Self-healing technology for asphalt pavements

Tabakovic, A; Schlangen, E

DOI
10.1007%2F12_2015_335

Publication date
2016

Document Version
Accepted author manuscript

Published in
Advances in Polymer Science

Citation (APA)
Tabakovic, A., & Schlangen, E. (2016). Self-healing technology for asphalt pavements. *Advances in Polymer Science*, (November), 1-22. https://doi.org/10.1007%2F12_2015_335

Self-healing Technology for Asphalt Pavements

Amir Tabaković[1]; Erik Schlangen[1]

1. Materials and Environment, Faculty of Civil Engineering & Geosciences, Delft University of Technology, Delft, The Netherlands.

Email: A.Tabakovic@tudelft.nl and Erik.Schlangen@tudelft.nl

Abstract

Self-healing technology is a new field within material technology. It represents a revolution in materials engineering and is changing the way that materials behave. Incorporating self-healing technology into the road design process has the potential to transform road construction and maintenance processes by increasing the life span of roads and eliminating the need for road maintenance. By decreasing the unnecessary premature ageing of the asphalt pavements, self-healing asphalt will reduce the amount of natural resources used to maintain road networks, decrease the traffic disruption caused by road maintenance processes, decrease CO_2 emissions during the road maintenance process and increase road safety. As well as environmental savings, self-healing materials have the potential to deliver significant cost savings for road network maintenance across the EU. There are three main self-healing technologies available for asphalt pavement design; nanoparticles, induction heating and rejuvenation. This paper reviews all three options and outlines the future development of the self-healing asphalt technology.

Key words: Self-healing, Asphalt Pavements, Induction Heating, Microcapsule, Rejuvenation, Nanoparticles.

1 Introduction

The global road network spans 16.3million km [1], of which 5millionkm is in EU, 4.4mil.km is in USA and 3.1mil.km is in China [2]. Road networks fulfil a major economic and social goal by facilitating the movement of goods and people. The operational health of the road network is of the utmost importance for national and regional economic and social life. As a result governments invest heavily in the development and maintenance of national and regional road networks. In 2009, EU governments invested 42% (€4.5bil.) of the EU transport network fund (€10.74bil.) into the development and maintenance of EU road networks [2]. The development and maintenance of the EU road network is critical to the growth and competitiveness of the EU economy.

A typical, modern, road system is comprised of double or triple asphalt layers [3] which have an expected lifespan of 20 to 40 years [4]. Recent research highlights the importance of developing long-life or perpetual pavements and has called for innovation to prolong pavement lifespan and reduce maintenance [5, 6]. The development of self-healing asphalt and its use in road paving is an innovation which could potentially double road lifespan to between 40 and 80 years and could significantly reduce road maintenance activity. In comparison to current maintenance processes, self-healing asphalt has the potential to improve traffic flow, reduce demand for fresh aggregates, reduce CO_2 emissions and enhance road safety. The excellent durability of self-healing materials does not arise from the classical approach of minimising damage but from the novel approach of designing materials with 'self-healing' capabilities.

The objective of self-healing technology is to enable/assist material systems to heal after damage . It aims to reduce the level of damage and to extend or to renew the functionality and life-time of the damaged part [7]. Fisher defines the self-healing and self-repair of a material or system as: "*the ability to substantially return to an initial, proper operating state or condition prior exposure to a dynamic environment by making the necessary adjustments to restore to normality and/or the ability to resist the formation of irregularities and/or defects*"[7].

The repair is, in principle, an automatic initiated response to damage or failure. In order to perform repair, any self-healing system must be capable of identifying and repairing damage. Fisher classifies repair into two categories:

Attributive repair – restoring the attributes of the system to its original state, i.e. to full capacity.

Functional repair – restoring the function of the system. If full functionality cannot be restored, the remaining available resources will be employed/used to maximise the available functionality.[7]

Attributive repair is the optimal solution. If the attempt to restore the system to its complete original condition fails, there is still significant benefit to be gained, in most instances, if the system continues to operate, even with reduced functionality. Living organisms possess intrinsic self-healing properties, enabling them to recover from damage or injuries sustained. This repair or healing occurs with no external intervention. Some natural self-healing composite systems - such as bones - go beyond simple healing to continuous remodelling and strengthening [8]. Over the past decade, self-healing technology has entered the field of materials engineering [7]. Self-healing technology represents a revolution in materials engineering. Examples of engineering materials to which self-healing technology has been successfully applied are presented in Table 1.

Table 1. Materials to which self-healing technology has been successfully applied.

Material	Healing Mechanism	Reference	Year
Polymer	Healing agent encapsulation	Jin et al. [9]	2012
Concrete	Bacteria	Jonkers and Schlangen [10]	2009
	Hollow Fibres	Dry [11] cited in [12]	1996
	Microencapsulation	Boh and Šumiga [13] - cited in [12]	2008
	Expansive agents and mineral admixtures	Kishi et. al. [14] - cited in [12]	2007
Asphalt	Nanoparticles	Tabatabee and Shafiee [15]	2012
	Steel fibres – Induction heating	Garcia et. al.[16]	2011
	Rejuvenator encapsulation	Su et. al. [17]	2013
Coatings	Healing agent (resin) encapsulation	Wilson and Magnus[18]	2011

Composites	Memory alloys	Kirkby et al. [19]	2008
Metals and Alloys	Press and sinter powder metallurgy	Lumley [20]	2007

1.1 Self-healing properties of asphalt pavement

Asphalt pavement is a self-healing material. When subjected to rest periods, asphalt pavement has the potential to restore its stiffness and strength by closing the microcracks which occur when the pavement is subjected to traffic loads. Research to date has focused on its autogenous healing properties (see Table 2).

Table 2. Factors influencing the autogenous healing properties of asphalt pavement.

Factors influencing healing		Reference	Year
Bitumen properties	Bitumen type	van Gooswiligen et al. [21]	1994
	Viscoelastic properties	Kim and Little [22]	1991
	Surface free energy	Lytton et al. [23]	1993
	Ageing	Edward [24]	2006
	Diffusion	Bhasin et al. [25]	2011
	Modifiers	Lee et al. [26]	2000
Asphalt mix composition	Bitumen content	van Gooswiligen et al. [21]	1994
	Aggregate structure	Kim and Roque [27]	2006
	Gradation	ABO-Qudais and Suleiman [28]	2005
	Thickness	Theyse et al. [29]	1996
Environment	Temperature	Verstraeten [30]	1991
	Loading history	Castro and Sanchez [31]	2006
	Rest period	Little and Bhasin [25]	2007
	Water/Moisture	Hefer and Little [32]	2005

A crack repair in an asphalt pavement system occurs due to the wetting and inter-diffusion of material between the two faces of a micro-crack to achieve properties of the original material [7, 33]. The three primary steps in the autonomous asphalt self-healing process are as follows:

1) wetting of the two faces of a micro-crack,

2) diffusion of molecules from one face to the other and

3) randomization of the diffused molecules to reach the level of strength of the original material.

Binder is key to the self-healing process in an asphalt pavement. Self healing takes place on a molecular level where when broken (non-associated) molecules are available, to form links and chains via hydrogen bonds [7]. The process is termed “reversible hydrogen bonding” [34]. This is achieved by bringing together the associated molecules to form both chains and crosslinks via hydrogen bonds [7]. A repaired molecular network can be formed by linking ditopic and tritopic molecules [35], which are able to associate with each other, see Figure 1. This system, when broken or cut, can be simply repaired by bringing in contact two fractured surfaces, [34-36].

Qiu et al [36] reported that self-healing process in an asphalt pavement system is a viscosity-driven process, dependent on time (rest periods) and temperature. Qiu et al [36] also demonstrated the self-healing time and temperature dependency of bituminous materials, see Figure 2. A longer healing time and increased healing temperature leads to better healing [36]. Shorter time to heal will result in the formation of fewer bridges across the interface and the development of a weaker bond across the break. However, if broken bonds are not healed immediately, i.e. if the fractured surfaces are not brought into contact with each other, the number non associate groups available for linking decreases, i.e. healing efficiency decreases[35]. This is because, immediately after breakage, the free (non-associated) groups begin to seek other free groups within the broken part to link with [35].

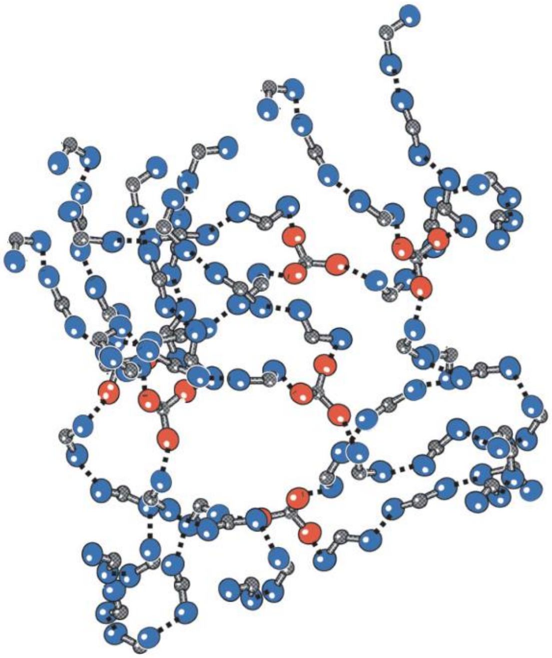

Figure 1. Supramolecular network. Schematic view of a reversible network formed by mixtures of ditopic (blue) and tritopic (red) molecules associating by directional interactions (represented by dotted lines)[35].

Qiu et al. [36] successfully modelled the time-temperature dependency of the self-healing process in asphalt mastic using a time-temperature superposition principle, which can be expressed the following formulation:

$$H(t,T) = 100 \times \left[1 + \left(\frac{m}{t \times \alpha_T}\right)^{\frac{log2}{n}}\right]^{\frac{n}{log2}} \quad (1)$$

Where: the time-temperature superposition shift factor in equation (1) is based on the Arrhenius equation and is calculated using the following formulation:

$$log\alpha_T(T) = \frac{\Delta E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_0}\right) \quad (2)$$

Where: α_T – is the time-temperature superposition shift factor; m, n – are the model parameters; ΔE_a – is the apparent activation energy, (J/mol) and R – is the universal gas constant, 8.314 J/(mol·K).

The healing of an asphalt pavement that occurs at high temperatures is governed by the so-called 'Thixotropic effect', which describes the transformation of asphalt binder from a solid to a gel state, allowing recovery from structural damage [30].Wu reported that visible in-situ cracks within asphalt pavements disappear during periods of warm weather only to reappear during cold weather [37]. At high temperatures, surface cracks close, but high temperatures dissipate quickly throughout the pavement depth [38], meaning that cracks 20 – 30 mm below the pavement surface do not heal and re-appear during lower temperatures or as a result of heavy traffic loading. Results presented in Figure 2 show that the healing progress of both the PBmas and the SBSmas is only 10% after healing at 10°C. Following the results from Qiu et al.[36], it can be concluded that temperatures below 20^{o}C are insufficient to initiate full recovery of asphalt pavements. However, the self-healing properties of asphalt can be enhanced either by heating the asphalt material or by adding, modifiers or a healing agent, i.e. rejuvenator.

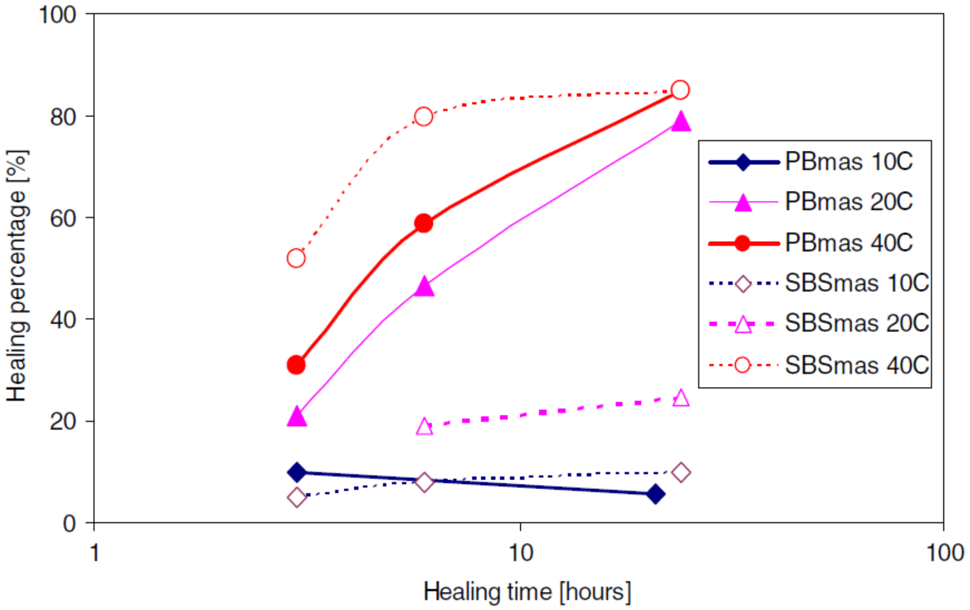

Figure 2 Self-healing results of PBmas (asphalt mastic mix containing limestone filler and 70/100 pen bitumen) and SBSmas (asphalt mastic mix containing limestone filler and Styrene-Butadiene-Styrene (SBS) polymer modified bitumen) [36].

2 Examples of Self-healing Technology for Asphalt Pavements

The asphalt pavement design standards focus on enhancing asphalt pavement performance, i.e. aim to increase its durability and improve its load-carrying capability [39]. However, the authors consider that future of asphalt pavement design lies not within the enhancement of asphalt pavement properties, but in allowing it to repair itself to its original state.

As in nature, the self-healing performance of an asphalt pavement can be improved, e.g. modifiers and additives can be introduced to the asphalt mix to upgrade its self-healing properties. In order to work in an asphalt pavement system, the self-healing technology must have the capacity to survive harsh conditions that prevail during asphalt pavement construction (mixing and compaction) and service life (traffic loading and environmental conditions, such as: rain, ice, snow, high temperatures, etc.). Qiu et al. [34] outlined five essential conditions for self-healing to be included into asphalt pavement design:

1. good compatibility with bitumen,
2. high temperature stability,
3. the ability to survive mixing and construction conditions,
4. a healing temperature of between -30^{o}C and 40^{o}C and
5. capable of continuous/multi-time healing.

In this section a number of existing self-healing approaches for Asphalt Pavement design are presented and critically analysed with respect to their functional design and performance.

Three self-healing methods for asphalt pavements have been reported to date, they are:

1. Nanoparticles,
2. Induction heating and
3. Rejuvenation.

2.1 Nanoparticles

2.1.1 Nanoclay

The nanoclay materials are used in asphalt pavement design in order to improve the ageing, rheological and thermal properties of asphalt mixtures [40]. However, they also have the potential to repair microcracks in asphalt [34]. The nanoparticles tend to move towards the tip of the crack driven by the high surface energy, thus stop the crack propagation and to heal damaged asphalt material [34]. Tabatabee and Shafiee [15] studied effect of rest periods on fatigue life of organoclay modified asphalt mix and found that introduced rest periods at 3% and 5% strain level increased fatigue resistance of asphalt mixes containing organoclay modified asphalt mixes. This finding illustrates that nanoclay material can be used for improving the self-healing properties of asphalt mixtures. However, the nanoclay self-healing technique has not been researched in any great detal to date and there is insufficient data available on the long term effect of the nanoclay particles on the self-healing asphalt mix performance. This is an interesting area for future research.

2.1.2 Nanorubber

As with nanoclay material example above, polymer and rubber modifiers are used in the bitumen mix to improve the physical and mechanical properties of the binders and as such to improve in-situ performance of an asphalt pavement [41-43]. The rubber modifiers in form of nanoparticles have also been used to improve healing properties of the asphalt mastic [34]. Qiu et al. [34] studied the repair of asphalt mastic with nanorubber modified binder (70/100 pen binder). They conducted ductility self-healing tests to assess the self-healing capacity of the asphalt mastic, containing two different types of nanorubber modifier (NanoA and NanoB) and varying percentages of the modifier (0% - 5%), where 0% was a control mix. The tests were performed on dog bone test specimens. The test specimens were cut at centre, joined and left to heal for 4 hours at room temperature(20-22°C). The test results showed good self-healing for non modified asphalt mastic mixes, up to 70%. Recovery of the modified asphalt mixtures varied from 15% - 90%, depending on the type of nanorubber modifier and the amount

[34]. Unfortunately, the authors did not present the composition of the nanorubber modifier, so it is difficult to determine what type of healing mechanism activated the healing process and to understand the variability of the healing performance. Nevertheless, the study shows that nanorubber modifiers can be used to improve the self-healing properties of asphalt mixtures. Future studies should show properties of nanorubber modifiers, i.e. whether they are styrene-butadiene-rubber (SBR), styrene-isopane-styrene (SIS) or oilfinic rubber. This would enable a determination of the type of healing mechanism that has occured, i.e. whether it was reverse hydrogen bonding. The clear advantage of this self-healing modifier is its double role, it can improve asphalt mix durability, but also it could be used as self-healing modifier in the mix. However, the disadvantage of polymer based modifiers is the thermodynamic incompatibility with asphalt binder due to the large differences in material density, polarity, molecular weight and solubility between the polymer and the asphalt [40]. This can result in delamination of the composite during thermal storage, which is not readily apparent and adversely affects the asphalt mix when it is use [40]. The thermodynamic incompatibility of nano modifiers need to be studied, because at high temperatures the separation of nanorubber modifier and binder could take place, which would result in a detioration of asphalt pavement performance.

The nano effect and reverse hydrogen and ionic bonding are known for their multi healing abilities [34], which is a benefit of this type of self-healing mechanism. However, the effect of healing time and temperature need to be further investigated to determine what effect time has on the healing of the asphalt mix. If ineffective at lower temperatures and without improvements in healing times relative to autonomous bitumen healing, the technology would be rendered unsuitable for the self-healing of asphalt pavements.

Although the nanoparticle self-healing technology demonstrated its potential in asphalt pavement mix design, more substantial evidence of its performance must be demonstrated before it becomes acceptable as viable self-healing technology.

2.2 Induction heating

Induction heating in asphalt pavement design was pioneered by Minsk [44, 45]. He developed and patented the first electrically conductive asphalt pavement using graphite as a conductive medium for the purpose of melting snow and ice on roadway surfaces by induction heating. More recently, induction heating has regained popularity in asphalt pavement research, to improve self-healing in asphalt pavements [46-49]. The electrically conductive fibres and fillers (carbon fibres, graphite, steel fibres and wool and conductive polymer Polyoniline (PANI)) were added to study the electrical conductivity in asphalt pavement and showed that the electrical resistivity significantly varied with the type, shape and size of fibres and filler. Wu et al. [46] studied induction heating in asphalt pavement using conductive carbon fibres, carbon black and graphite as conductive media and demonstrated that adding conductive fibres to the mixture increases conductivity more effectively than adding conductive filler. Subsequent research by Garzia et al. [47] and Liu et al. [48] initiated the development of a self-healing asphalt pavement mix by inclusion of electrically conductive steel and wool fibres into the asphalt mix and activating self-healing by induction heating.

The induction process operates by sending an alternating current through the coil and generating an alternating electromagnetic field. When the conductive asphalt specimen is placed under the coil, this electromagnetic field induces currents flowing along the conductive loops formed by steel fibres [50]. This method can be repeated if damage returns. A schematic diagram of induction healing is illustrated in Figure 3.

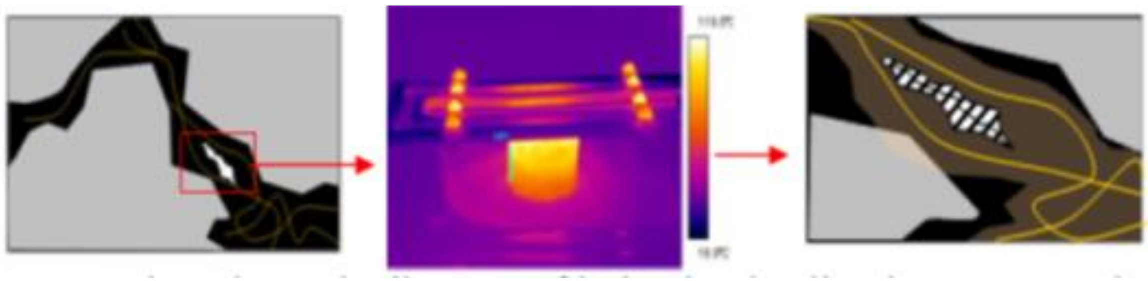

Figure 3. Induction healing in porous asphalt [51]

The major healing mechanism of induction healing is the capillary flow and diffusion of the asphalt binder (bitumen) at high temperatures. García [50] verified this healing mechanism using the bitumen capillary flow tests. Liu et al. [51] studied the induction healing effect of steel fibres and steel wool and characterised the asphalt healing via the following equation:

$$HI = \frac{C_2}{C_1} \qquad (1)$$

where:

HI = the healing index (%), where 100% - the complete healing of damaged is achieved and 0% - no healing at all;

C_1 = number of the loading cycles for the first time loading;

C_2 = number of loading cycles for the second time loading.

Figure 4 is a fatigue test result performed by Liu [51] showing two values of the loading cycle C_1 and C_2. The loading value C_2 illustrates the effect of the induction healing.

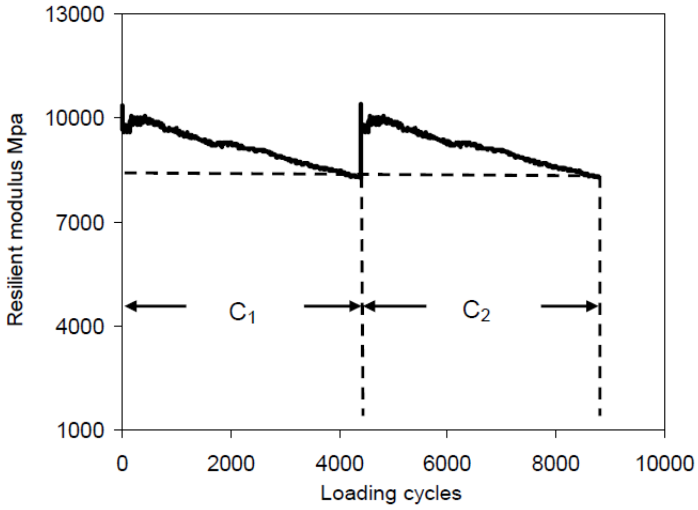

Figure 4. Fatigue recovery of porous asphalt concrete cylinder for resilient modulus reduction to 80% [51].

Liu et al. [48] investigated the effect of long steel wool type 000 vs short steel fibre. The results showed that long steel wool, is better than short steel fibre for making porous asphalt concrete electrically conductive.

Liu et al. [48] demonstrated that the addition of steel fibres reinforces the mastic (bitumen, filler and sand) of porous asphalt concrete, which would delay the ravelling effect in asphalt pavement. Liu et al also demonstrated that the inclusion of steel fibres into the asphalt pavement mix prevents the drainage of bitumen from the surface of the asphalt pavement. The advantage of this is that it achieves a better bond between the large aggregates (stones) in the pavement.

Although induction healing has demonstrated that it can enhance the self-healing capacity of asphalt pavement, an adverse effect is that heating the asphalt mix ages the bitumen. Furthermore, overheating (> 110^{o}C) the asphalt mix can cause binder swelling and drainage, which will adversely affect the pavement performance. Liu et al. [48], suggested that the optimal heating temperature for a porous asphalt mix is 85^{o}C. Liu [51] demonstrated that the degree of damage incurred by over-heating also affects the healing ratio, i.e. the heating should not be applied too early or too late. If applied too early (when resilient modulus is >80% of original asphalt pavement stiffness value), the asphalt pavement can heal itself and heating is not required. However, if the asphalt is heated too late (when resilient modulus value is < 80% of the original asphalt pavement stiffness value), the healing effect will be poor, because structural damage such as permanent deformation or stone aggregate cracking can occur and such damage is beyond the healing capacity of the induction healing process. Liu [51] further concluded that the best healing results were achieved when induction heating was combined with a rest period. This study demonstrated that healing can be improved by 15% if the autogenous healing process is aided by induction heating.

In December 2010, researchers from TU Delft in cooperation with the Dutch National Roads Authority resurfaced a road (the A58 in Netherlands) using an induction self-healing asphalt mix, i.e. an asphalt mix containing 1cm long steel fibres [52]. The testing of the self-healing process within the A58 motorway is ongoing at present [52].

Inductive heating is the most progressive self-healing technology for asphalt pavements reported to date. This technology has transitioned from lab to site in a short period of time (3 years). Although its ageing effect can be compensated for by the healing effect, a problem that has not been addressed by research is the loss of conductivity via oxidation (corrosion) of the steel wool and fibres. However, this should not be an insurmountable problem, as steel could be replaced with carbon fibres and/or conductive polymer [49, 53]. In addition, the piezoresistivity of conductive asphalt, which refers to the change in electrical resistivity with applied mechanical pressure, can be used for self-sensing of strain [54]. Self-sensing of damage for evaluating pavement distress is possible if the relationship between the electrical property and internal damage is provided. Moreover, some conductive additives may improve the durability of asphalt concrete, thereby increasing the service life of the pavement systems [48, 55, 56].This aspect of self-healing induction technology needs to be further developed for the initiation of healing process and also for self-health assessment of asphalt pavement.

2.3 Binder healing agent (Rejuvenation)

During the service life of a pavement, the volatile components of bitumen evaporate and oxidation and polymerisation may occur [57] and as a result, the bitumen ages and loses part of its viscoelastic properties. Asphalt binder is a combination of asphaltenes and maltenes (resins and oils). Asphaltenes are more viscous than either resins or oils and play a major role in determining asphalt viscosity [58, 59]. The oxidation of aged asphalt binder during construction and service cause the binder oils to convert to resins and the resins to convert to asphaltenes, resulting in age-hardening and a higher viscosity binder than fresh binder [59, 60]. Although this process is irreversible, the viscoelastic state of the asphalt mix can be recovered through the addition of either bitumen with a higher penetration value or a rejuvenating agent such as cationic emulsions [61-63].

A rejuvenator is an engineered cationic emulsion containing maltenes and saturates. The primary purpose of a rejuvenator is to reduce the stiffness of the oxidized asphalt binder and to flux the binder to extend the pavement life by adjusting the properties of the asphalt mix (Brownridge, 2010). Some commercially available rejuvenating agents are: Reclamite, Paxole 1009, Cyclepave and ACF Iterlene 1000. A recent study by Su et al.

[64] demonstrated that a by-product of waste cooking oil can also be used as binder rejuvenator.

2.3.1 Self assembled monolayers

When the cracks within the surface layer of the asphalt pavement are still in an early phase, it is possible to apply a rejuvenator to the wearing course to prevent further crack propagation and pavement failure [65]. By applying the rejuvenator to the surface course, the life span of the asphalt pavement can be extended by several years, however, this only applies to the top centimetres of the asphalt pavement. Shen et al. [66] reported on the use of three different types of rejuvenators and found that none could penetrate further than 20mm into asphalt concrete. A further issue encountered when applying these materials is the necessity of road closures for a period of time after the application. The rejuvenators may also cause a significant reduction in the surface friction of the pavement and may also be harmful to the environment. Microencapsulation of the rejuvenators represents a potential means of overcoming these problems.

2.3.2 Microcapsule technique

The inclusion of a rejuvenator into the asphalt mix via micro capsules to restore the original binder properties is a self-healing method studied by Su et al. [64, 67], Su and Schlangen [68] and García et al. [69]. The principle behind this approach is that when micro cracks begin to form within the pavement system, they will encounter a capsule in the propagation path. The fracture energy at the tip of the crack will open the capsule, and release the healing agent. The healing agent will then mix with the asphalt binder to seal up the crack, thus preventing its further propagation. This healing process is illustrated in Figure 5. The process prevents the formation of micro cracks within the pavement mix and will prevent the complete failure of the pavement system. Su and Schlangen [68] and García et al. [69] demonstrated that various types of capsules containing rejuvenator can be produced and that these capsules are sufficiently thermally and mechanically stable to survive the asphalt production process.

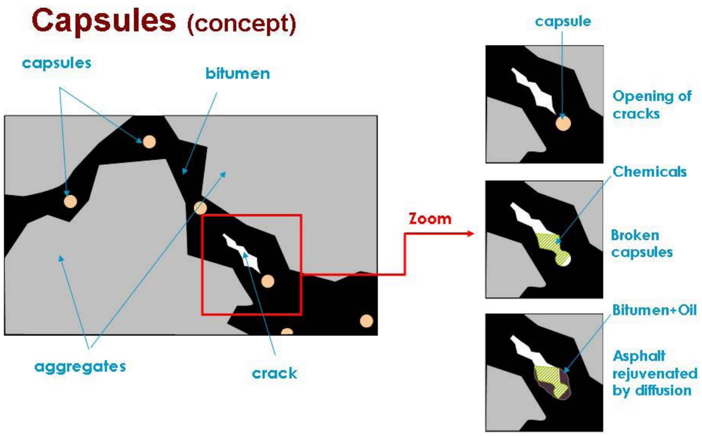

Figure 5. Self-Healing Mechanism in Asphalt Concrete[69].

To date, the most successful micro capsule shells have been made of a prepolymer of melamine – formaldehyde modified by methanol (solid content was 78.0%) and the rejuvenator is an oily product [17]. Figure 6 illustrates the fabrication process of double-shell microcapsules containing rejuvenator by a two-step coacervation (TSC). The efficiency of the microcapsule fabrication is measured by amount of rejuvenator retained within the microcapsule [68]. The highest efficiency achieved is 70% [67] under following production conditions: core:shell ratio of 1:3, stirring speed 3,000rev/min and 2.0 – 2.5 Styrene maleic anhydride (SMA) copolymer dispersant. Figure 7 shows SEM morphology of dried microcapsules with core/shell ratio 1:3 and with an average shell diameter of 25μm.

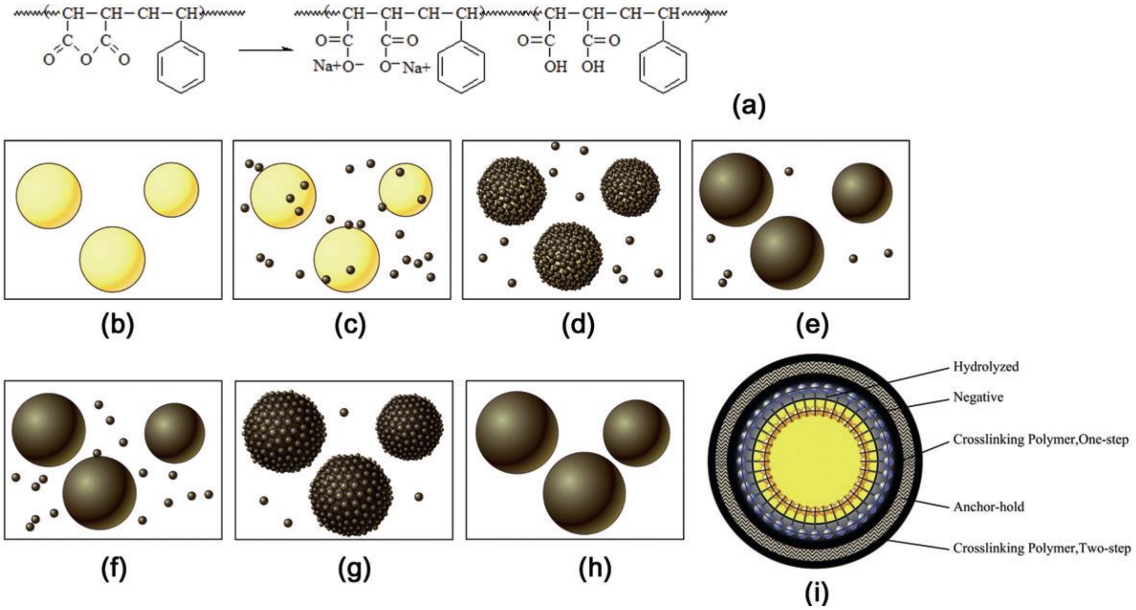

Figure 6. Sketch mechanism of the fabrication process of double-shell microcapsules containing rejuvenator by a two-step coacervation (TSC) method: (a) chemical structure of SMA alternating copolymer and hydrolysis polymer, (b–e) the first step coacervation, (f–h) the second step coacervation, and (i) the micro-structure of microcapsules by TSC method [68].

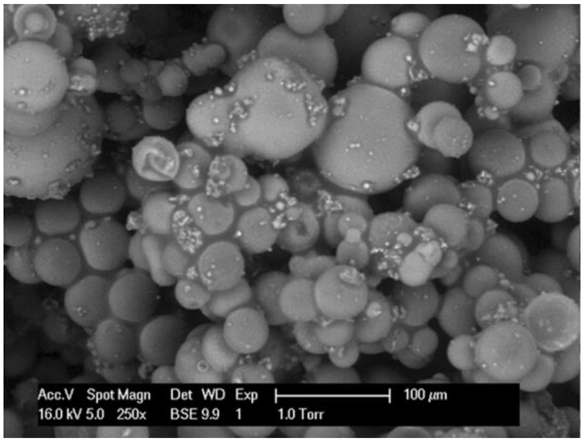

Figure 7. SEM morphologies of microcapsules containing rejuvenator [67].

The asphalt mortar films between aggregate particles in an asphalt pavement are found to be ≈ 50μm [67]. In order to avoid being squeezed or pulverised during the asphalt pavement mixing and compaction process, the size of the capsule needs to be less than 50μm. However, Su et al. [67] stated that micro capsules of 10μm and smaller size are unsuitable for self-healing as they do not contain sufficient rejuvenator to rejuvenate the aged binder. The size of the capsule can be controlled by regulating the core:shell ratio (weight ratio between core and shell material). This can be achieved by modifiying the prepolymer and the speed and emulsion stirring rate [67]. Figure 8 shows the morphology of bitumen containing varying capsule content (10% – 30% of total binder volume) and size (10 µm – 30 µm). Figure 8a_1, a_2, shows that microcapsules with a mean size of below 10µm tend to congregate/attract due to the electrostatic attraction of tiny particles. In Figure 8b_1, b_2, microcapsules of 20µm size have a homogeneously distillation preventing from hard agglomeration. Figure 8c_1, c_2 shows larger microcapsules (30µm size) with bitumen dispersing content of 10% and 30%. Figure 8c_2 shows that large micro capsules will occupy more space, where the bitumen dispersion content is 30%. This phenomenon may lead to the interface separation between microcapsules and binder and may result in the formation of microcracks or other structural defects [67, 70]. This may result in poor mechanical performance of the asphalt pavement and may result in premature pavement failure. In conclusion, the optimum content of microcapsules in bitumen must comprise no more than 30% of overall bitumen volume within an asphalt mix needs to be less than 30% of bitumen volume in an asphalt mix [67].

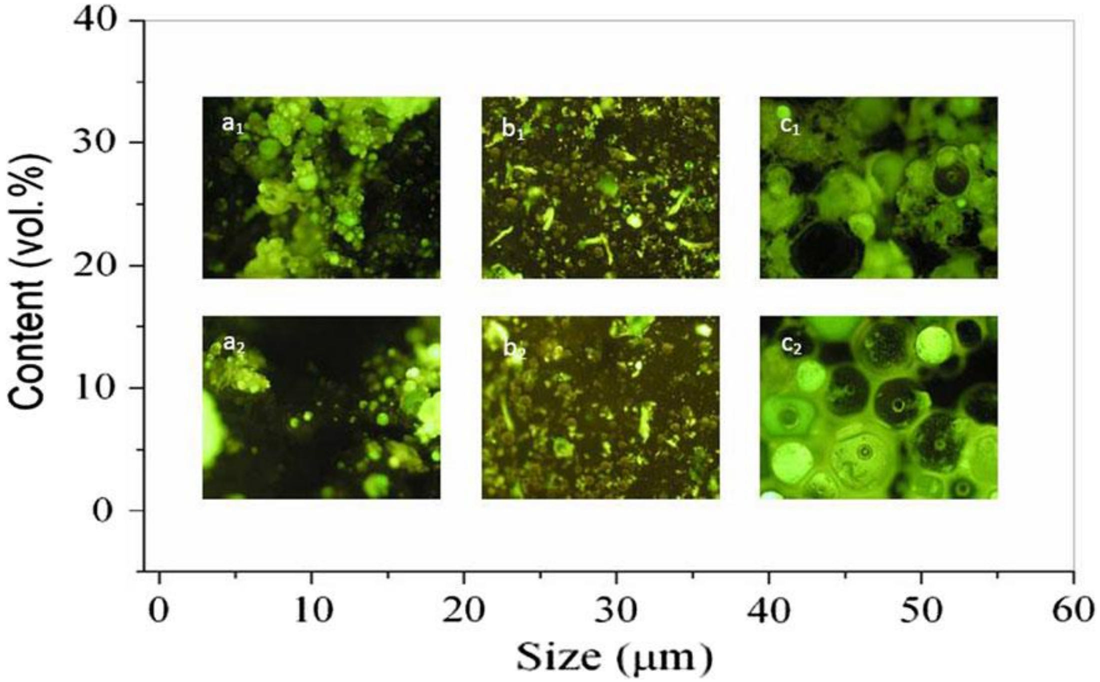

Figure 8. Fluorescence microscope morphologies of bitumen samples with different contents of microcapsules [67].

More recently Su et al. [64] demonstrated that rejuvenators produced from recycled waste cooking oil (WCO) can be encapsulated and used in the asphalt self-healing technology. The capsules can survive the harsh asphalt production process, with high capsule shell strength, of 1.0 – 1.52GPa – c/s ratio of 1:3 and good thermal stability (a melting point of 180^{o}C). This research demonstrated that WCO rejuvenator can successfully penetrate and rejuvenate standard bitumen binder of 80/100pen value, and defuse it at low temperature (0^{o}C), see Table 3.

Table 3. Properties of virgin and WCO rejuvenated bitumen at 0^{o}C [64].

Material property	Original bitumen (80/100pen)	Aged bitumen (40/50pen)	Rejuvenated aged bitumen with microWCOs (wt.%)					
			2	4	6	8	10	12
Penetration @ 25^{o}C (d-mm)	86	43	52	61	74	82	84	88
Softening point (^{o}C)	46.7	53.5	52.0	51.2	50.3	48.4	46.4	45.0
Viscocity @ 135^{o}C (mPa s)	325	578	570	520	470	390	333	310

The microcapsule approach presents a more favourable solution for the asphalt self-healing process, as it allows for the rejuvenation of aged binder, i.e. returns it to its original physical and mechanical properties. However, the downside to this approach is that it works only once, i.e. once the healing material is released from the microcapsule it cannot be replenished [34]. Nevertheless, this self-healing process is still in its early development stage and its full potential will be demonstrated in coming years. Methods for introducing a reasonable dose of micro capsules into the asphalt mix to achieve appropriate dispersion of capsules throughout the asphalt mix and enhancement of the multi-phase self healing process need to be the focus of future research work in this field.

3 Towards New Generations of Self-healing Asphalt Pavements

The key aim of the self-healing asphalt pavements is to develop asphalt pavement material that will be capable of healing itself without external intervention. Therefore the ultimate goal for road designers is to develop an asphalt pavement material that will mimic nature itself. To achieve this, the self-healing processes embedded within the asphalt pavement system should be capable of self-assessment. This would enable the material to assess its structural and material health and to trigger a response to initiate self-healing where necessary [7].

To develop this new generation of self-healing asphalt pavements, based on findings of currently available self-healing technologies, presented in section 2 of this paper, three specific working areas are identified that need particular effort:

1) **Development/design of damage sensing and repair triggering elements** to be incorporated within pavement systems with the capacity to to trigger the self-healing process (i.e. signalling the activation of the healing mechanism). This means that the sensory function has to be enhanced and extended with an active learning functionality, able to differentiate and to detect damage, to interpret the obtained information and to trigger/stimulate the healing action on demand. These sensor elements should ideally be a structural component of the pavement system and should not deteriorate the general functionality of the pavement system. The development of the sensory mechanism within the pavement system will allow for healing-on-demand action, such an action could be triggered by a fall in current/resistivity in the pavement system or by a concentration of stress, which will initiate the repair action while activating an initiator (healing agent or heating).

2) **Development of multiple self-healing processes**. To date, only a limited number of self–healing mechanisms for asphalt pavements have been developed, such as the induction heating [16, 48] and rejuvenator encapsulation [17, 64, 68]. To explore the additional potential of self-healing asphalt technology, new self-healing mechanisms must be developed to respond to broader range of performance demands, such as healing/rest time. All three self-healing mechanisms presented in section 2 require at least 4 hours of rest time in order for the asphalt pavement to achieve full recovery. On roads with high traffic flow, this will be difficult to achieve . Perhaps technology can improve

the repair times for self healing asphalt pavements. Another, essential part of the self-healing mechanism in asphalt pavements is multi-phase self healing. If a self-healing mechanism is ‘once off’, it is vulnerable to cracking after the first repair. This will ultimately lead to asphalt pavement failure. This requirement of a self-healing mechanism is directly linked to the sensory/triggering mechanism. If a healing-on-demand technology can be achieved within asphalt pavements, the repair action will be re-activated which will make self healing asphalt more efficient.

3) **Development of self-healing assessment mechanism** to achieve self-assessment of the asphalt pavement system and to quantify the success of the self-healing process. To date there has been only a limited understanding of quantification of the success of self-healing, mostly by measurement of mechanical performance, such as material strength [63]. This requires in-situ pavement evaluation, or a laboratory material evaluation of test samples obtained from site. This requires traffic control and potential traffic delays, which increases the cost and reduces the benefit of self-healing asphalt pavements. A mechanism for the autonomous self-assessment of asphalt pavement system health and the assessment of the self-healing process should be a focus for future research in this field.

If these developments in the self-healing process are met, then it will be possible to create a truly smart asphalt pavement system, which senses its internal state and external environment and responds in an appropriate manner to this information. The primary advantage of moving towards smart/self-healing technology is the potential cost benefit of condition-based maintenance strategies and the prospective lifespan that may be achieved for asphalt pavements materials, through *in-situ* health management.

The potential benefits of self-healing asphalt technology in material performance, environmental and social benefits will undoubtedly stimulate interest for the wider use of self-healing technology in asphalt pavement design and construction. However, for self-healing technology to become accepted as the industry standard, its superiority in the construction and maintenance of asphalt pavements must be demonstrated, from a functional , economic and environmental perspective.

4 Cost and Environmental Benefits of Self-healing Technology for Asphalt Pavement Design

To accurately assess the cost reductions that can accrue from self-healing materials, it would be best to compare the change (increase) in materials costs with the change (decrease) in maintenance costs. Depending on the application, other costs such as operating costs, disposal costs and environmental costs could be factored in the cost benefit analysis. It is expected that periods between road maintenance will extend when self-healing asphalt is employed, resulting in a decrease in traffic conjestion and associated costs. For example in the Netherlands the combined annual savings related to major repairs and traffic jam costs are approximately €65 million euros at an asphalt life span extension of 25% and over 100 million euros at a life span extension of 50%, for the entire porous asphalt pavement area in the Netherlands [71]. Even if the price of self-healing asphalt was double that of standard bitumen, the Netherlands would save approximately 90 million euros annually by investing in self-healing asphalt, with a 50% extended life span, compared to traditional porous asphalt. The Netherlands is a fairly small country by European standards and represents only 3% of total European asphalt production and only 1/3 of this (1%) is used in surface layers [52]. If we extend the potential savings in the Netherlands to the EU as a whole, the potential savings could total €9 billion [52].

These figures outline the clear financial benefits to be accrued from self-healing technology in asphalt pavement design. However, the full potential benefits of self-healing technology on asphalt pavement design can only be understood when the full life cycle costs of asphalt pavements are known (financial, environmental and societal). Butt et al. [72] studied the effect of self-healing on the lifetime, energy and environment of asphalt pavements. Using a Life Cycle Analysis (LCA) framework performed in conjunction with a numerical model which simulates the self-healing capacity of asphalt pavements [73], they determined that self-healing asphalt pavements increased the lifetime of the pavement by 10% (from 20 years to 22 years) in comparison to asphalt pavements without any self-healing capacity. This increase in lifetime would result in a reduction of energy consumption by 3% (22GJ) and CO_2 emissions by 3% (1.5T). If the increased lifetime of an asphalt pavement is projected to 100% (from 20 years to 40 years, based on the assumption that self-healing technology can double asphalt pavement lifespan), the benefits in terms of reduced cost, reduction of energy consumption and CO_2 emission would increase accordingly.

A greater insight into the potential of self-healing technology for the asphalt pavement industry will be achieved with full scale in-situ implementation of the self-healing technology in the asphalt pavement design, as in the A58 Road in the Netherlands [52]. However, the clear benefits of self healing asphalt materials , in the form of an extended lifespan of the asphalt pavement and reduced maintenance costs, will only become apparent over time. Steyn explains [65]: "*The important point to take from reality is that for any innovation to provide real benefit in the pavement engineering field, there has to be a real positive benefit/cost ratio".*

It is unlikely that decisions of implementation of self-healing technology in the asphalt pavement design will be taken at a local level due to high initial costs and long timeframe for savings. It will requires regional (European) leadership, informed by a sound evidence base (i.e. research) to convince all that these technological advances are worth considering at a national and European level. Initial research results are positive, as shown in section 2 and there is optimism that this technology has strong potential in the asphalt pavement design.

5 Concluding Remarks

"*Roads . . . [are] the most ancient of human monuments, surpassing by many tens of centuries the oldest thing of stone that man has reared to mark his passing. The tread of time. . . has beaten only to a more enduring hardness the pathways that have been made throughout the world*" [74].

Throughout the centuries, a civilisation’s prosperity and economic development was measured and ensured by the quality of its road network, which were used for economic, social and military purposes. In its latest report “Road Infrastructure – the backbone of transport system” [75], the European Commission stated that: “*Transport infrastructure influences both economic growth and social cohesion. A region cannot be competitive without an efficient transport network*”.

Today roads designs are sophisticated engineering creations. Despite this, the materials used in asphalt mixes have remained largely unchanged for the past 100 years. The main ingredient of a modern road is the bitumen. It is a co product of crude oil, whose production is in decline [76], meaning that the financial and environmental costs of bitumen are on the rise [76, 77], which will result in an increased cost of road/asphalt pavements. Unless investment levels keep apace of increased costs, poorer standard road network could result.

Incorporating self-healing technology into the asphalt pavement design presents a solution to some of the difficulties facing asphalt. Currently available self-healing road technologies are paving the way for the evolution of road design. Existing technologies have demonstrated the potential in repairing distressed asphalt pavements. They offer great opportunities for increased durability and reliability, reduced maintenance and overall costs of asphalt pavements. This includes reduced material resources, since the usual over-design of materials is no longer required. The repair of an asphalt pavement is addressed in-situ by its internal self-healing system at the very position of first appearance of damage, eliminating the need for classical in-situ maintenance process.

However, the key objective of the self-healing technology for the asphalt pavement design is the development of a design for a truly smart asphalt pavement system, which will be capable of self assessment automatic response. Despite the progress made in the development of self-healing asphalt technology further work is required to achieve truly smart asphalt pavements. Future work needs to focus on:

i. damage sensing and repair triggering element,

ii. the development of multiple self-healing processes, and
iii. the development of self-healing assessment mechanism.

The development of such areas of the self-healing technology for asphalt pavements will truly revolutionise asphalt pavement design. This will also lead to another evolutionary step in road construction and design. It will bring the idea of the self-healing roads from science fiction to reality.

5. Acknowledgements

This research has been conducted under the Marie Curie IEF research funding, research project Self-Healing Asphalt for Road Pavements (SHARP), project number 622863.

6. References

1. (OECD), O.o.E.C.a.D., *Road traffic, vehicles and networks*. 2013 in Environment at a Glance 2013: OECD Indicators, OECD Publishing.
2. European Union Road Federation (ERF), *European road statistics 2012*. 2012: European Union Road Federation Publications.
3. Sherwood, P.T., *Alternative materials in road construction*. 2nd ed. 2001: Thomas Telford.
4. Merill, D., *Guidance on the development, assessment and maintenance of long-life flexible pavements*. 2005, Transport Research Laboratory, UK.
5. (FEHRL), F.o.E.N.H.R.L., *NR2C; New Road Construction Concepts; Towards reliable, green, safe & smart and human infrastructure in Europe*. 2008, Forum of European National Highway Research Laboratories (FEHRL): FEHRL publications.
6. Association, P.W.R. *Technical Committees for Road Infrastructure*. 2014; Available from: www.pirac.org.
7. Fisher, H., *Self repairing materials – dream or reality.* Natural Science, 2010. **2** (8): p. 873 – 901.
8. March, D.R. and G. Li, *The biology of fracture healing,.* British Medical Bulletin, 1999. **55;4,pp. 856 – 869.**(4): p. 856 – 869
9. Jin, H., et al., *Self-healing thermoset using encapsulated epoxy-amine healing chemistry,.* Polymer, 2012. **53**(2): p. 581 – 587.
10. Jonker, H.M. and E. Schlangen, *A two components bacteria based self-healing concrete*. 2009, Concrete Repair, Rehabilitation and Retrofitting: Tailor Francis Group, Lndon, UK.
11. Dry, C., *Procedure developed for self-repair of polymer matrix composite materials,.* Composite Structures, 1996. **35**(3): p. 263 – 239.

12. Wu, M., B. Johnnesson, and M. Geiker, *A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material.* Construction and Building Materials, 2012. **28**: p. 571 - 583.
13. Boh, B. and B. Šumiga, *Microencapsulation technology and its applications in building construction materials.* Materials and Geoenvironment, 2008. **55**: p. 329 – 344.
14. Kishi, T., et al., *Self-healing behaviour by cementitious recrystallization of cracked concrete incorporating expansive agent,*, in *1st International Conference on Self-healing Materials*. 2007: Noordwijk aan zee, the Netherlands.
15. Tabatabaee, N. and M.H. Shafiee. *Effect of organoclay modified binders on fatigue performance*. in *7th RILEM International Conference on Cracking in Pavements*. 2012. Delft, The Netherlands: RILEM Bookseries
16. García, A., E. Schlangen, and M. van de Ven, *Induction heating of mastic containing conductive fibers and fillers.* Materials and Structures, 2011. **44**(2): p. 499–508.
17. Su, J.F., J. Qiu, and E. Schlangen, *Stability investigation of self-healing microcapsules containing rejuvenator for bitumen.* Polymer Degradation and Stability, 2013. **98**(6): p. 1205-1212.
18. Wilson, G.O. and H. Magnus, *Self-healing systems for industrial and marine protective coatings.* Journal of Protective Coatings and Linings, 2011.
19. Kirkby, E.L., et al., *Embedded shape-memory alloy wires for improvements of self-healing.* Advanced Functional Materials, 2008. **18**: p. 2253 – 2260.
20. Lumley, R., *Self healing in aluminium alloys*, in *1st International Conference on Self Healing Matserials*. 2007: Delft, The Netherlands.
21. van Gooswiligen, G., E. de Hilster, and C. Robertus. *Changing needs and requirements for bitumen and asphalts*. in *6th Conference on Asphalt Pavement for South Africa*. 1994. Cape Town, South Africa
22. Kim, Y.R. and D.N. Little, *SEM analysis on fracture and healing of sand-asphalt mixtures.* ASCE Journal of Matsaterials in Civil Engineering, 1991. **3**(2): p. 140-153.
23. Lytton, R.L., et al., *Development and validation of performance prediction models and specifications for asphalt binders and paving mixes*. 1993, Strategic Highway Research Program (SHRP), National Research Council, Washington DC, USA.
24. Edward, K.O.A., *Fatigue resistance of hot-mix asphalt concrete mixtures using the calibrated mechanistic with surface energy measurements approach*. 2006, Texas A&M University, USA.
25. Bhasin, A., et al., *Use of molecular dynamics to investigate self-healing mechanisms in asphalt binders.* ASCE Journal of Materials in Civil Engineering, 2011. **23**(4): p. 485-492.
26. Lee, H.J.D., J.S. and Kim Y.R., 2000, “Laboratory performance evaluation of modified asphalt mixtures for Inchon airport pavements”, , Vol. 1(2), 151-169., *Laboratory performance evaluation of modified asphalt mixtures for Inchon airport pavements.* International Journal of Pavement Engineering, 2000. **1**(2): p. 151 - 169.
27. Kim, B. and R. Roque. *Evaluation of healing property of asphalt mixture*. in *85th Annual Meeting: Conference Recording*. 2006. Washington, D.C., USA.
28. Abo-Qudais, S. and A. Suleiman, *Monitoring fatigue famage and crack healing by ultrasound wave velocity.* Nondestructive Testing and Evalucation, 2005. **20**(2): p. 125 - 145.

29. Theyse, H.L., M. de Beer, and F.C. Rust. *Overview of the South African mechanistic pavement design analysis method*. in *75th Annual TRB Meeting*. 1996. Washington DC., USA.
30. Verstraeten, J. *Fatigue of bituminous mixes and bitumen thixotropy*. in *19th World Road Congress, AIPCR*. 1991. Marrakech, Morocco.
31. Castro, M.a.S., J.A., 2006, “Fatigue and healing of asphalt mixtures: Discriminate analysis of fatigue curves”, ASCE Journal of Transport Engineering, Vol. 132 (2), 168-174., *Fatigue and healing of asphalt mixtures: Discriminate analysis of fatigue curves.* ASCE Journal of Transport Engineering, 2006. **132**(2): p. 168-174.
32. Hefer, A. and D.N. Little, *Adhesion in bitumen-aggregate systems and quantification of the effects of water on the adhesive bond*. 2005.
33. Kim, Y.R.L., D.N. and Lytton, R.L., 2003, “Fatigue and healing characterization of asphalt mixes”. Journal of Materials in Civil Engineering, ASCE, Vol. 15; 1, 75 – 83., *Fatigue and healing characterization of asphalt mixes.* ASCE Journal of Materials in Civil Engineering, 2003. **15**(1): p. 75 - 83.
34. Qiu, J., et al., *Investigation of self healing capability of bituminous binders.* Road Materials and Pavement Design; SPECIAL ISSUE ON ASPHALT MATERIALS (ICAM 2009—China), 2009. **10**(1): p. 81-94.
35. Cordier, P., et al., *Self-healing and thermoreversible rubber from supramolecular assembly.* Nature, 2008. **451**: p. 977 - 980.
36. Qiu, J., et al., *Evaluating self healing capability of bituminous mastics.* Experimental Mechanics, 2012. **52**: p. 1163–1171.
37. Wu, C., *Highway, Heal Thyself; cracking the code of self-healing asphalt could extend the life of roads*, in *Science News*. 1998. p. 60 - 63.
38. Mallic, R.B., et al., *Heating and its effect on hot in-place recycling of asphalt pavements with rejuvinator.* International Journal of Pavement Research and Technology, 2012. **5**(6): p. 347 - 359.
39. Newcomb, D.E., M. Buncher, and I.J. Huddleston, *Concepts of Perpetual Pavements*. 2001, Transport Research Board, Washington, USA.: Transport Research Circular.
40. Fang, C., et al., *Nanomaterials Applied in Asphalt Modification: A Review.* Journal of Material Science and Technology, 2013. **29**(7): p. 589 – 594.
41. Manh, H.T. and A.P. Viet. *Influence of fiber polymer reinforced asphalt concrete pavement in high temperature environment*. in *2nd International Interdisciplinary Conference*. 2013. Žilina, Slovak Republic.
42. McNally, T., *Ch. 2: Polymer Modified Bitumen, PmB*, in *Polymer modified bitumen properties and characteristics*. 2011, Woodhead publishing.
43. Abtahi, S.M., M. Sheikhzadeh, and S.M. Hejazi, *Fiber-reinforced asphalt-concrete – A review.* Construction and Building Materials, 2010. **24**: p. 871 - 877.
44. Minsk, L.D., *Electrically conductive asphalt for control of snow and ice accumulation.* Transport Research Board, 1968(227): p. 57– 63.
45. Minsk, L.D., *Electrically Conductive Asphaltic Concrete*. 1971.
46. Wu, S., et al., *Self-monitoring electrically conductive asphalt-based composite containing carbon fillers.* Transaction of Nonferrous Metetals Society of China, 2006. **16**: p. 512 – 516.
47. García, A., et al., *Electrical conductivity of asphalt mortar containing conductive fibers and fillers.* Construction and Building Materials, 2009. **21**(10): p. 3175–3181.
48. Liu, Q., et al., *Induction heating of electrically conductive porous asphalt concrete.* Construction and Building Materials, 2010. **24**: p. 1207–1213.

49. Zhang, H., X.H. Wu, and X.L. Wang, *Conductivity mechanism of asphalt concrete with the PANI/PP compound conductive fiber.* Materials Science Forum, 2011. **689**: p. 69-73.
50. García, A., *Self-healing of open cracks in asphalt mastic.* Fuel, 2012. **93**: p. 264 – 272.
51. Liu, Q., *Induction healing of porous asphalt concrete*, in *Faculty of Civil Engineering and Geosciences*. 2012, TU Delft, The Netherlands.
52. Schlangen, E., *Other Materials, Applications and Future Developments*, in *Self-Healing Phenomena in Cement-Based Materials*, M. e Rooij, et al., Editors. 2013, RILEM Series: State-of-the-Art Reports. p. 241 – 256.
53. Wu, S., et al., *Investigation of the Conductivity of Asphalt Concrete Containing Conductive Fillers.* Carbon, 2005. **43**(7): p. 1358–1363.
54. Liu, X.M. and S.P. Wu, *Research on the conductive asphalt concrete's piezoresistivity effect and its mechanism.* Construction and Building Materials, 2009. **23**(8): p. 2752–2756.
55. Wu, S., Y. Zhang, and M. Chen. *Research on Mechanical Characteristics of Conductive Asphalt Concrete by Indirect Tensile Test*. in *4th International Conference on Experimental Mechanics*. 2010. SPIE.
56. Liu, X. and S. Wu, *Study on the graphite and carbon fiber modified asphalt concrete.* Construction and Building Materials, 2011. **25**(4): p. 1807–1811.
57. Gerardu, J.J.A. and C.F. Hendriks, *Recycling of Road Pavement Materials in the Netherlands*. 1985, Road Engineering Division of Rijkswaterstaat, Delft, The Netherlands.
58. Airey, G.D., *Rheological properties of styrene butadiene styrene polymer modified road bitumens.* Fuel, 2003. **82**(14): p. 1709–1719.
59. Wu, S., et al., *Investigation of temperature characteristics of recycled hot mix asphalt mixtures.* Conservation and Recycling, 2007. **51**: p. 610–620.
60. Kandhal, P.S., et al., *Performance of recycled hot mix asphalt mixtures*. 1995, National Center for Asphalt Technology.
61. Silva, H.M.R.D., J.R.M. Oliveira, and C.M.G. Jesus, *Are totally recycled hot mix asphalts a sustainable alternative for road paving?* Resources, Conservation and Recycling, 2012. **60**: p. 38– 48.
62. Brownridge, J. *The role of an asphalt rejuvenator in pavement preservation: use and need for asphalt rejuvenation*. in *1st International Conf. on Pavement Preservation*. 2010. Newport Beach, USA.
63. Tabaković, A.G., A.; McNally, C. and Gilchrist, M.D., 2010, "The Influence of Recycled Asphalt Pavement on the Fatigue Performance of Asphalt Concrete Base Courses". ASCE Journal of Materials in Civil Engineering, Vol. 22, 6, pp. 643 – 650., *The influence of recycled asphalt pavement on the fatigue performance of asphalt concrete base courses.* ASCE Journal of Materials in Civil Engineering, 2010. **22**(6): p. 643 - 650.
64. Su, J.F., et al., *Investigation the possibility of a new approach of using microcapsules containing waste cooking oil; in-situ rejuvenation.* Construction and Building Materials, 2015. **74**: p. 83–92.
65. Steyn, W., *Potential application of nanotechnology in pavement engineering.* ASCE Journal of Transport Engineering, 2009. **135**(10): p. 764 – 772.
66. Shen, J., S. Amirkhanian, and J.A. Miller, *Effects of rejuvenating agents on superpave mixtures containing reclaimed asphalt pavement.* ASCE Journal of Materials in Civil Engineering, 2007. **19**(5): p. 376–84.

67. Su, J.F., et al., *Experimental investigation of self healing behaviour of bitumen/microcapsule composites by modified beam on elastic foundation method.* Materials and Structures, Springer publication, RILEM, 2014.
68. Su, J.F. and E. Schlangen, *Synthesis and physicochemical properties of high compact microcapsules containing rejuvenator applied in asphalt.* Chemical Engineering Journal, 2012. **198-199**: p. 289-300.
69. García, Á., E. Schlangen, and M. van de Ven, *Two ways of closing cracks on asphalt concrete pavements: Microcapsules and Induction Heating.* Key Enginering Materials, 2010. **417-418**: p. 573-576.
70. Su, J.F., et al., *Interface stability behaviors of methanol– melamine–formaldehyde shell microPCMs/epoxy matrix composites.* Polymer Composites, 2011. **32**: p. 810–820.
71. Agency, N., *Self healing materials concept and application – 2nd edition*. 2011, NL Ministry of Economic Affairs, Agriculture and Innovation.
72. Butt, A.A., B. Brigisson, and N. Kringos, *Optimizing highway lifetime by improving the self-healing capacity of asphalt.* Procidia – Social and Behavioural Sciences, Transport Research Arena-2012, 2012. **48**: p. 2190 – 2200.
73. Kringos, N., et al., *Towards understanding of the self-healing capacity of asphalt mixtures*, in *Self healing materials*, E. Schlangen, Editor. 2011, HERON. p. 45 – 74.
74. O'Brien, F., *The third policeman*. 2007: Harper Collins Publishers (First published in Great Britain by MacGibbon & Kee Ltd. In 1967).
75. Vita, L. and M.C. Marolda, *Road Infrastructure – the backbone of transport system*. 2008, EU Directorate General for Research and Sustainable Surface Transport, Brussels, Belgium, EU.
76. Worth, J., *Ending the oil age*, in *New Internationalist*. 2014. p. 12-16.
77. Leggett, J., *Big oil's looming bubble*, in *New Internationalist*. 2014. p. 20-21.