an asphalt pavement (A58 near Vlissingen, the Netherlands) and (b) of heated asphalt pavement surface at high resolution with the schematic of induction healing, (b.1) asphalt mortar with micro-cracks induced by eddy currents and (b.2) closure of micro-cracks through the heat generation in the asphalt mortar

MATERIAL AND PREPARATION

The original asphalt mortar without electrically conductive additives consists of sand (2697 kg/m3), weak limestone (WL) filler (2781 kg/m3), produced limestone (PR) filler (2699 kg/m3) and SBS modified bitumen (1030 kg/m3). The weight percentage of these components in the original asphalt mortar is 33%, 5%, 34% and 28 % m/m for mineral filler WL, PR, sand and bitumen, respectively.

For the development of conductive asphalt mortar, iron powder (7507 kg/m^3) was added as a filler-sized additive after substituting the equivalent volumetric part of mineral fillers - WL mineral filler and PR mineral filler - in order to avoid volumetric degradation. Figure 2 shows the used different filler-size particles, mineral and additives, and steel fibers. Steel fibers (7756 kg/m^3) are mixed with the other components without replacing any of them added as a volume percentage of bitumen. In this investigation, the conductive asphalt mortars are prepared with different volume percentages of iron powder 5%, 10%, 15%,20% and 25%) and the amount of steel fiber by volume of bitumen is kept constant (4%). The compositions of the different conductive asphalt mortars (MA_F()_P()) are given on Table 1. The notation MA indicates asphalt mortar, F represents filler, P represents iron powder. The values in the brackets indicate the corresponding volume of the components.

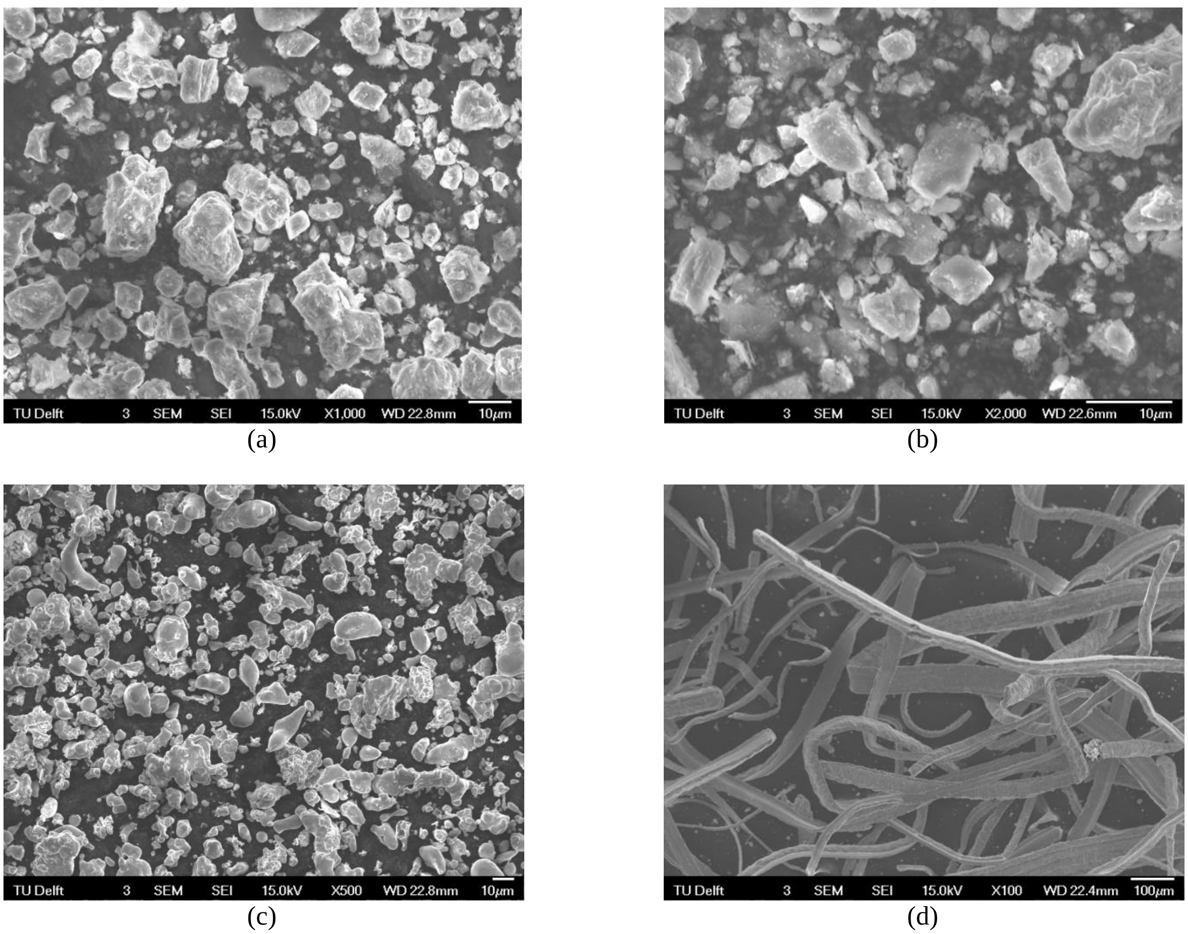


FIGURE 2 SEM SEI images of the filler-size mineral particles: (a) weak limestone (WL) and (b) produced limestone (PR), the conductive additives: (c) iron powder and (d) steel fibers

TABLE 1 Composition of different conductive asphalt mortars

Type of Asphalt Mortar	Bitumen (% m/m)	Sand (% m/m)	Mineral filler WL (% m/m)	Mineral filler PR (% m/m)	Iron powder (% m/m)
MA_F100_P0	28.00	34.00	33.00	5.00	0.00
MA_F95_P5	28.00	34.00	31.35	4.75	5.15
MA_F90_P10	28.00	34.00	29.70	4.50	10.30
MA_F85_P15	28.00	34.00	28.05	4.25	15.45
MA_F80_P10	28.00	34.00	26.40	4.00	20.60
MA_F75_P25	28.00	34.00	24.75	3.75	25.75

MA: asphalt mortar, F: mineral filler, P: iron powder, steel fiber (volume of bitumen): 4%

A volume combination of iron powder and steel fibers in the asphalt mortar are determined from the electrical conductivity measurements as reported in this paper and this will be used for the further experimental investigations.

EXPERIMENTAL METHODS

Electrical Resistivity and Thermal Conductivity

After the preparation of the conductive asphalt mortar, the material was poured in silicon-rubber moulds, to obtain samples with rectangular dimensions 125 × 20 × 25 mm. The electrical resistivity measurements were done by performing the two-electrode method, see Figure 3.a, at a room temperature of 20 ^{o}C. The geometry and the electrical resistivity of the conductive asphalt mortars are the only parameters that influence the resistance. Therefore, the electrical resistivity was obtained from the second Ohm-law:

$$\rho = \frac{RS}{L} \tag{1}$$

where ρ is the electrical resistivity, measured in Ωmm, L is the internal electrode distance, measured in mm, S is the electrode conductive area measured in mm^2 and R is the measured resistance, in Ω.

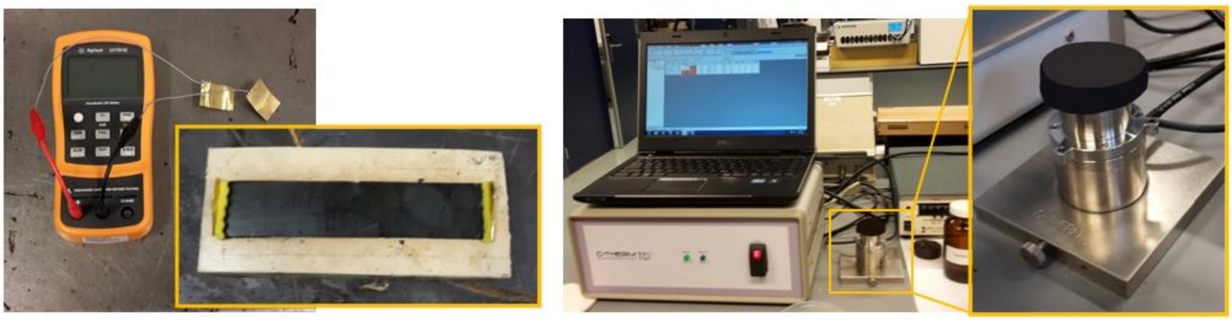
Thermal conductivity measurements were performed by using the C-Therm TCi thermal analyzer, shown in Figure 3.b. The sensor is working according to the Modified Transient Plane Source Method to determine the thermal resistivity and effusivity of the conductive asphalt mortar. The prepared specimen for this test has a diameter of 17 mm to cover the entire sensor. The sensor is heated by a small current and the response is monitoring while in contact with the specimen. The resistivity and effusivity of the specimen were measured and obtained directly from the sensor. From the inverse of the resistivity the conductivity was acquired. Using the effusivity concept other thermal properties like heat capacity and diffusivity can be derived. The effusivity is given by:

$$Effusivity = \sqrt{k \cdot \rho \cdot c_p} \tag{2}$$

where k is the thermal conductivity [W/m·K], ρ is the density [kg/m^3] and c_p is the heat capacity [J/kg·K]. The thermal conductivity is defined from the Fourier law as:

$$q = -k \cdot \frac{dT}{dx} \tag{3}$$

where q is the heat flux (the amount of thermal energy flowing through a unit area per unit time), $\frac{dT}{dx}$ is the temperature gradient and k is the coefficient of thermal conductivity, often called thermal conductivity. The heating, reading and cooling process was repeated 6 times per specimen to obtain an average of the reading.



(a) (b)

FIGURE 3 (a) Digital multimeter for electrical resistivity measurement and (b) C-Therm TCi thermal analyzer for thermal properties measurements

Direct Tensile Strength and Fatigue Performance

In order to investigate the impact of conductive additives on the mechanical properties of the asphalt mortar, direct monotonic tensile tests are carried out. A 25 kN electro-hydraulic servo testing machine is used, see Figure 4.a. The monotonic tension tests with freely rotating hinges are performed on specimens from conductive asphalt mortar, see Figure 4.b. In order to reduce undesired eccentricities, the specimens were carefully positioned in the special designed steel hinges, see Figure 4.b.1. Furthermore, the conductive asphalt mortar specimens have a parabolic geometry, with height of 34 mm for the parabolic part and a thickness of 10 mm in the middle. The monotonic tension tests were performed at different displacement rates. The fatigue performance is tested in load control mode. All tests are carried out at a constant temperature of -10 ^{o}C.

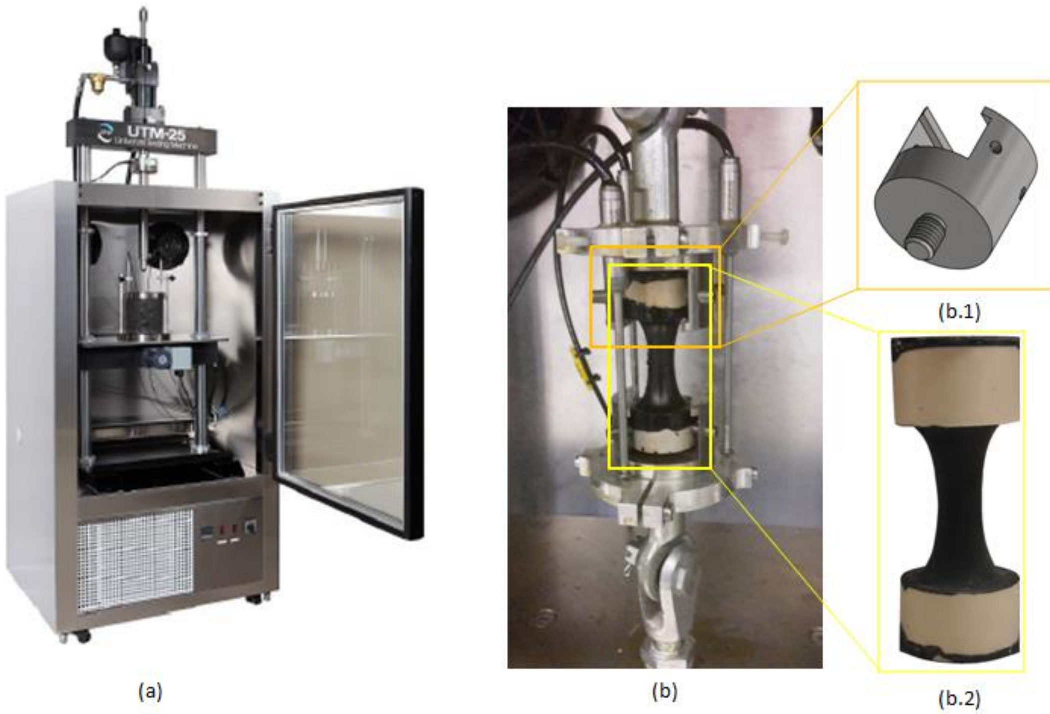


FIGURE 4 Universal Testing Machine UTM-25 (a), the frame (b) with modified hinges (b.1) and asphalt mortar specimen (b.2)

Induction Heating and Healing Performance

Among the objectives of this research is to determine the induction heating efficiency of the asphalt mortar with different combinations of additives. The induction heating experiment was performed with a 550 V RF generator 50/100 (Huttinger Electronic, Germany), see Figure 5.a, at a maximum frequency of 63.5 kHz. The distance from the mortar sample (125 × 20 × 25 mm) to the coil was 10 mm and the data were obtained from the surface of the specimen by using an infrared (IR) thermometer.

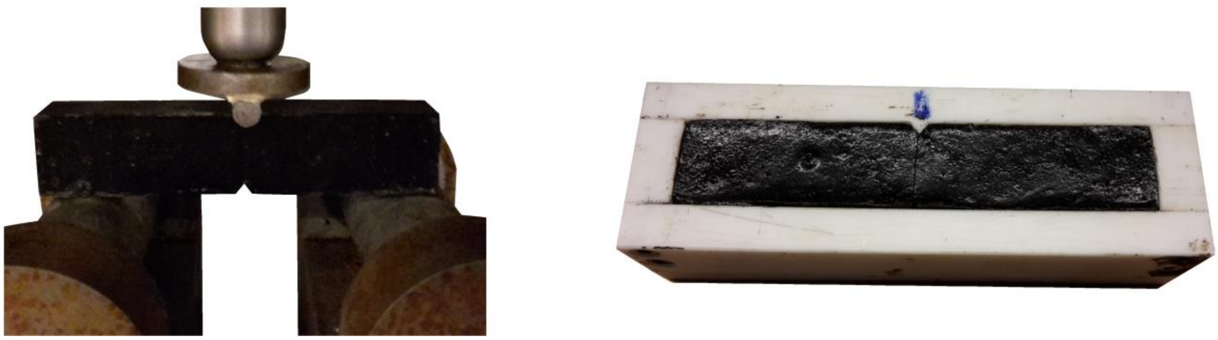
Additionally, in order to determine the healing efficiency of asphalt mortar after mixing conductive additives, asphalt mortar beams are produced with dimensions 105 × 25 × 13 mm in a mould and with a notch at the middle, see Figure 5.b. A similar experimental procedure as proposed by Liu et al (*8*) was selected to test the healing capacity of the asphalt mortar. The sample is placed in a chamber at -10 ^{o}C and is broken into two pieces using the three point bending setup, see Figure 5.b. The two pieces are then placed back into the mould. At the final stage, the two pieces are heated via induction energy until the surface temperature reaches 120 ^{o}C. This process is continued after resting the sample for 2 hours at 20 ^{o}C. Moreover, this process is repeated until the damage is too high to continue the healing process (*8*). Concerning the temperature, -10 ^{o}C was chosen in order to avoid permanent deformation of the material and to obtain a brittle fractured surface. For the induction healing analysis, 5 samples were used for each type of conductive mortar.

The induction healing performance is evaluated by using the relation given in equation 4:

$$S(t) = \frac{F_i}{F_0} \quad (4)$$

where F_0 is the fracture force of the sample during a three point bending test, and F_i is the fracture force after the induction heating.

(a)



(b)

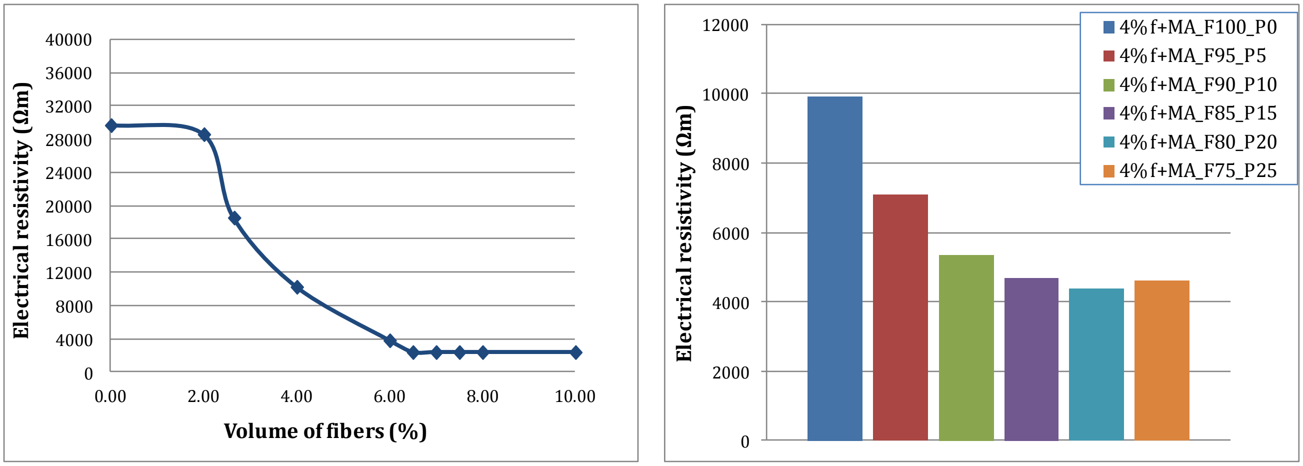
FIGURE 5 (a) Induction heating machine used at laboratory and (b) the three point bending setup with the asphalt mortar specimen used for the induction healing within mould

RESULTS

Electrical Resistivity and Thermal Conductivity

The change of the electrical resistivity of an asphalt mortar with steel fibers, but without iron powder is shown in Figure 6.a. The conductive paths formed by steel fibers develop and lead to a gradual decrease of the resistivity above 2% volume of fibers. It is clear that the increase of the volume of steel fibers reduces the resistivity or increases the electrical conductivity of asphalt mortar. The optimum steel fibers content reached when no longer increases the electrical conductivity by adding more than 6.4% of steel fibers. For adding iron powder in the mortars with constant steel fibers content, it was selected asphalt mortar with 4% of steel fibers as a conductive mortar with amount of steel fibers beyond the percolation threshold.

The combination of steel fibers and iron powder further improves considerably the electrical conductivity of the asphalt mortar, see Figure 6.b. It can be seen that, by choosing asphalt mortar with 4% of steel fibers and adding the iron powder stepwise in parallel with the reduction of mineral filler, the replacement of mineral filler with iron powder decreases the electrical resistivity of the asphalt mortar further. The optimum combination of additives in the asphalt mortar is 4% of steel fibers and 15% of iron powder. This combination leads to a shorter conductive pathway in the mortar and hence the electrical resistivity of the asphalt mortar decreases significantly. This volume combination of steel fiber and iron powder will be used for the further steps of this research.



(a) (b)

FIGURE 6 Effect of (a) the volume content of steel fibers and of (b) iron powder after substituting mineral filler with iron on the electrical resistivity of asphalt mortars

For composite materials such as asphalt mixture, the thermal properties can be determined by the properties, dispersion and proportion of individual components in the final mix. By increasing the proportion of a component in the mix, the thermal properties of the final mix can be increased or decreased depending on the type and the nature of the component. An asphalt mixture can be considered as a combination of the components mortar and stone fraction. In this study, CTherm Analyzed was used to examine the thermal conductivity of the conductive asphalt mortars.

It is observed that adding steel fibers to the asphalt mortar leads to increase of thermal conductivity, see Figure 7. Because of the thermal conductivity of steel fiber is quite high, when the volumetric part of steel fibers into the asphalt mortar is increased or decreased, the thermal properties of the whole mix will increase or decrease respectively. The increase of thermal conductivity is slightly higher in the case of asphalt mortars mixed with both iron powder and steel fibers.

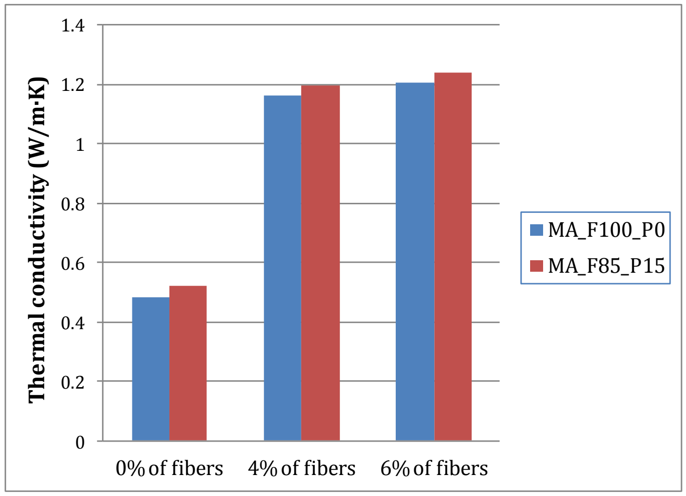


FIGURE 7 Effect of the volume content of steel fibers on the thermal conductivity of asphalt mortar with and without substituting mineral filler with iron powder

Tensile Strength and Fatigue Performance

The direct tensile strength and fatigue tests provide crucial information about the impact of additives on the mechanical performance of the conductive asphalt mortar. The asphalt mortar is the first decentralized system of an asphalt mixture and represents the matrix of the asphalt mixture between the aggregates. This implies that the mechanical behaviour of the mortar has a direct effect on the behaviour of the asphalt mixture on roads. The typical stress-strain curves at low temperatures (-10^{o}C) and at different displacement rates are presented in Figures 8. It is obvious that the amount of steel fibres influences the maximum tensile stress. The tensile strength of the asphalt mortar increases with increasing fibre content. Therefore, the reinforcing effect of fibres on the asphalt mortar is apparent in Figure 8.c, where the average values of the maximum tensile stresses are presented.

The effect on brittleness and ductility of the conductive asphalt mortar can be observed in Figure 8. At high displacement rates, all samples show brittle response. More ductility can be observed for lower fiber contents and lower displacement rate. Particularly, the replacement of the part of mineral filler with iron powder, it did not influence significantly on the tensile strength of the asphalt mortar and the reinforcing effect of the fibers.

In order to study the fatigue response of asphalt mortar with different combinations of conductive additives, the cyclic sinusoidal load is utilized. The magnitude of the loading is defined as the 40% of the ultimate tensile strength (0.3 kN). The loading frequency was 5 Hz. and all the tests were carried out at -10 ^{o}C.

It can be observed that all the asphalt mortar samples show the tertiary phase of deformation after certain loading time, see Figures 9.a. and 9.b. Particularly, by increasing the amount of steel fibers within the asphalt mortar from 0% to 4%, the tertiary phase is significantly delayed and the fatigue life increases. Moreover, the fatigue life is extended when steel fibers were added from 4% to 6% within the asphalt mortar. It can be seen that the asphalt mortar with 15 % of iron powder appear slightly higher fatigue life than the one without iron powder, see Figure 9.c.

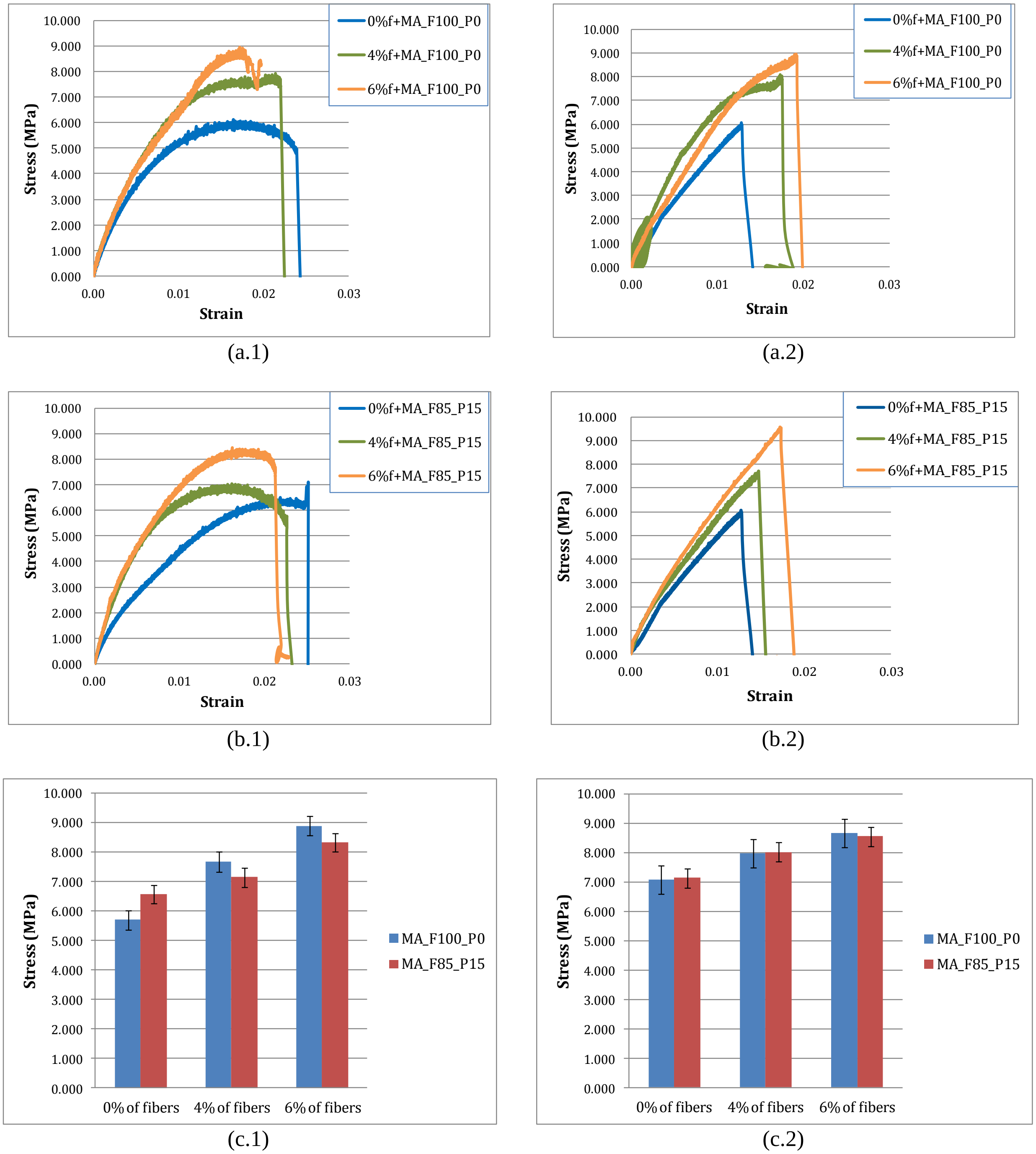
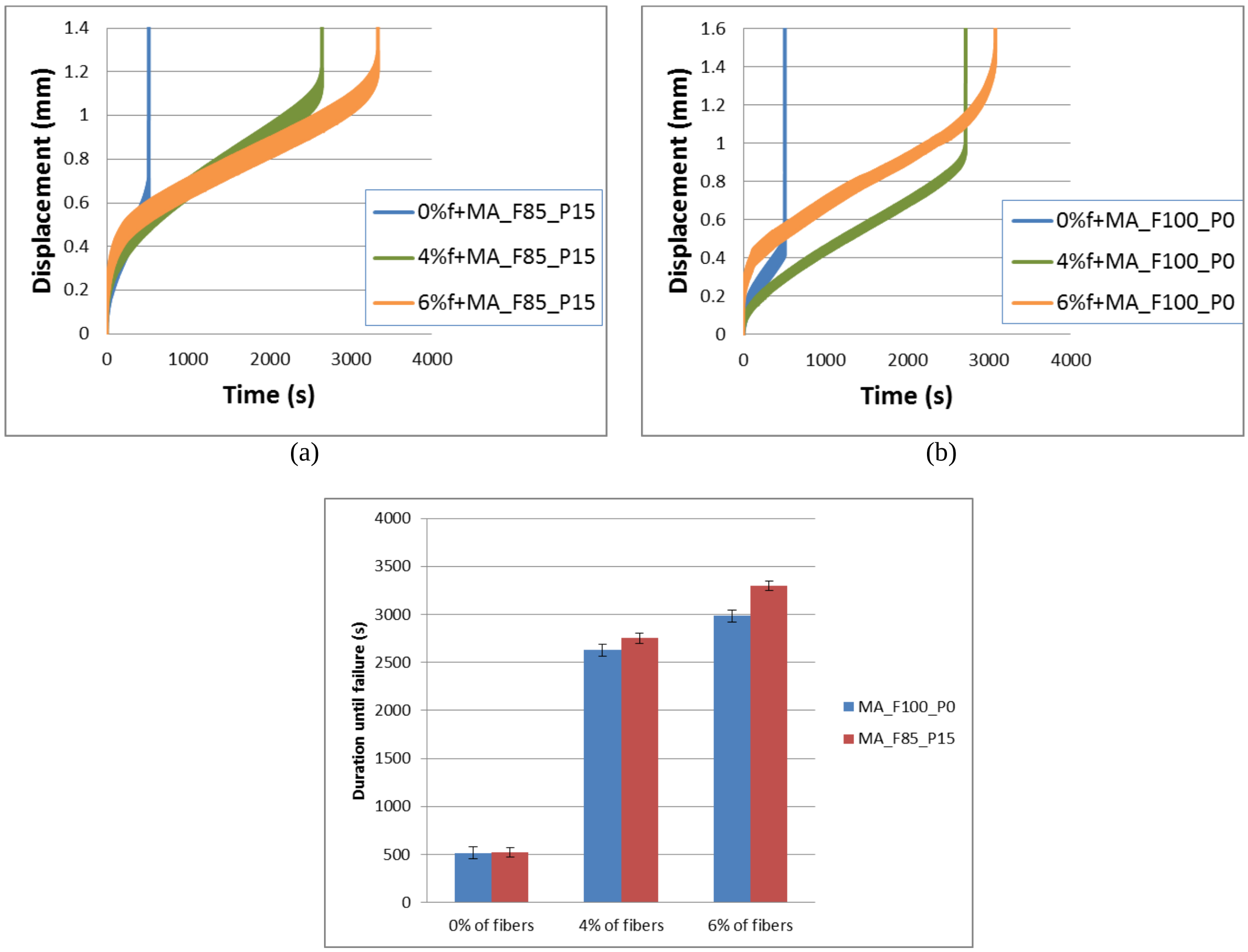


FIGURE 8 Stress-strain curves for asphalt mortars; with mastic MA_F100_P0 and different amounts of fibers, (a.1) displacement rate: 0.0275 mm/s and (a.2) 0.05 mm/s; with mastic MA_F85_P15 and different amounts of fibers, (b.1) displacement rate: 0.0275 mm/s and (b.2) 0.05 mm/s; and the total graphs with the tensile strength of asphalt mortars: displacement rate (c.1) 0.0275 mm/s and (c.2) 0.05 mm/s



(a) (b)

(c)

FIGURE 9 Influence of steel fibres on fatigue performance of asphalt mortars (a) with and (b) without iron powder, and (c) the total graph with the fatigue life of different mortars

Induction Heating and Healing Performance

In order to investigate the induction heating efficiency of the conductive asphalt mortar, at ambient temperature (20 ^{o}C), the test samples were heated for 120 seconds by inductor. The test samples were mixed with different volumetric combinations of steel fibers and iron powder. Figure 10 presents that the average temperature at the top surface of samples at 120 seconds induction heating. It can be observed that the maximum surface temperature is related to the volume of steel fibers added in the asphalt mortar. The higher amount of fibers in the mortar sample led to the higher surface temperature and hence the higher induction heating efficiency of the asphalt mortar. However, the tendency of increasing heating efficiency of the mortar is not linear increase. For example, after 6% of fibers added in the mortar, the tendency of increasing temperature is not significant and it is stabilized. It means that the mortars achieve the induction heating saturation limit where all the conductive paths are linked.

Similar observation can be found for the samples mixed with both iron powder and steel fibers. It can be seen that the induction heating efficiency can be enhanced by combination of iron powder and steel fibers into the asphalt mortar. The average surface temperature of the samples with 15% iron powder is higher than the samples without powder.

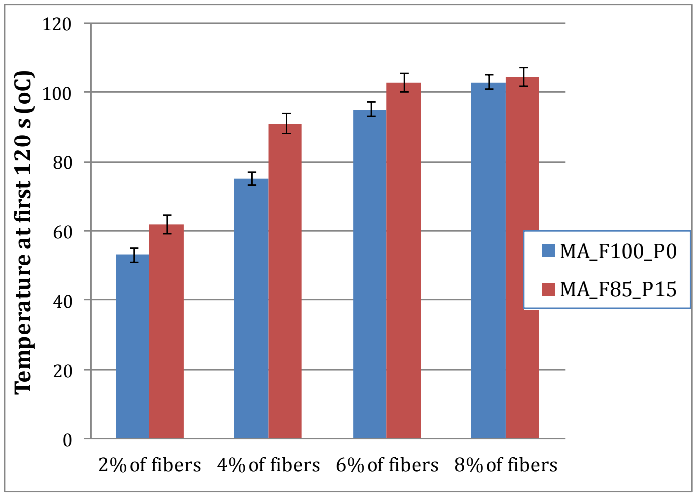
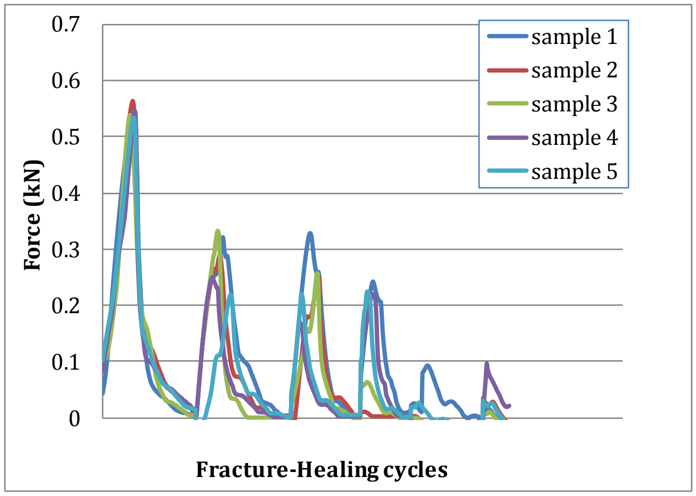
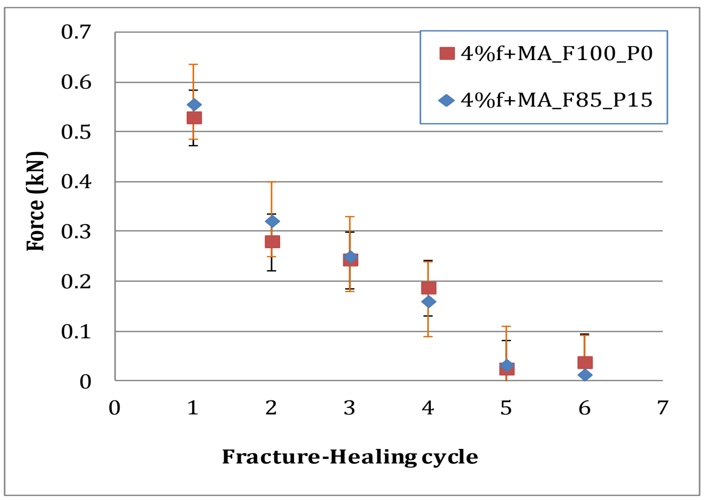


FIGURE 10 Temperature reached after 120 seconds induction heating for asphalt mortar with constant volume of steel fibers and different volumes of iron powder

The induction healing efficiency of asphalt mortar with steel fibers is presented in Figure 11.a. The cracks were healed by induction heating. However, after the first healing cycle, the strength was recovered by 60% of its original strength. This phenomenon can be explained by the loss of reinforcing effect of steel fibers in mortar (*12*). Apart from the induction healing of asphalt mortar, the use of steel fibers offers a reinforcing matrix with a network of random oriented fibers. However, when mortar is fractured, the interconnection among the fibers at the cracked surfaces is lost and mechanical performance of conductive mortar is as a material without fibers. In the second and third cycles, the strength recovery remained approximately constant. In the fourth cycle, material lost its strength completely. After several fracture - healing cycles, the cracked surfaces of fractured mortars were covered mostly by asphalt binder without steel fibers. As a result, the diffusion of binder from the one side of surface to the other was prohibited and subsequently the closure of crack of asphalt mortar. The fracture - healing process was continued successive in six cycles. Similar to the case of mortar mixed with fibers, the combination of steel fibers and iron powder can provide the same induction healing capacity to the mortar, see Figure 11.b.



(a)



(b)

FIGURE 11 (a) Stress-strain curves for asphalt mortar containing 4% of steel fibers and (b) strength comparison for two types of asphalt mortars

CONCLUSIONS

The findings of this research were within the efforts to enhance the induction heating of asphalt mixtures preparing simultaneously materials with improved mechanical performance during their service. Based on the results presented in this paper, the following conclusions can be made:

1. The increase of conductive additives (e.g. iron powder and/or steel fibers) contributes to the enhancement of the electrical and thermal conductivity of asphalt mortar. The utilization of steel fibers has significant improvement on the electrical conductivity of asphalt mortar than the one with iron powder. Moreover, combining steel fibers and iron powder within the asphalt mortar, the thermal conductivity is slightly higher than using only steel fibers as conductive additives.

2. When steel fibers are added in the asphalt mortar, the tensile strength is improved and the fatigue life is extended. Similar mechanical response is obvious also by combining iron powder and steel fibers.
3. The induction heating efficiency is increased when iron powder and steel fibers are added to a certain limit, where the temperature does not increase anymore, independently. Apart from the highest induction heating efficiency, asphalt mortars have similar induction healing capacity with mortars with steel fibers when iron powder is mixed.

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