Construction and Building Materials 23 (2009) 3175–3181

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Electrical conductivity of asphalt mortar containing conductive fibers and fillers

Álvaro García [a,*], Erik Schlangen [a], Martin van de Ven [b], Quantao Liu [a]

[a] Delft University of Technology, Faculty of Civil Engineering and Geosciences, Micromechanics Laboratory (MICROLAB), Stevinweg 1, 2628 CN Delft, The Netherlands
[b] Delft University of Technology, Faculty of Civil Engineering and Geosciences, Road and Railway Engineering, Stevinweg 1, 2628 CN Delft, The Netherlands

ARTICLE INFO

Article history:
Received 17 February 2009
Received in revised form 15 June 2009
Accepted 18 June 2009
Available online 23 July 2009

Keywords:
Conductive asphalt mortar
Induction heating
Steel wool
Graphite
Sand–bitumen ratio
Self-healing

ABSTRACT

The objective of this research is to examine the conductivity of asphalt mortar through the addition of electrically conductive fillers and fibers: graphite and steel wool, and prove that this material can be heated with induction energy. The effect of fibers content, sand–bitumen ratio and the combination of fillers and fibers on the resistivity of asphalt mortar was investigated. It was found that the percolation threshold happened sooner by adding electrically conductive fibers than by adding fillers. Percolation threshold was also found to be function of the sand–bitumen ratio and of the volume of fibers content. There is an optimum content of fibers for each sand–bitumen ratio, above which it is difficult to make the mixture and the electrical resistivity increases exponentially. Besides, in case of adding conductive fillers or a mixture of conductive fibers and fillers to the mastic, once the maximum conductivity is reached, it remains constant, independently of the volume of conductive filler added. Nano CT-scan (computed axial tomography) reconstructions were also used to visualize the fibers connected inside the mixture. Finally, to validate the research, three different samples were induction heated and their temperature variation was measured.

1. Introduction

Asphalt concrete is one of the most commonly used materials in pavements due to its excellent performance in comfort, durability and water resistance, but it usually exhibits distresses over time due to repeated loading, environmental conditions and normal wear. In order to maintain these characteristics during its lifetime, asphalt concrete wearing courses should be constantly maintained and repaired. Little cracking on highway runway can mean the start of some big distress. It is theoretically feasible to repair cracks in asphalt concrete by the addition of conductive fibers and fillers, improving its conductivity, and heating with induction energy to increase its self healing rate. So, the objective of this research is to show how the conductivity of asphalt mortar changes with the addition of different volumes of conductive particles, and prove that this material can be heated with induction heating techniques.

It is well known that asphalt concrete is a self healing material. As Little and Basin explain [1], healing occurs only after a stress or strain is induced, which is sufficiently large to generate damage. Immediately after the load that generated the damage has been removed, and both faces of the crack are in contact, the diffusion of molecules from one face to the other starts. This process will happen, while there are not more loads, until the microcrack has completely disappeared and the repaired material has the level of strength of the original material. It is also well known that the amount of healing increases when the material is subjected to a higher temperature during the rest period [2,3]. The problem comes because it is difficult to stop traffic circulation on a road to allow enough self healing recovery at ambient temperature.

Conductive asphalt concrete may be defined as the mixture of bitumen, aggregates and electrically conductive components to obtain high electrical conductivity. The first attempt of making an electrically conductive road for deicing dates back to the 1950s [4]. Only very recently, in a series of researches at the Wuhan University of Technology, asphalt concrete has been considered as a serious candidate to be an electrically conductive material, for deicing [5] and for having a self-monitoring material [6].

In many previous studies about electrically conductive cement and asphalt systems [4–10] it has been demonstrated how the conductivity is proportional to the volume of conductive filler or fibers added. Wu et al. [6] indicate how an excess of conductive particles can cause the degradation of the pavement properties such as the strength or the workability of fresh materials. It has been also proved that the sand–cement ratio has great influence on the conductivity of cement-based composites [10]. Otherwise, by adding steel or carbon fibers to the mixture, fatigue life of asphalt concrete could be extended by approximately 20–25 times that of plain asphalt mixtures [11].

Wu et al. [6] explain how the conductivity of asphalt concrete can be highly improved by adding small volumes of carbon fibers

* Corresponding author. Tel.: +31 (0) 15 2782774.
E-mail addresses: a.garciahernandez@tudelft.nl, alvarogarcia007@hotmail.com (Á. García).

0950-0618/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2009.06.014

to the system aggregates-bitumen-conductive powder (filler). In their research, this happens because conductive fillers exhibit short range contacts in the form of clusters whereas fibers have a bridging effect between these clusters. Traditionally, in conductive roads, heat was generated due to the electrical resistance in the conductive particles when connected to a power source, but in this research, authors are trying to make asphalt suitable for induction heating and subsequently healing of cracks, which has the advantage of high volumetric heating rates. For that, as induction heating only works with electrically conductive materials, and as Wu et al. [6] have already shown the effect of conductive powders on the electrical conductivity of mastic; authors have decided to investigate the effect on the electrical conductivity of asphalt mortar with different volumes of conductive fibers and sand–bitumen ratios, so as the effect on the conductivity of building mixed composites with conductive powders and fibers. To get a better understanding of the fibers distribution in the system, 3D nano CT-scan reconstructions were used to elucidate the morphology of this conductive asphalt concrete. And to prove that the system works, three test samples were induction heated.

2. Experimental method

2.1. Materials

More than 120 asphalt mortar specimens were prepared with different sand–bitumen ratios and volumes of conductive particles. Five different sizes (<0.120, 0.120–0.250, 0.250–0.5, 0.500–1.0, 1.0–2.0 mm) of crushed silica mineral, with density 2.67 g/cm^3, were mixed to have uniform grading (20 wt% each size). The virgin bitumen used was 70/100 pen, obtained from Kuwait Petroleum, with density 1.032 g/cm^3.

With regard to the electrically conductive particles, two different types were used, conductive fibers and filler. The first ones were steel wool, of type 000, with diameters between 0.00635 mm and 0.00889 mm, chopped by hand, always by the same operator. To find the size, more than 100 fibers were checked by taking photographs under the optical microscope and measuring their length with an image processing program, obtaining the distribution shown in Fig. 1. Their electrical resistivity was 7×10^{-7} Ω cm. The conductive filler used was graphite with a particle size of less than 20 μm, and a carbon content of more than 99.0%. Its electrical resistivity was 10^{-4} Ω cm.

2.2. Methods

Conductive fillers and fibers, aggregates and bitumen were blended for 15 min at 285 r.p.m. and 150 °C of temperature. Thereafter, the mass was hand-compacted in silicon-rubber moulds, obtaining specimens as the one shown in Fig. 2.

The electrical resistivity measurements were done at room temperature 20 °C. The electrodes were made of nickel and placed at both short ends of the test sample to measure the electrical volumetric resistance. Dry graphite powder (<20 μm) was used to fill the gaps between the electrodes and the specimens and to ensure a perfect contact between them. The total contact resistance between the electrodes and the graphite was less than 0.1 Ω, which is very small if compared to the great resistances studied (higher than 20 Ω in the samples). A digital multimeter was used to measure the resistance below 36×10^6 Ω. A resistance tester was used to measure the resistance higher than this value. From the resistance data, the electrical resistivity was obtained from the second Ohm-law:

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

where ρ is the electrical resistance, measured in Ω cm; L is the internal electrode distance, measured in cm; S is the electrode conductive area measured in cm^2 and R is the measured resistance, measured in ohms (Ω). The electric field is assumed constant and the end-effects considered negligible.

To prove that mastic could be heated with induction energy, some of the samples studied were heated and their temperature change measured with a 640 × 480 pixels, full colour infrared camera. The induction heating experiment was performed by using an induction heating system with a capacity of 50 kW and at a frequency of 70 Hz. Although the system was not fully optimized, it had not influence on the research objectives.

3. Results and discussion

3.1. Effect of sand–bitumen ratio

The volume resistivity variation against different sand–bitumen ratios for samples with the volumetric conductive particles–bitumen ratio fixed is displayed in Fig. 3. The objective of this picture

Fig. 2. Test samples used in the research.

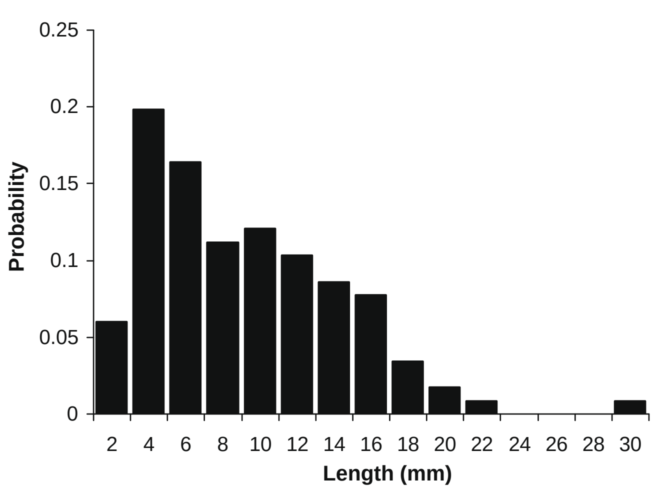

Fig. 1. Chopped steel wool length distribution.

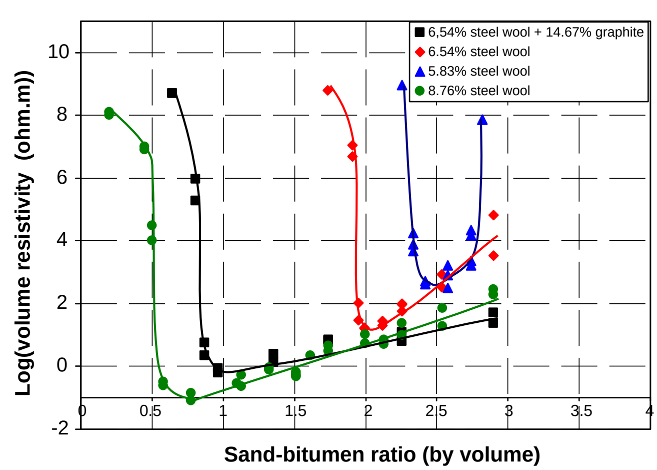

Fig. 3. Effect of sand–bitumen ratio on the electrical resistivity of the system for different conductive particles–bitumen ratios.

is to show how the volume resistivity cannot be considered separately from the sand–bitumen ratio (s–b) and quantify the influence of the sand–bitumen ratio on the conductivity of asphalt mortar. There is an optimum conductive particles–bitumen ratio for each sand–bitumen ratio where the resistivity decreases to a minimum: 5.83% for s–b 0.51, 6.54% for s–b 2.00% and 8.76% for s–b 2.50 (percentages related to the total volume of bitumen in the mixture). In addition, a sudden increase in the volume resistivity takes place when reducing the sand–bitumen ratio bellow the optimum. This is called percolation threshold in the resistivity [5]. It can also be observed how the resistivity in the optimum decreases almost exponentially with less volume of sand in the mixture: $82.50 \times 10^{-2}\,\Omega$ m, $17.54\,\Omega$ m and $420.00\,\Omega$ m for sand–bitumen ratios 0.77, 2.00 and 2.50, respectively (see Table 1).

Otherwise, if beyond the optimum, for a fixed fibers and fillers-bitumen ratio in the mixture, the sand–bitumen ratio is linearly increased, the volume resistivity is also increased, but exponentially. During the mixture it could be seen how the samples with sand–bitumen ratio above the percolation threshold were difficult to mix, with clusters of fibers that grew when increasing the volume of sand in the mixture. Besides, as in the 5.83% steel wool curve can be appreciated, if the volume of sand is increased above a certain limit, the volume conductivity depercolates and the resistivity increases suddenly. Samples with sand–bitumen ratio higher than 2.74% and 5.83% steel wool simply lost all the conductive properties. In addition, they looked porous and weak. Definitively there was not enough bitumen to make a resistant mastic or enough fibers to attach the aggregates (if the sand–bitumen ratio is increased, the total volume of fibers inside the mixture is reduced). Finally, in Fig. 3 can be observed how the optimum sand–bitumen ratio can be decreased a lot by adding graphite to the conductive fibers.

3.2. Effect of fiber volume content

Volume resistivities versus fibers and fillers content (conductive particles–bitumen ratio) with a fixed sand–bitumen ratio 2.25 are displayed in Fig. 4. For small volumes of fibers or fillers, the resistivity is similar to that of a plain asphalt mortar, exhibiting insulating behaviour. Both with fibers and fillers, a sudden change in the resistivity takes place after a certain volume of conductive particles has been added, for example 6.02% in the case of steel wool. Differently than with the sand–bitumen ratio variations, when the volume of fibers added is higher than the optimum, the resistivity remains constant or decreases very slowly, but once the mixture is at this point, it is difficult to mix and clusters of fibers appear during the mixing process.

Besides, in Fig. 4 can be seen how steel wool has much greater influence in the electrical resistivity than the graphite powder. For example, the resistivity of steel wool filling asphalt mortar drops from 750 MΩ m to 89.12 Ω m with steel wool volume increasing from 6.02% to 6.14%. Otherwise, the influence of graphite on the resistivity at the sand–bitumen ratio studied is very weak. The resistivity seems to drop slowly, but with high volumes of graphite, mastic is difficult to prepare.

Finally, the combination of fibers and fillers was analyzed. For that, two sets of experiments were prepared: steel wool volume was fixed at 5.83% and 6.57% and different volumes of graphite

Table 1
Sand–bitumen ratios, % of fibers and electrical resistivities of the three mixtures studied at the optimum.

s–b	0.51	2.00	2.5
% of fibers	5.83	6.54	8.76
Resistivity (Ω m)	82.50×10^{-2}	17.54	420.00

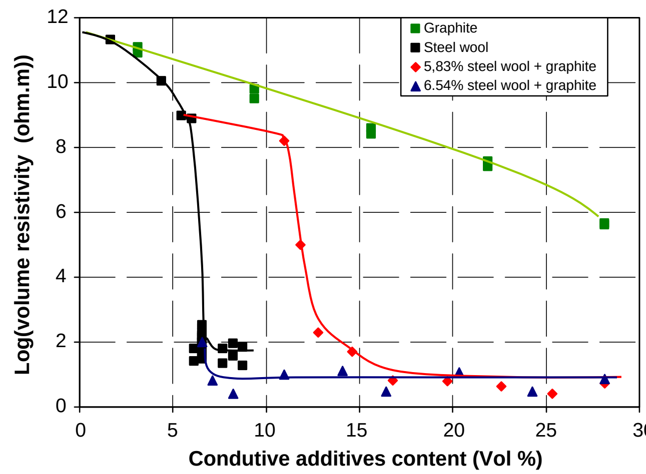

Fig. 4. Volume resistivity versus conductive particles–bitumen ratio for asphalt mortar systems.

were added. It was found that the resistivity will continue reducing with the volume of graphite, but much slower, tending to a certain value, constant and independent of the volume of fibers added or even if there are not any fibers. Finally, further increasing of graphite concentration does not produce any effect on the asphalt mortar volumetric conductivity.

3.3. Analysis and discussion

Let us imagine conductive fibers as small roads for electrons. In the beginning, when few fibers are added to the mixture, if they are well distributed, they will remain completely isolated from each other. If then the electrical resistivity of the sample is measured, it is found that it is a little lower to that of a plain mastic. One can think it is because electrons find high electrical resistances thorough the bitumen, but suddenly they find an electrically conductive fiber that makes their way easier. If more fibers are added, electrons will have more conductive paths and the resistivity will continue decreasing. Eventually, there will be so many fibers that they will connect both ends of the sample, and electrons will not need to go thorough the bitumen anymore. This first conductive path will be a very tortuous one (Fig. 5). A short volume of fibers more will work tending bridges along this conductive path, straightening it and increasing the conductivity a lot. As logic, once the conductive path has reached its shortest length, more conductive fibers will not reduce the resistivity in the mixture. Following these ideas, it is logic that fibers are much more effective than fillers when reducing the composite resistivity: they form long conductive paths, while the same volumetric amount of filler will be dispersed all around the mixture.

In Fig. 5, a scheme of the volume resistivity variation versus the total conductive additives content is showed. As stated in the percolation theory [12,13], it is possible to observe that the magnitude in the electrical resistivity strongly decreases with the increase of fiber content once there is enough volume of fibers. Based on the results showed above, changes in the resistivity under conductive additive content variations can be divided in four phases: Insulated Phase (1), where the fibers are so separated that there is not a conductive path between both extremes of the test sample; here the resistivity of the system is presumably similar to that of plain asphalt concrete. Transition Phase (2), where the first percolation paths form and the resistivity drops very fast. In this phase, samples are conductive, and fibers start being in contact; this phase ends with a minimum in the electrical resistivity, called Conduc-

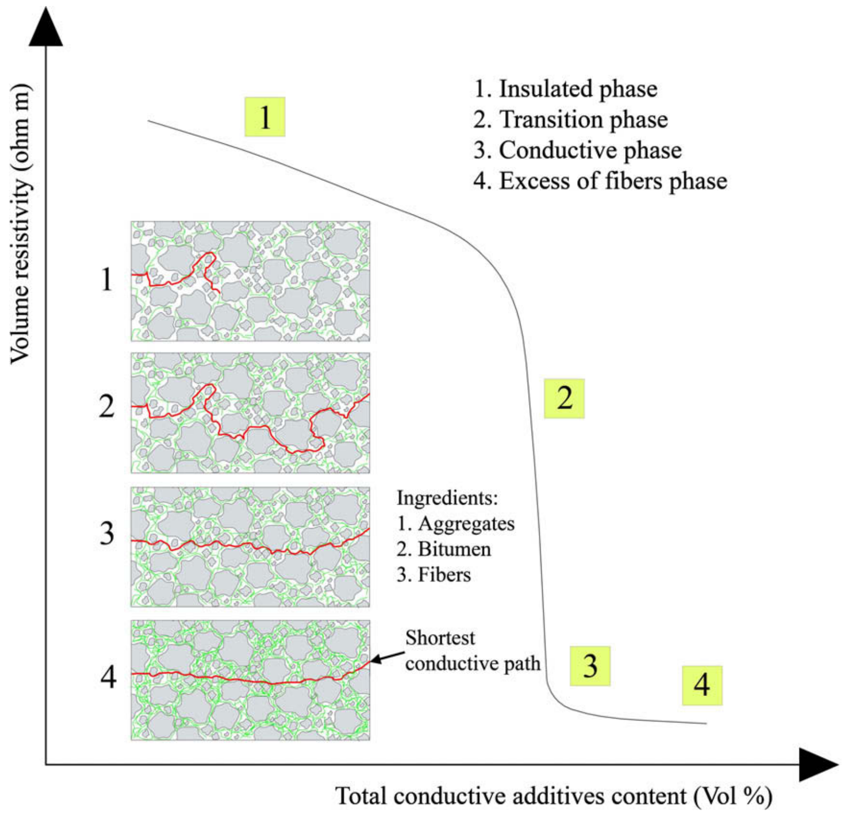

Fig. 5. Volume resistivity versus total conductive additives content scheme.

tive Phase (3) in Fig. 5, where fibers have reached their maximum dispersion level in the mixture; this could be considered as the optimal content of fibers for each sand–bitumen ratio. Finally, in the Excess of Fibers Phase (4), there are so many fibers that the length of conductive paths does not decrease any more, with what the composite resistivity decreases slightly with the increase in fiber content: once the shortest conductive path has been reached, an increase in the volume of conductive particles does not produce any increment in the conductivity. In fact, this phase can be easily distinguished during the mixing process because the fibers volume is so high that they are impossible to mix and clusters of fibers start appearing.

Following the same idea, results showed in Fig. 4 for asphalt mortar mixed with conductive fillers and fibers seem to be completely logic. Graphite decreases a little the optimum resistivity because, if there is enough concentration, its particles tend bridges between the fibers [5], minimizing the conductive path length. Nevertheless, this conductivity increase has a limit imposed by the minimum distance between both ends of the samples studied. Once in the optimum, statistical deviations in the values obtained will come through different aggregate configurations inside the sample.

Using cement concrete as the base material and carbon fibers as the conductive elements, it has been reported that the conductivity decreases with increasing sand–cement ratio for a given carbon fiber volume fraction [10]. In Fig. 3 can be appreciated how this is true only when very high volume of fibers is added to the mixture. Then, the maximum conductivity takes place when sand–bitumen ratio is zero or almost zero and, as a consequence, the resistivity cannot do anything but increase. This is just because the volume of fibers inside the mixture is inversely proportional to the volume of bitumen or cement paste on it (see Eq. (3)). In addition, when decreasing the volume of fibers, the optimum sand–bitumen ratio grows, and the resistivity below it drops to that of a non conductive material. This happens because the fibers can only be in the free spaces around big aggregates. If these spaces are too big and the volume of fibers is not enough, they simply do not percolate; the same happens when varying the volume of fibers by fixing the sand–bitumen ratio during the Insulation Phase. When these fibers start being in contact, something similar to the Transition Phase happens, and when the resistivity reaches its minimum it could be considered to be the Conductivity Phase. When increasing the sand–bitumen ratio above the optimum, the mixture becomes difficult to work with, and fibers are not easily mixed: there is not enough bitumen for a uniform dispersion of the fibers, clusters of fibers appear and the resistivity grows exponentially. Finally, as in the 5.83% steel wool curve can be seen, if the sand bitumen is increased too much and the volume of fibers is too low, the fibers simply depercolate, and the sample becomes non conductive; besides, in this phase, addition of fibers do not improve the conductivity.

In Fig. 6, the electrical conductivity surface of asphalt mortar depending on the sand–bitumen ratio and on the total volume of conductive additives is showed. This figure was made to show the dependence between both parameters studied and how both cannot be studied separately: there is an optimum of fibers for each sand–bitumen ratio. In the optimum, fibers are easy to mix, and the resistivity is a minimum. Outside the optimum, the resistivity increases exponentially and the fibers are difficult to mix. Each mixture is different and the optimum volume of fibers should be found for each sand–bitumen ratio or for each aggregates type. In Fig. 3, it is shown how this optimum can be increased by adding graphite to the mixture. The problem of graphite is that it reduces the mechanical properties of the material [5], so it should be limited to a minimum, just to stabilize the mixture and avoid the conductivity dropping when the volume of fibers is not enough. In this

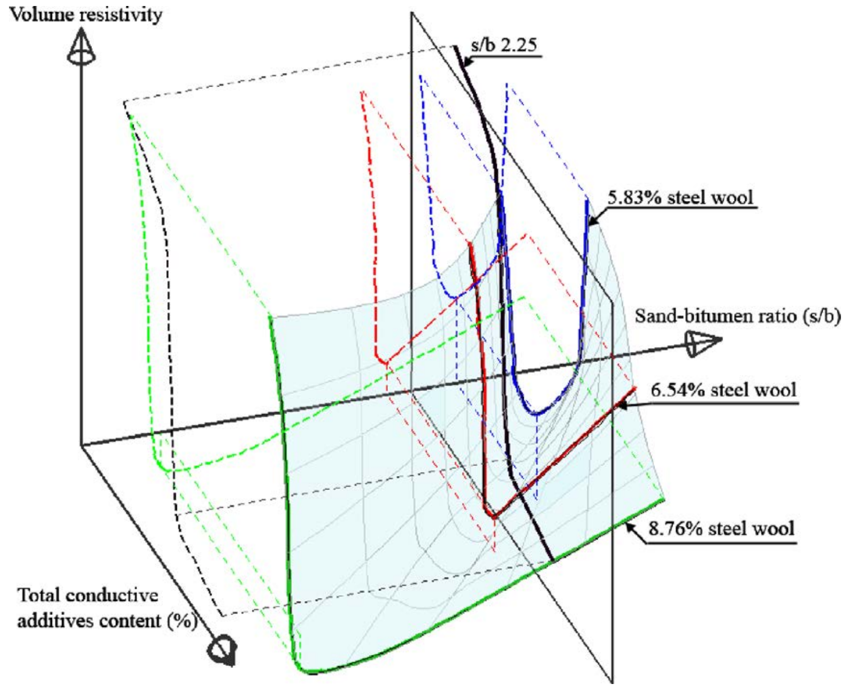

Fig. 6. Electrical conductivity surface of asphalt mortar against the sand–bitumen ratio and the total volume of conductive additives.

Figure can be seen how to obtain the smallest electrical resistances, volume of fibers should be in the optimum or above it. If the volume of fibers is lower, then the volume of graphite needed is very high. If the volume is higher, with a very low quantity of graphite, the conductivity will be improved, but clusters of fibers will appear in the mixture.

3.4. Statistical considerations

To check the repeatability of the data and their distribution function, the probability–probability plot (*P–P* plot) for 22 samples with 6.57% steel wool (related to the bitumen content) and sand–bitumen ratio 2.26 was made (Fig. 7). The linear fitting obtained has a dispersion coefficient of 0.986 and a slope of almost 45°. It was found that if the logarithms of the observed resistivities are plotted as a frequency distribution, the resulting distribution is normal. Besides, in Fig. 3, data after the optimum for all the volumes of fibers tested grew exponentially. This is very important, because it means that a small error will make the resistivity grow exponentially.

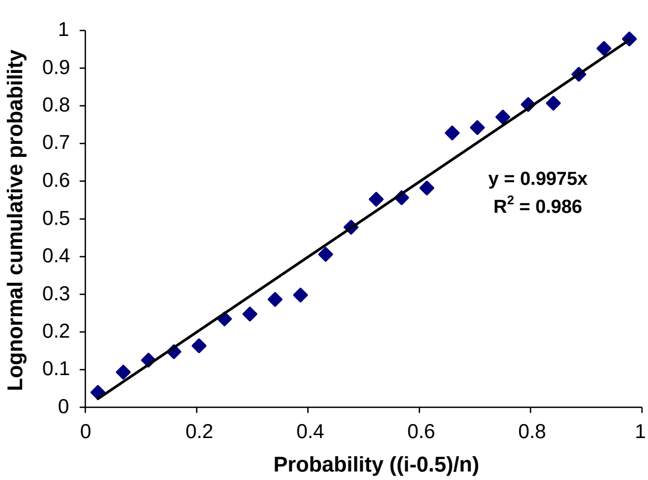

Fig. 7. *P–P* plot for samples with 6.57% steel wool (related to the volume of bitumen) and sand–bitumen 2.26.

Clusters of fibers do not reduce the conductivity; they just appear because there is not enough space for all the fibers; it is shown in Fig. 4, by fixing the sand–bitumen ratio in the curve with only steel wool: after the optimum, conductivity remains almost constant. The exponential behaviour is a very similar effect to that of a conductive composite under traction: Conductive composites show an exponential or power relation between the electrical resistance and the tensile strain due to fiber breakage and/or electrical percolation under tensile loading [14]. It seems to be an effect of reducing the volume of fibers inside the composite: by increasing the sand content, the resistivity increases in an exponential way.

Otherwise, knowing that:

$$\%tot\,fib = \frac{Vfib}{Vbit + Vs}; \quad Vfib = Vbit \cdot c \quad \text{and} \quad \frac{Vs}{Vbit} = sb \tag{2}$$

where *Vfib* is the total volume of fibers, *Vbit* is the total volume of bitumen, *Vs* is the volume of sand, *sb* is the sand–bitumen ratio,*%tot fib* is the total fibers percentage inside the mixture and *c* is the conductive particles–bitumen ratio.

Combining these equations it can be found that the total amount of fibers in the mixture is inversely proportional to the sand–bitumen ratio:

$$\%tot\ fib = \frac{c}{1 + sb} \tag{3}$$

In spite of having much less fibers in the mixture when increasing the sand–bitumen ratio, clusters of fibers continue appearing, from which it can be concluded that they are function of the total film thickness around the fibers and the aggregates: it is necessary to have a minimum amount of bitumen around the aggregates to obtain a good mixture; if this minimum film thickness does not exist, then it is impossible to mix the fibers in the asphalt concrete.

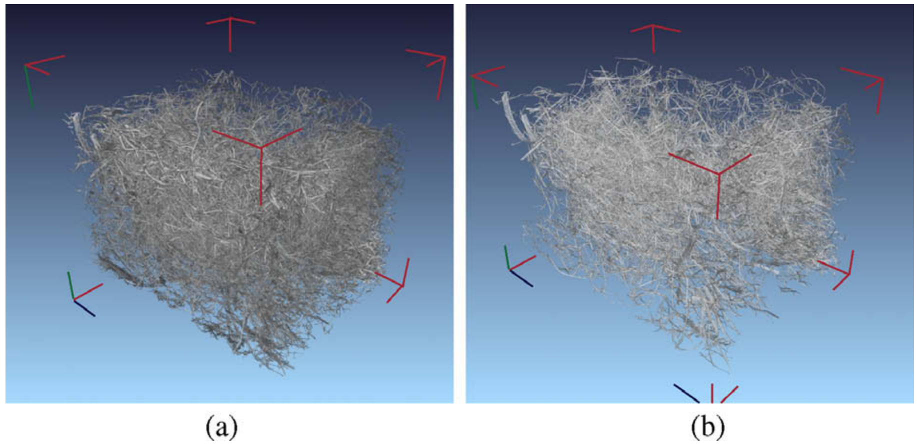

Fig. 8. Nano CT-scan images of the test samples with 6.54% steel wool and sand–bitumen ratio 2.90 showing (a) all the fibers (b) and only the connected fibers.

3.5. CT-scan reconstructions

In Fig. 8 nano CT-scan reconstructions of a sample with 6.54% steel wool and sand–bitumen ratio 2.90 are showed. In Fig. 8a are shown all the fibers inside the sample, and in Fig. 8b only the fibers connected. This sample had a relatively low conductivity and, although in Fig. 8a cannot be clearly appreciated due to the high density of fibers, clusters of fibers appeared during the mixing process. In Fig. 8b can be seen how the volume of fibers connected is lower than the total volume of fibers in the sample and how, once the non-connected fibers have been removed, clusters of fibers can be visually observed. Nevertheless, in both images can be seen how, independently if all they are connected or not, fibers are distributed all around the sample, which is especially positive when trying to reach uniform heating.

To analyze the images, a burning algorithm, initially developed at NIST [15] was adapted to the CT-scan data. The burning algorithm is a kind of algorithm similar to point diffusion: to check the continuity, the fibers pixels are thought as combustible. Fibers pixels are set on fire along one face of the test sample, and fire diffuses to adjacent connected points until no more pixels can be burned. If all the pixels are connected, the fire will extend completely across the sample. For the sample with sand–bitumen ratio 2.90, it was found that the total volume of fibers in the mixture was 2.14%, and if burning from one side, 74.16% of fibers were connected in a path to the other side. Otherwise, for the sample with sand–bitumen ratio 2.26, the total volume of fibers in the mixture was 3.38% and 86.4% of them were connected in a though path to the other side. In both cases, fibers were connecting both sides of the sample. From these values is confirmed how in a mixture with the volume of fibers fixed, if the sand–bitumen ratio is increased above the optimum, the total volume of fibers and the percentage of fibers connected are reduced, and how if the sand–bitumen ratio is increased, the total length of the shortest conductive path is also increased. Finally, this also means that it is possible to use CT-scan reconstructions to check if the volume of fibers is enough to percolate.

Otherwise, from the visual inspection of the pictures it is evident that the fibers are connected in closed-loop circuits. This is very important for the induction heating, because a condition imposed on the material is that closed-loop circuits must be present for eddy currents to be induced [16]: when a magnetically susceptible and electrically conductive material is placed in the vicinity of the coil, eddy currents are also induced in the material, with the same frequency of the magnetic field. Heat is generated through the energy lost when eddy currents met with the resistance of the material

4. Application sample

In this paper we point out that one of the main applications of conductive asphalt is heating it with induction energy to increase its self-healing rate. It is well known that asphaltic materials are self-healing and that an increase of temperature is a key factor for the self-healing rates. Traditionally, it was thought that to obtain some healing in roads, rest periods should be introduced in traffic. Although this research is still the first step on a long way to obtain fast self-healing roads, authors think that it would be helpful to show how asphalt is heating.

To have an idea of the applicability of the system, in Fig. 9 the heating curves for three different samples with 3.27%, 6.14% and 8.77% steel wool (related to the volume of bitumen) and sand–bitumen ratio 2.26 are showed. For the three samples studied, temperature clearly increases very fast with the induction heating. The heating system was not optimized, so the heating could even be faster, but it is enough to show how the system works. These three curves correspond to samples in Fig. 4. The samples with 3.27%, 6.14% and 8.77% steel wool have resistances of $3.16 \times 10^{11}\ \Omega$ m, 98 Ω m and 37 Ω m, respectively. It is shown that, differently to the traditional electrical heating, mastic is heated independently if it is electrically conductive or not, which gives this system clear advantages. The difference is the speed of heating, which will be higher if the resistivity is lower. The reason for heating was explained above, for induction heating it is not necessary to have a

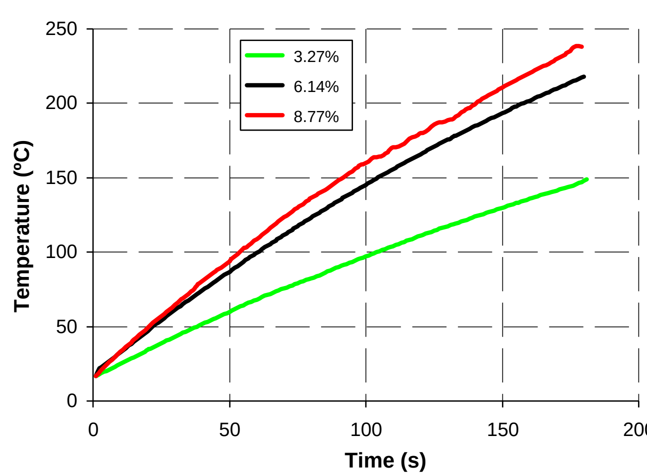

Fig. 9. Heating curves for samples with different volumes of steel wool (related to the volume of bitumen) and sand–bitumen ratio 2.26.

conductive material; the only condition is that fibers should build conductive closed-loops. Of course, if the volume of fibers is enough to percolate, eddy currents will increase their action range and heating will be faster and deeper. In addition, steel wool is also heat-conductor, which means that if the fibers are not isolated, the heating will be faster.

From these data can be concluded that the decision of the optimum volume of fibers will depend on the optimum speed of the inductor on the road and on the temperature needed for healing. Although these tests are not enough to check the applicability of the concept, they give a very good idea of how the system works. Future research will focus on the relationship between the temperature reached and the electrical conductivity of asphalt mortar, so as the definition of the healing parameters with the induction heating.

5. Conclusions

In this paper, knowledge about how to make conductive mastic has been greatly improved. It has been discovered that sand–bitumen ratio is a key factor in the design of the conductive mixture and that it cannot be considered separately from the volume of conductive particles added. It has been also discovered that it is much more effective to reach the desired conductivity with conductive fibers rather than with conductive fillers. There is an optimum volume of conductive fillers for each sand–bitumen ratio, above which clusters of fibers start appearing in the mixture and bellow which, asphalt mortar is bellow the percolation threshold and the mixture is not conductive any more. Otherwise, it is necessary to have a minimum amount of bitumen around the aggregates to have a good mixture; if this minimum film thickness does not exist, then it is impossible to mix the fibers in the asphalt concrete. Besides, it was demonstrated that it is possible to use CT-scan reconstructions to check if the volume of fibers is enough to percolate.

It has also been discovered that if the optimum conductivity is reached with fibers, a small increment in the sand–bitumen ratio can force an increase in the resistivity or a small decrement on the sand–bitumen ratio can make the mixture non conductive. Each mixture is different; it depends on the type of aggregates used, the sand–bitumen ratio, the type of conductive fibers, its length and thickness, the type of fillers, etc. For that reason, a combination of fibers and filler has been proposed: fibers to reach the optimum conductivity and a small volume of filler to stabilize the resistivity. Each mixture should be analyzed separately by increasing the volume of fibers added until the percolation threshold is found. Once there, enough conductive filler should be added, until the conductivity does not change any more. It has been also discovered that these data follow a lognormal distribution. A small error in the mixture will make the resistivity to grow exponentially

Finally, the applicability of the system has been experimentally demonstrated: three different samples with a fixed sand–bitumen ratio and different volumes of fibers were heated. It is concluded that even with a minimum volume of fibers, not enough to have a conductive asphalt mortar, the mixture can be heated. This happens because fibers form magnetically susceptible and electrically conductive closed-loops circuits. It was also observed that the lowest the resistivity, the highest the heating rate, so the healing system should be engineered depending on the speed of the inductors on the road.

Acknowledgments

The authors acknowledge the financial support from the Delft Centre for Materials (DCMat) in the form of Project SHM0617, "Unravelling of porous asphalt". Furthermore, the helpful discussions with Prof. A. Molenaar (Delft University of Technology) on self-healing materials and the help of Arjan Thijssen are gratefully acknowledged.

References

[1] Little DN, Bhasin A. Exploring mechanisms of healing in asphalt mixtures and quantifying its impact. In: van der Zwaag S, editor. Self healing materials an alternative approach to 20 centuries of materials science. Series in materials science, 100. Springer; 2007. p. 205–18.
[2] Bonnaure FP, Huibers AH, Boonders A. A laboratory investigation of the influence of rest periods on the fatigue characteristics of bituminous mixes. J Assoc Asphalt Pav Technol 1982;51:104–28.
[3] Jo SD, Richard KY. Laboratory evaluation of fatigue Laboratory evaluation of fatigue healing of asphalt mixtures. J Mater Civ Eng 2001;13(6):434–40.
[4] Farrar JJ. Electrically conductivity concrete. GEC J Sci Technol 1978;45(1):45–8.
[5] Wu S, Mo L, Shui Z, Chen Z. Investigation of the conductivity of asphalt concrete containing conductive fillers. Carbon 2005;43(3):1358–63.
[6] Wu S, Liu X, Ye Q, Li N. Self-monitoring electrically conductive asphalt-based composite containing carbon fillers. Trans Nonferr Metals Soc China 2006;16:512–6.
[7] Sherif YH, Christopher YT. Conductive concrete overlay for bridge deck deicing. ACI Mater J 1999;96(3):382–90.
[8] Tang ZQ, Li ZQ, Hou ZF. Mechanism analyzing on deicing of snow melting of electrical conductive concrete. Concrete 2001;141(7):25–36.
[9] Tuan CY. Electrical resistance heating of conductive concrete containing steel fibers and shavings. ACI Mater J 2004;101(1):65–71.
[10] Chen B, Wu K, Yao W. Conductivity of carbon fiber reinforced cement-based composites. Cem Concr Compos 2004;26:291–7.
[11] Lee SJ, Rust JP, Hamouda H, Richard Y, Borden R. Fatigue cracking resistance of fiber reinforced asphalt concrete. Text Res J 2005;75:123–8.
[12] Stauffer D. Introduction to percolation theory. London: Taylor and Francis; 1985.
[13] Weber M, Kamal MR. Estimation of the volume resistivity of electrically conductive composites. Polym Compos 1997;16(6):711–25.
[14] Sevkat Ercan, Li Jackie, Liaw Benjamin, Delale Feridun. A statistical model of electrical resistance of carbon fiber reinforced composites under tensile loading. Compos Sci Technol 2008;68:2214–9.
[15] Garboczi EJ, Bentz DP. In: Mindess S, editor. Advances in Cementitious Materials. Ceramics Transactions 1991;16:365–80.
[16] Ahmed TJ, Stavrov D, Bersee HEN, Beukers A. Induction welding of thermoplastic composites-an overview. Composites: Part A 2006;37:1638–51.