SELF-HEALING PAVEMENTS : A REVOLUTION IN PAVEMENT MATERIALS

Sampath Kumar Pasupunuri, Dr. Devesh Tiwari, Sunil Jain and Pradeep Kumar
CSIR-Central Road Research Institute, New Delhi
sampathkumar.crri@nic.in; devesht.crri@nic.in; sunjain.crri@nic.in & pkumar.crri@nic.in

ABSTRACT

Self-repairing is an intrinsic property of bitumen. When it is subjected to a rest period, bituminous material has the potential to restore its stiffness and strength by closing the micro cracks that occur when the pavement is subjected to traffic loads. It requires adequate amount of rest time to undergo the complete process which is practically not possible. The aim of this work is to go beyond the scope of classical review which almost entirely focused only onto conventional and passive systems. Therefore, by extensive literature review specific choices from the existing literature have been made for this analysis, which either show new principles or contribute to this aim without repeating already existing systems in a similar or slightly different way. The phenomenon of healing and especially self-heal pavements is understood, together with the principal design features and requirements that enable a self-repair to take place. There are three main approaches for self-healing of pavements: Use of Nanoparticles, use of rejuvenators like microcapsules, induction heating of bitumen containing conductive fiber. Incorporating self-healing technology into flexible pavement design presents a solution for some of the major difficulties like limited natural resources, increase in maintenance costs etc. This technology helps in conservation of material resources, since the usual over-design of materials is no longer required. Repair will be addressed at the very position of first appearance of damage, minimizing the need to reconstruction and overlaying of pavements. The development of such technologies for bituminous pavement will truly revolutionize the bituminous pavement design.

KEYWORDS

Self-healing, Nanoparticles, Rejuvenators, Induction heating, Bituminous pavements

1. INTRODUCTION

Road Transport is the primary and preferred mode of transport for most of the population and India's Road Transport system is among the most heavily utilized system in the world. India has second largest road network in the world covering 4.87 million Kms. The length of National Highways is expected to grow 100,000 Kms by end of 2017 according to Ministry of Shipping, Road Transport and Highways (MORT&H), India*(1)*. There is tremendous growth in road infra development as the Government permitting 100 percent foreign direct investment (FDI) in the road sector, several foreign companies have formed partnerships with Indian players to capitalize on the sector's growth. Road Transport has emerged as a dominant segment in India's transportation sector with a share of 4.8% in India's GDP*(2)*. The Union Budget will earmark about □970 billion for the roads and highways sector, also significant percentage of annual budget for roads are spent on rehabilitation, repair and maintenance of the roads.

Although the need for maintenance is widely recognized, it is still not getting adequately done. Regular road maintenance is required to achieve safer and efficient transport. Many countries including India spend almost 20–50 percent of what they should be spending on maintenance of their road network. According to world road association *(3)* all maintenance can be described as preventive maintenance. The need for maintenance increases as road infrastructure ages, since it becomes more fragile, less resilient and journeys are more susceptible for disruption. These aged pavements will lead to pavement failures such as surface cracks, reflection cracks and raveling etc. The pavement could not be able to serve its complete service life as there is a lag between building new roads and maintenance.

Many innovative methods and applications are emerging in India and throughout the globe for improving the life of the pavements like Emulsified bituminous mix, Foam bituminous mix, Fiber reinforced bituminous mix, composite pavements, perpetual pavements etc.*(4)*. The primary goal of all the innovative methods is to increase the design life of the pavements. The design life of the conventional flexible pavements is about 15 to 20 years for highways *(5)*. Self-healing technology is one among the innovative approaches to enhance the design life of the pavements which has the potential to double the life span of the pavements. According to Swapan K. Gosh*(6)*, self-healing can be defined as the ability of material to heal damages automatically and autonomously that is without any external intervention. Incorporation of self-healing properties in manmade materials very often cannot perform self-healing action without an external trigger. Thus a self-healing can be two types Autonomic and Non autonomic. Here self-healing refers to the recovery of the mechanical strength of the pavements. Self-healing aims to reduce the level of damage and to extend or renew the functionality and life of the damaged part. Materials perform as a function of time. As shown in Figure 1, conventional materials only accumulate damage and fail after a certain period of use. For improved conventional materials the mechanisms remain the same and the improvement is rather marginal. Self-healing materials may show some early deterioration, yet its self-healing character makes sure that total failure only occurs after very long times.

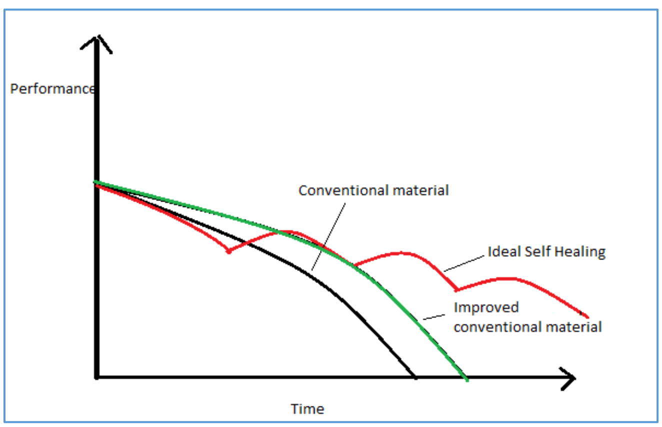

FIGURE 1 Behavior of Material with Time

2. SELF-HEALING OF BITUMINOUS PAVEMENTS

The healing mechanism varies from material to material. Although the healing mechanisms are addressed in literature like self-healing polymers *(7)*, thermosetting resins*(8)*, Concrete materials *(9)* and Aluminum alloys*(10)* etc. but the self-healing of bitumen is reported by very few people. According to Chowdary*(11)* healing is the molecular reorientation occurring within the materials under certain conditions. The healing capability was addressed long back in 1967 by Bazin and Saunier*(12)*, where deformability, fatigue and healing properties were studied. In their investigation it was found that the fractured beams gains 50 percent of the strength when they are allowed for rest period of one day. Later many investigations and laboratory work were carried out. Thompson (1981) stated that a bituminous binder consists of micelles. These interactions between these micelles internal and between the micelles with aggregates, determines largely cohesion and bond strengths. Later some of the most recent, significant documentation of healing in the laboratory was demonstrated by Kim et al. and by Carpenter and Shen(2006) *(13-14)*.

Bitumen is considered as one of the most complex civil engineering material because of its viscoelastic nature. It is used as the binder component in bituminous mixtures which coats around the aggregate. The bitumen has a capacity to heal if it is allowed to rest after continuous application of load. With every load application, the material will undergo some load deformation. After the removal of load, it recovers over a period of time depending upon the intensity, temperature and duration of the loading *(15)*. The relaxation and recovery of stress in viscoelastic is well understood, but to analyze bituminous mixture is a complex thing and need to be studied in depth. Fewer studies were done to analyze the strain recovery and stress relaxation for asphalt mixture using various linear and nonlinear viscoelastic models *(16)*. Based on the results of several studies, it can be observed that rest periods indeed improve the response of asphalt mixtures to the loading cycles.

Healing is observed because of change in the internal structure of the bitumen and takes place on molecular level. After removal of external loading two processes will undergo internally, one is viscoelastic recovery and other is healing in fracture process. Viscoelastic recovery is due to the rearrangement of molecules within the bulk of material *(17)*. As shown in Figure 2, healing is due to the wetting and inter diffusion of materials between two faces of the micro cracks, so that original properties of material can be regained. The primary steps in healing process are *(18):*

1. Rearrangement of the molecules on the surface
2. Surface Approach
3. Wetting of two faces of micro crack
4. Diffusion of molecules from one face to the other
5. Randomization of diffused molecules to reach the level of strength of original material.

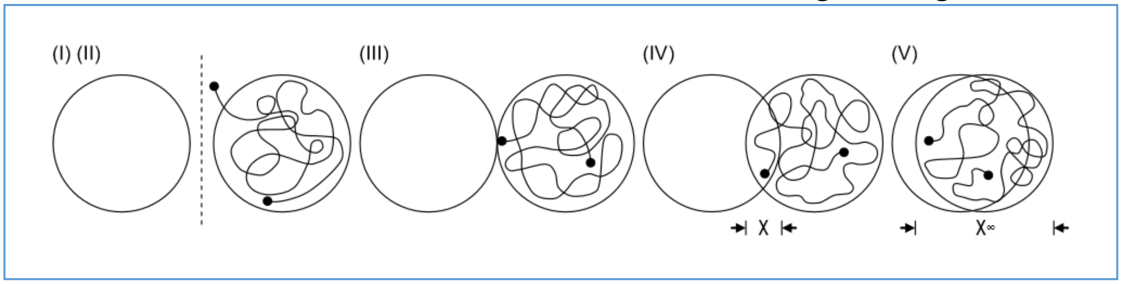

FIGURE 2 Schematic of Chain Motion during Healing of a Fractured Interface *(18)* Stages: (I) Rearrangement, (II) Approach, (III) Wetting, (IV) Diffusion and (V) Randomization

However the time needed to establish a contact of the fractured surfaces determines the healing efficiency. Longer healing times lead to the better healing but even the contact time is as short as Fifteen minutes, a repaired sample can be deformed upto about 200% without breaking *(19)*.

2.1 Factors Influencing the Self-Healing of Bituminous Pavements

2.1.1 Loading Condition

Loading intensity plays an important role in healing capacity of the bituminous mix. Little and Lytton *(20)* conducted different types of cycle loading tests with varying rest periods and notched bituminous concrete beams to observe the healing potential. It was shown that loading intensity has potential in healing capacity. The self-healing capability is a temperature dependent phenomenon. It is universal that as the temperature increases, the healing rate also increases. It is observed in previous studies that micro damage healing occurs during rest periods of reasonable length simulative of actual intermittent periods between design axle loads. This healing has a significant influence on fatigue damage.

TABLE 1 Factors Influencing the Self-Healing of Bituminous Pavements

Loading Parameters *(20,23)*	1. Intensity of Loading
	2. Duration of loading
	3. Temperature & time of loading
	4. Rest period
Bitumen Properties *(21, 22)*	1. Bitumen type
	2. Chemical composition
	3. Viscoelastic properties
	4. surface free energy
	5. Ageing
	6. Diffusion
	7. Modifiers
Bituminous mixture composition *(19,22)*	1. Bitumen content
	2. Aggregate structure
	4. Gradation
	5. Thickness

2.1.2 Bitumen Properties

Bitumen acts as the binder in any bituminous mix, one can't deny that bitumen plays an important role in self-healing potential of the bituminous concrete mix. Van Gooswiligen *(21)* studied the healing rate effect on dense bituminous asphalt with different bitumen types from softer grade to harder grade. It was observed that softer bitumen heals faster than stiffer ones. The viscoelastic property of bitumen also affects the healing potential of bitumen. The chemical composition of bitumen also one of the factors affecting the self-healing rate. Joshua *(18)* conducted extensive studies on the effects of the chemical composition on its self-healing. Other properties of bitumen as stated in Table 1 like diffusion and modifiers used in bitumen also have a considerable effect on the healing potential of bituminous mixes

2.1.3 Bituminous Mixture Composition

The bituminous mixture composition, including bitumen content, aggregate structure characteristics and gradation, also influences the self-healing rate of bituminous concrete. Van Gooswiligen *(21)* showed that a bituminous mix with higher binder content shows more healing rate. Thicker bituminous layer will favor the healing rate is the conclusion of the study conducted by Thyese *(24)* because of increase in the shift factor. Other mixture properties influencing the self-healing are gradation of the aggregates adopted in the mix, structure of the aggregate, type of filler etc.

3. METHODS OF SELF-HEALING TECHNOLOGY IN BITUMINOUS PAVEMENTS

There are number of approaches for self-healing. It occurs at molecular level and to attain the healing phenomenon, the technology applied should so effective that the molecular changes should occur at nano level. There are few self-healing techniques which are already applied to many materials, where there is possibility to apply for bitumen mixtures as well as given in Table 2.

TABLE 2 Possibilities of Self-healing Systems for Bituminous Mixtures

Technology	Theory	Advantage	Disadvantages
Microcapsule *(25,26)*	Healing agent (reclamite, paxole) and rejuvenator (Sunflower oil, byproduct of waste cooking oil)	Good strength recovery	Works only once
Hollow glass fibers *(27)*	Healing agent and catalyst	Good strength recovery	Works only once
Microvascular networks *(28)*	Healing agent and catalyst	Good strength recovery	Complex structures
Nanoparticles *(29)*	Nano effect Nanoclays (organo clay modified binders), Nano rubbers	Prevent crack growth	Distribution
Using polymers *(30)*	Reversible chemical reaction	Multi time healing	High healing temperature
Induction heating *(31)*	Wetting and Diffusion	Multi time healing	Aging
Microwave heating *(32)*	Wetting and Diffusion	Multi time healing	aging

One should be careful in deciding the technique that should be adopted for self-healing. It should not be only effective under the laboratory conditions but sustain the harsh conditions which prevail during the construction like mixing, laying and compaction and during its service life when the traffic is plying on the road. According to Qiu et al.*(33)*,the four essential conditions for self-healing agents to be included into asphalt pavement design.

1. Good compatibility with bitumen
2. High temperature stability
3. Ability to survive mixing and construction conditions
4. Capable of continuous/multi-time healing

Though there are many possibilities to apply the above self-healing technologies to the bituminous mixtures, there are three self-healing techniques for asphalt pavements have been reported to date which are: 1. Binder healing agent (Rejuvenation), 2. Nanoparticles and 3. Induction heating

3.1 Binder Healing Agent (Rejuvenation)

During the service life of an asphalt pavement, it is subjected to physical aging and oxidation, which is attributable to its reaction with atmospheric oxygen. Aging mechanisms cause hardening of the asphalt and therefore affect the rheological properties of the binder *(34)*. As a result of aging, asphalt concrete becomes brittle, its surface cracking susceptibility increases, and eventually, pavement performance is negatively affected. Yut and Zafka*(35)* conducted several studies and observed that severe oxidative hardening can also cause the deterioration and failure of low-volume roads. 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 *(36)*. The oxidation of aged asphalt binder during construction and service causes the binder oils to convert to resins and the resins to convert to asphaltenes, resulting in age-hardening and a higher viscosity than for fresh binder *(37)*. Although this process is irreversible, the viscoelastic state of the asphalt mix can be recovered through the addition of either bitumen with a high penetration value or a rejuvenating agent such as a cationic emulsion, Sunflower oil, Bi product of waste cooking oil etc. 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 *(38)*. Some commercially available rejuvenating agents are Reclamite, Paxole 1009, Cyclepave and ACF Iterlene1000.

3.1.1 Microcapsulation Technique

The inclusion of a rejuvenator into the asphalt mix via microcapsules to restore the original binder properties is a self-healing method that has been studied by Garcia et al. *(40)*. Microencapsulation has been evaluated in various construction materials including mortar, lime, cement, concrete, marble, sealant and paints *(41)*. It has also been patented and tested in the food, chemical, textile, and pharmaceutical industries. However, only a limited number of studies have evaluated the use of self-healing technologies in asphalt concrete. Microencapsulation is a process in which micron-sized particles, liquids, or gases are enclosed in an inert shell, which protects the contents against unwanted reactions with the external environment. Different types of microcapsules, depending on the physical and chemical properties of the encapsulated contents and the microencapsulation techniques can be produced. When a crack occurs as a result of chemical or physical damage, the shell ruptures as shown in Figure 3, the healing agent is released, and it flows into the material, which consequently results in healing the crack.

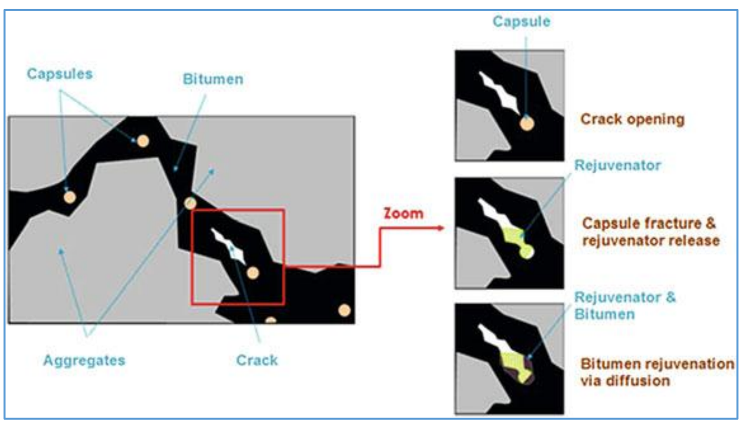

FIGURE 3 Rejuvenator Encapsulation — a Self-healing Mechanism in Asphalt Mix

The principle behind this approach is that when micro-cracks begin to form within the pavement system, they encounter a capsule in the propagation path. The fracture energy at the tip of the crack opens the capsule and releases the healing agent. The healing agent then mixes with the asphalt binder to seal the crack, thus preventing further propagation.

This healing process is illustrated in Figure 3. The process prevents the formation of micro-cracks within the pavement mix and prevents complete failure of the pavement system. To avoid being squeezed or pulverized during the asphalt pavement mixing and compaction processes, the size of the capsule needs to be less than 50 µm. However, Su et al. *(39)* stated that microcapsules of 10 µm and smaller are unsuitable for self-healing as they do not contain sufficient rejuvenator to rejuvenate the aged binder. Microcapsules are small particles that contain solid, liquid, or gas as a core material surrounded by a coating layer or shell.

This microcapsule technique is helpful for asphalt self-healing by rejuvenating the aged binder. The limitation of this approach is that it works only once (i.e. once the healing material is released from the microcapsule it cannot be replenished). Nevertheless the self-healing using microcapsules in early stages of result, further research is required in this field to finalize the parameters such as optimizing the quantity of capsules to be mixed, dosage of rejuvenators etc. The potential of self-healing using microcapsules will be demonstrated in the coming years.

3.2 Nanoparticles

Incorporation of Nanoparticles into bituminous pavements enhances the rheological, Thermal properties and ageing of the bitumen. Additional to that it also have the potential to heal the micro cracks that are developed in the bituminous mix *(33)*. The clay nano particles are the primary materials that could have application in asphalt construction based on a literature review of nano particles and nano materials. Carbon nano tubes (CNT), silica, alumina, magnesium, calcium, and titanium dioxide (TiO2) nano particles can also have a significant effect on asphalt performance *(42)*.

3.2.1 Nanoclay

Clay that can be modified to make the clay compatible with organic monomers and polymers is called Nanoclay. The short term ageing and long term ageing resistance of the bitumen was improved by adding the montmorillonite nanoclay, whereas Bentonite clay and organically modified Bentonite were used to reinforce and modify the bitumen. Polymeric nano composites are one of the recent discoveries which are proven to be very successful in improving the physical properties when polymer is modified with nanoclay material. The sodium montmorillonite (Na-MMT) and Organophilic Montmorillonite (OMMT) nanoclays have promising potential to reduce the permanent deformation or rutting of asphalt pavements. Tabatabee and Shafiee *(43)* demonstrated rest periods at 3% to 5% strain level increased the fatigue resistance of these mixes. Thus by enhancing the physical and performance of the bituminous mixes will indirectly improving the self-healing property. There are few studies carried out in concept of Nanoclay self-healing technique and there is good scope for future research in this area.

3.2.2 Nanosilica

Silica is the most abundant element in the planet and is majorly used in glass manufacturing industry, foundries, construction, ceramics, and the chemical industry etc. Silica in its finest form is also used as functional filler for paints, plastics, rubber, water treatment plants etc. Nano sized silica are drawing attention from the scientific community because of high performance and low cost in their production*(44)*. The nanosilica is proved to improve the property anti-ageing, anti-fatigue cracking and anti-stripping significantly but was not successful at low temperatures. The addition of nanosilica into controlled bitumen improved the recovery ability*(42)*.

3.2.3 Nanorubber

Along with nanoclay and nanosilica, polymer or rubber modifiers are used to improve the physical and mechanical properties of bitumen *(45).* Two types of nanorubbers (Nano A and Nano B) were used to study the healing effect of asphalt mastic. Upto 20% more recovery was observed in nano rubber modified bitumen when compared to conventional bitumen depending upon the type and dosage of nanorubber used *(33)*. The healing of a bitumen may decrease or becomes limited after ageing or at low temperatures. The other major limitation is that few types of Nano rubbers are not compatible with thermodynamic properties of bitumen because of large difference in density, polarity and molecular weight which requires further studies.

Through engineering selection of type of nanoparticle and optimum dosage of these particles depending upon the application, very good results in terms of healing capacity will be achieved. Polymer nano composites are one of the most exciting materials because of the nano-particle addition and nano scale dispersion. Using Nano-particles can improve the storage stability of polymer modified bitumen. Few extension of the studies like multi time healing using nanoparticles, performance of healed pavements need to be demonstrated to gain the global acceptance as a feasible self-healing technology.

3.3 Induction Heating

After few years, due to some environmental factors bitumen will start degrading and loses the property of adhesion with aggregate minerals which results in propagation of cracks. At present there are no methods to close a crack especially when it is in developing stage. It is also proven that healing rate increases with the increase in temperature during this rest periods. The heating of bituminous mixtures by in-situ heating has been long in use especially for remixing, patchworks etc. Infrared heaters are often used to heat up the bitumen surfaces. As the bituminous mixtures is not thermally conductive because of the aggregate minerals present in it, to reach the desirable temperature at the bottom of the layer, the top surface has to be overheated which results in burning and oxidation of bitumen. This method also results in non-uniform heating of mix, to overcome this problem the newly developed induction technique is used, which is called induction heating technique. During the production of the bituminous mixture, a small amount of highly refined steel filaments (or fibers) is added. With these steel fibers within the layer of the wearing surface that makes it possible to heat the bituminous layer via induction.

The concept of induction heating of bituminous roads was pioneered, developed and patented by Minsk *(46)* for melting the snow and ice using the induction energy. Wu et al. (2006) *(47)* studied induction heating in bituminous pavement using conductive carbon fibers, carbon black and graphite as conductive media and demonstrated that adding conductive fibers to the mixture increases conductivity more effectively than adding conductive filler. Research by Garcia.(2009) *(48)* and Liu et al.(2010) *(49)* initiated the development of a self-healing bituminous pavement mix by inclusion of electrically conductive steel and wool fibers into the bituminous mix.

The induction process operates by sending an alternating current through the coil and generating an alternating electromagnetic field. The induced currents flow against the electrical resistivity of the conductor, generating heat in the conductor because of the "Joule effect".

The steel fibers added to provide conductive property of bituminous mix also have influence on the mechanical and physical properties of the bituminous mix. To evaluate this Garcia et al. *(48)* studied 25 different mixtures, with the same aggregate gradation and amount of bitumen, but with two different fibers lengths, four different percentages, and four different diameters of steel wool have been considered. Additionally, the influence of fibers on test specimens with three different types of damage: water damage, salt water damage and ageing have been evaluated through particle loss tests. It was found that steel wool fibers do not significantly improve the mechanical properties and damage resistance of dense bituminous concrete. On the other hand, steel wool fibers can change the air void distribution of a mixture, and therefore even reduce its particle loss resistance. Liu et al. (2010) *(49)* demonstrated that the addition of steel fibers reinforces the mastic (bitumen, filler and sand) of porous asphalt concrete, which can delay the raveling effect in bituminous pavement as shown in Figure 4.

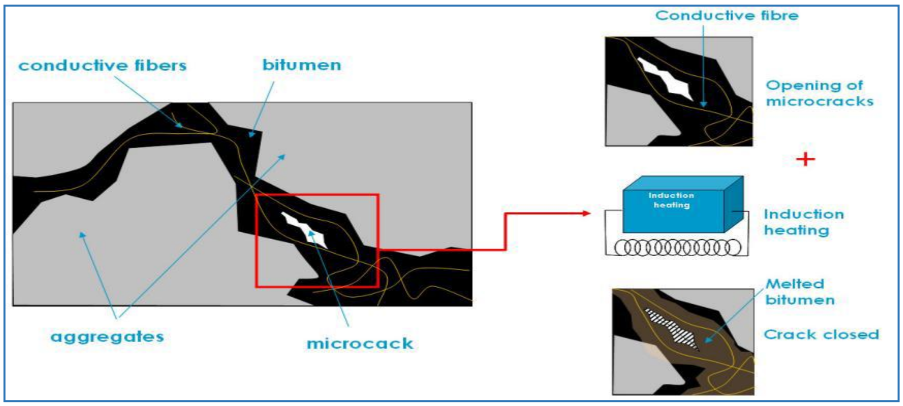

FIGURE 4 Induction Healing in Porous Asphalt by Liu et al. (2010)*(49)*

Though the self-healing through induction energy is the most progressively used technology compared to other self-healing techniques, there are few limitations such as overheating, draining, ageing of bitumen, loss of conductivity due to corrosion of steel fibers. More studies are required to optimize the temperature, dosage of fibers, duration of heating etc. for better performance and successful application if this technology. This is the only self-healing technology which translated to field from laboratory studies when Dutch Nationals Roads Authority along with cooperation from TU Delft, resurfaced a road using induction self-healing bituminous porous mix for a length of 400 m in 2010, regular inspection and maintenance will be done every year and first healing was done in the year of 2014. Moreover self-assessment by using the concept of change in piezoelectric resistivity whenever there is any mechanical pressure is also possible. Further research is required to derive the relation between the internal damage and piezoelectric resistivity for fulfilling the concept of self-healing in bituminous pavements using induction technology.

4. ECONOMIC AND ENVIRONMENTAL BENEFITS BY SELF-HEALING PAVEMENTS

The bituminous pavement design standards focus on enhancing bituminous pavement performance, that is, the aim to increase its durability and improve its load carrying capability. However, it is proven now and then that future of bitumen pavement design lies not only with the enhancement of flexible pavement properties, but also allowing to repair itself to its original state. The above described applications show that the use of Self-Healing bituminous pavements in practice is possible. It can be a solution for areas with dense traffic and with a strong need for urban areas where maintenance is a serious issue. Even the first experiments of a healing action have taken place but however the economic effect has to be validated. Highway authorities and state governments are investing huge amount of money for rehabilitation and maintenance of the national and state highways; with this technology the maintenance cost will be reduced drastically. Road user cost will be decreased significantly which will directly benefit the road user.

The additional cost involved in self-healing pavements are mainly of additional filler such as Nanoclay or Nanotubes, rejuvenators and conductive fibers for self-healing using Nano particles, Binder healing agent and steel fibers respectively is the 10-15% more on project cost, which is compensated as the life period of the pavement is almost doubled, negligible maintenance cost and the longevity of the road. It is not precise to just compare the construction cost of conventional and self-healing pavements, the other costs should also be factored such as maintenance cost, operation cost, disposal cost and environmental cost to assess the benefit cost analysis of the self-healing pavements. The time taken for maintenance of road will also involves in congestion cost, diversion cost, fuel costs etc. are also accountable for increase overall cost in conventional pavements. For example, the periodic maintenance includes resurfacing or overlay with a layer of surface course can cost upto 2.0 million rupees for a two lane road of one kilometer, to extend the life span of 5 to 8 years which will be around 20% of the total construction cost, whereas increase in material cost will not be more than 10-15% for any of the self-healing pavement technique but life of pavement will be doubled. Repair will be addressed at the very position of first appearance of damage, minimizing the need to reconstruction and overlaying of pavements. The benefits in terms of reduced energy consumptions and the carbon emissions caused by the maintenance activities will also be completely eliminated if this technology is successfully deployed.

5. CONCLUDING REMARKS

Though there are sophisticated and advanced pavement design techniques has evolved from time to time, but the basic ingredients of the bituminous pavements like aggregate, bitumen and filler were not replaced from past five to six decades. All of them being a non-renewable resources, it requires special attention so that something is also left for future generation. This technology helps in conservation of material resources, since the usual over-design of materials is no longer required. The major objective of the self-healing pavement technique is to develop a smart bituminous pavement which can assess, anticipates and heals by itself in time without any human intervention and substantially returns to its original state. For this the following areas are needed to be explored and studied

1. Development of multiple healing process which is sufficient for its complete design life.
2. To develop a mechanism that initiates/stimulates the healing action on demand.
3. To develop a method to quantify the success of self-healing action.

The development of such areas require interdisciplinary approach to understand the complexity of the technique and will have great future especially for the roads with limited access, areas where maintenance of the pavement causes lot of hindrances/cost/disturbance to traffic flow and this will truly revolutionize the pavement materials and its design in the future.

REFERENCES

1. http://morth.nic.in/ebook2015/index.html#book5. Accessed Nov 11, 2016. 12.35 PM
2. Dr. Harendra Mohan Singh. Revenue from Road Transport India, Journal of Business Management & Social Sciences Research (JBM&SSR), Volume 3, No. 4 April 2014.
3. Sally Burnigham and Natalya Stankevich. Why Road Maintenance is Important and How to Get it Done, The World Bank, Washington DC, Transport Note No. TRN-4, June 2005.

4. Amit Goel, Animesh Das. Emerging Road Materials and Innovative Applications, National Conference on Materials and their Applicaction in Civil Engineering. August 26-27, 2004
5. IRC 37-2012, Tentative Guildelines for the Design of Flexible Pavements, Indian Roads Congress,Third Revision, August-2012.
6. Swapan Kumar Ghosh. Self-healing Materials: Fundamentals, Design Strategies, and Applications, John Wiley and Sons, August 2009.
7. Andersson H.M., Keller M.W., Moore J.S., Sottos N.R., White S. Self Healing Polymers and Composites. In: van der Zwaag S. Self Healing Materials. Springer Series in Materials Sc., vol 100.
8. Jones F.R., Zhang W., Hayes S.A. Thermally Induced Self Healing of Thermosetting Resins and Matrices in Smart Composites. In: van der Zwaag S. (eds) Self Healing Materials. 2007 Springer Series in Materials Science, vol 100.
9. Victor C. Li and En-Hua Yang S. van der Zwaag (ed.). Self Healing Materials: An Alternative Approach to 20 Centuries 161 of Materials Science, PP. 161–193.
10. Roger Lumley. Self Healing in Aluminium Alloys. S. van der Zwaag (ed.), Self Healing Materials. An Alternative Approach to 20 Centuries of Materials Science, PP. 219–254
11. Venkaiah Chowdary and J.Murali Krishnan. A Thermodynamic Framework for Modelling Healing of Asphalt Mixtures. International Journal of Pavement Research and Technology, Vol. 3, No. 4, Jul 2010.
12. Bazin P, Saunier JB. Deformability, fatigue and healing properties of asphalt mixes, August 7–11 2nd international conference on the structural design of asphalt pavements, MI, PP. 553–569.
13. Kim Y.R., Lee H., Little D.N. (2001) A viscoelastic continum damage fatigue model of asphalt concrete with microdamage healing. Vol IV: Microdamage healing in asphalt and asphalt concrete, project summary report. FHWA-RD-98-141, Texas Transportation Institute, Texas
14. Carpenter S.H., Shen S. (2006) A dissipated energy approach to study HMA healing in fatigue. 85th annual meeting of the Transportation Research Board, Washington DC.
15. Findley, W.N., Lai, J.S., and Onaran, K., (1989). Creep and Relaxation of Nonlinear Viscoelastic Materials with an Introduction to Linear Viscoelasticity, Dover Publications, New York, USA.
16. Krishnan, J.M. and Rajagopal, K.R., (2003). Review of the Uses and Modeling of Bitumen from Ancient to Modern Times, Applied Mechanics Reviews, 56(2), pp.149-214
17. Daniel, J.S., and Kim, Y.R. (2001). "Laboratory evaluation of fatigue damage and healing of asphalt mixtures." Journal of Materials in Civil Engineering, ASCE, Vol. 13, No. 6, 434-440
18. Joshua Gaskin (2013), Dessertation submitted on "Bitumen microstructure and effects on crack healing" to the university of Nottingham for the degree of Doctor of Philosophy.
19. Dessertation by Quantao Liu. "Induction Healing of Porous Asphalt Concrete". Wuhan University of Technology
20. Little D.N., Lytton R.L., Williams A.D., Chen C.W. (2001) Microdamage healing in asphalt and asphalt concrete, vol I: microdamage and microdamage healing, project summary report. FHWA-RD-98-141, Texas Transportation Institution, Texas.
21. Van Gooswiligen G, de Hilster E, Robertus C (1994). Changing needs and requirements for bitumen and asphalts. Proc. 6th Conference on Asphalt Pavements for Southern Africa.
22. Van den bergh, W.: The Effect of Ageing on the Fatigue and Healing Properties of Bituminous Mortars, PhD. Thesis, TU Delft, The Netherlands, 2011.
23. A. Tabakovic´ and E. Schlangen Self-Healing Technology for Asphalt Pavements. Springer International Publishing Switzerland December 2015, 10.1007/12_2015_335
24. Theyse HL, de Beer M, Rust FC (1996). Overview of the South African Mechanistic Pavement Design Analysis Method, Paper 96-1294, 75th Annual Transportation Research Board Meeting, Washington DC.
25. Sharareh Shirzad; Marwa M. Hassan, Evaluation of Sunflower Oil as a Rejuvenator and Its Microencapsulation as a Healing Agent DOI: 10.1061/(ASCE)MT.1943-5533.0001625

26. Jun Feng Su and Erik Schlangen " Stability investigation of self-healing microcapsules containing rejuvenator for bitumen" Article in Polymer Degradation and Stability, June 2013
27. Trask R.S., Williams G.J., and Bond I.P., 2007. Bioinspired Self-Healing of Advanced Composite Structures Using Hollow Glass Fibres, J. R. Society Interface, 4, PP. 363-371
28. T S Coope, D.F Wass, R S Trask and I P Bond Repeated self-healing of microvascular carbon fibre reinforced polymer composites, Sept. 2014 Smart Materials and Structures, Vol. 23, No. 11
29. Lee J.Y., Buxton G.A. and Balazs A.C., 2004. Using nanoparticles to create self-healing Composites, J. Chem. Phys. 121, 5531–40.
30. Wool R.P. and O'Conner K.M. 1982. A theory of crack healing in polymers, Journal of Applied Physics 52, 5953-5963
31. Alvaro Garcia, José Norambuena-Contreras and Manfred N Partl "Experimental evaluation of dense asphalt concrete properties for induction heating purposes" Constr. and Build. Mater. (2013)
32. José Norambuena-Contreras and Alvaro Garcia Self-healing of asphalt mixture by microwave and induction heating, Article in Materials & design (2016). DOI:10.1016/j.matdes.2016.05.095
33. Qiu J et al Investigation of self healing capability of bituminous binders. Road Mater Pavement Design 10(1):81–94, Special Issue on Asphalt Materials (ICAM 2009—China)
34. Petersen, J. C. A review of the fundamentals of asphalt oxidation Chemical, physicochemical, physical property, and durability relationships. Transportation Research Circular, No. E-C140
35. Yut, I., and Zofka, A. (2014). Correlation between rheology and chemical composition of aged polymer-modified asphalts. Construction Building Materials 62(2014), 109–117.
36. Gordon D. Airey Rheological properties of styrene butadiene styrene polymer modified road bitumens Article in Fuel 82(14):1709-1719 · October 2003
37. Wu S et al (2007) Investigation of temperature characteristics of recycled hot mix asphalt mixtures. Resour Conserv Recyc 51:610–620
38. Brownridge J. The role of an asphalt rejuvenator in pavement preservation: use and need for asphalt rejuvenation. International conference on pavement preservation 2010, USA
39. Su JF et al (2015) Investigation the Possibility of a New Approach of Using Microcapsules Containing Waste Cooking Oil; in-situ Rejuvenation. Construction Building Materials 74:83–92
40. Garcia A. Tabakovic and E. Schlangen, van de Ven M. Two ways of closing cracks on asphalt concrete pavements: microcapsules and induction heating. Key Eng Mater,2010 417–418
41. Boh, B., and Sumiga, B. (2008). "Microencapsulation technology and its applications in building construction materials." Mater. Geoenviron., 55(3), 329–344.
42. Jun Yang., et al. 2013. "A review of advances of Nanotechnology in asphalt mixtures" 13th COTA International Conference of Transportation Professionals (CICTP 2013) 1877-0428
43. Tabatabaee N, Shafiee MH Effect of organoclay modified binders on fatigue performance. In: 7th RILEM international conference on cracking in pavements. 2012 RILEM, The Netherlands.
44. Lazzara G., Milioto S., Dispersions of nanosilica in biocompatible copolymers, *Polymer Degradation and Stability*, 2010, PP. 610-617.
45. Sayyed Mahdi Abtahi. Mohammed Sheikzadeh, sayyed Mahdi hejazi. Fiber-Reinforced Asphalt-Concrete – A Review, Construction and Building Materials 24(6) PP. 871-877 · June 2010.
46. Minsk LD, Electrically Conductive Asphalt for Control of Snow and Ice Accumulation. Highway Research Record 227 PP. 57-63.
47. Wu S, Ye Q, Li N, Yue H. Effects of Fibers on the Dynamic Properties of Asphalt Mixtures. 2007 J Wuhan University of Technology - Material Science Ed 22:733-736.
48. Garcia A (2009) Electrical conductivity of asphalt mortar containing conductive fibers and fillers. Constr Build Mater 21(10):3175–3181
49. Liu Q et al (2010) Induction heating of electrically conductive porous asphalt concrete. Construction and Building Materials 24:1207–1213