Smart asphalt materials for future road infrastructure: advances in self-healing, self-sensing, and structural health monitoring in the mexican context

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ABSTRACT

Road infrastructure constitutes a strategic asset for Mexico's economic development, international trade, and regional connectivity. However, pavement networks are increasingly affected by accelerated deterioration resulting from heavy traffic loads, environmental aging, and extreme climatic conditions. Traditional reactive maintenance approaches have proven both technically and economically inefficient in addressing the challenges of twenty-first century transportation systems. This article provides a comprehensive review of recent advances in smarth asphalt materials as a transformative solution for enhancing pavement durability, functionality, and sustainability. Attention is given to self-healing technologies, including electromagnetic induction heating and rejuvenator-containing microcapsules, as well as self-sensing asphalt systems capable of traffic monitoring, weighing in motion applications, and early damage detection through piezoresistive behaivor. Additionally, developments in electrically conductive pavements for de-icing applications and Structural Health Monitoring (SHM) integrated with Internet of Things technologies are examined. The review highlights the opportunities for Mexico to leverage locally available industrial byproducts, such as steel slag, and bio-based resources to facilitate the transition toward resilient, intelligent, and sustainable road infrastructure. The findings indicate that smart asphalt technologies have significant potential to reduce maintenance costs, improve traffic safety, extend pavement service life, and support the digital transformation of transportation systems. Particular attention is given to encapsulated rejuvenators, whose field performance is governed by the survival of

the capsule through mixing and compaction and by the kinetics with which the healing agent is released and diffuses into the aged binder.

Keywords: Smart Pavements, Self-Healing Pavement, Mexican Infrastructure, Encapsulated Rejuvenators.

1 INTRODUCTION

Road infrastructure represents the backbone of the Mexican economy, facilitating national mobility and international freight transportation. Like global trends, most pavement systems in Mexico are based on asphalt binders due to their economic efficiency, flexibility, and ease of construction. Nevertheless, asphalt is inherently a viscoelastic material whose mechanical and rheological properties gradually deteriorate because of aging processes (Wang *et al.*, 2024).

In Mexico, asphalt degradation is intesified by environmental and operational factors. High levels of ultravioleta radiation in arid regions such as Sonora accelerate oxidative aging of asphalt binders, whereas heavy freight traffic along major logistics corridors, including the Mexico City-Laredo Route, subjects' pavements to severe cyclic loading conditions. These mechanisms initiate microscopic crakcs thet progressively evolve into potholes, rutting and structural failures, resulting in increased Maintenance costs, traffic disruptions, and greenhouse gas emmisions.

To address these chalenges, the concept of smart pavements has emerged as a promising development in transportation engineering. Smart pavements possess multifunctional capabilities that enable them to respond actively to external stimuli, transforming conventional passive infrastructures into inteligente systems capable of self-diagnosis, self-repair, and real-time monitoring.

The objective of this article is to review the currente state of the art in smart saphalt materials and assess their potential implementation within the Mexican transportstion sector. Emphasis is placed on self-healing and self-sensisng technologies as key enablers of predictive pavement management and sustainable infrastructure development.

2 SMART ASPHALT MATERIALS

Smart asphalt materials are engineered pavement systems capable of exhibiting electrical conductivity, thermal responsiveness, or strain sensitivity through the incorporation of functional additives. Conventional asphalt mistures behave as electrical insultaors, tipically presenting electrical resistivity values ranging from 10^9 to 10^{11} Ω·cm. However, when conductivity materials are incorporated

above the percolation threshold, electrical pathways are formed within the mixture, enabling advanced functionalities.

Based on their primary functionality, smart asphalt materials can be classified into three main categories:

2.1 SELF-HEALING ASPHALT MATERIALS

These systems promote autonomous or externally stimulated crack repair through thermal activation or embedded healing agentes (Xu *et al.*, 2018).

2.2 SELF-SENSING ASPHALT MATERIALS

These materials function as distributed sensors capable of monitoring traffic loads, strain, and structural deterioration through changes in electrical resistance.

2.3 MULTIFUNCTIONAL PAVEMENTS

These advanced systems combine multiple functionalities, including self-healing, self-sensing, de-icing, and energy harvesting capabilities.

3 SELF-HEALING ASPHALT MATERIALS

Self-healing representes one of the most promising advancements in pavement engineering. Although bitumen naturally possesses healing capabilities, these mechanisms occur slowly under ambient conditions and are insufficient to prevent long-term deterioration. Consequently, several technologies have been developed to enhance the healing capacity of asphalt pavements (Lu *et al.*, 2023; Xu *et al.*, 2019).

3.1 ELECTROMAGNETIC INDUCTION HEATING AND THE POTENTIAL OF MEXICAN STEEL SLAG

Induction heating technology involves the incorporation of conductive metallic fibers or ferromagnetic particles into asphalt mixtures, when exposed Binder Mobility and promoting crack closure (Penalva-Salinas *et al.*, 2024).

The heating process reduces asphalt viscosity, enabling the material to flow into microcracks and restore structural continuity. Recente studies have demostrated that steel fibers with diameters of approximately 40 μm provide an optimal balance between healing efficiency and mechanical performance (Pérez Mena *et al.*, 2020).

An importante opportunity for Mexico lies in the utilization of electric arc furnace steel slag, a byproduct generated by the domestic steel industry. Recent researches have shown that steel slag can enhance induction and microwave heating efficiency while simultaneously promoting circular economy principles through industrial waste valorization (Lu *et al.*, 2023).

3.2 REJUVENATOR-CONTAINING MICROCAPSULES

Microencapsulation constitutes an alternative self-healing strategy that enables autonomous crack repair without immediate external intervention. Microcapsules ranging from 2 to 25 μm in diameter are embedded wiyhin the asphalt binder and contain rejuvenating agents rich in maltenes. When cracks propagate through the material, the capsules rupture and release their contents, restoring the chemical composition and flexibility of aged asphalt.

Recent developments have proposed esternally activated microcapsules capable of releasing rejuvenators upon microwave irradiation, allowing infrastructure managers to trigger healing processes in specific pavement sections before visible damage occurs (Pérez Mena *et al.*, 2020).

3.2.1 Bio-based rejuvenators

Mexico's agricultural sector offers significant potential for producing sustainable rejuvenators from vegetable oils and waste cooking oils. These bio-based alternatives have demonstrated favorable diffusion characteristics and environmental benefits compared with petroleum-derived rejuvenators (Yi *et al.*, 2023).

Microencapsulation disperses discrete reservoirs of healing agent throughout the asphalt mixture, and their release is triggered by the damage itself. Capsules loaded with a low-viscosity rejuvenator are incorporated into the asphalt mixture as an additive. When a microcrack propagates and reaches a capsule, the stress concentration at the crack tip ruptures or deforms it, and the payload is released into the surrounding binder (Xu *et al.*, 2018). Bitumen behaves as a colloidal dispersion of asphaltenes in a maltenic medium (Lesueur, 2009), so the released oil restores the asphaltene/maltene ratio of the oxidised binder, reduces its viscosity and enables capillary flow to seal the crack.

The healing agent is released where and when it is required, with no external intervention and no interruption of traffic. Unlike the induction heating described in Section 3.1, which restores the mobility of the binder by supplying energy from outside, encapsulation restores its chemistry, and it does so without any equipment on site. The idea was formulated more than a decade ago and has since been reviewed several times (Tabaković and Schlangen, 2015; Xu *et al.*, 2018; Li *et al.*, 2021). Its performance, however, is not decided by the rejuvenator alone. It is decided by the encapsulant, by the survival of the capsule through mixing and compaction, and by the kinetics with which the rejuvenator leaves the capsule once it has been activated.

3.2.2 Capsule formulation and synthesis techniques

Capsule designs, as reported so far, span three orders of magnitude in size. García *et al.* (2010) produced macrocapsules of 1.6 to 7.1 mm by adsorbing the rejuvenator into a porous stone coated with a cement and epoxy shell. Core-shell microcapsules of 40 to 130 μm were assembled by in situ polymerisation of melamine-formaldehyde (Su and Schlangen, 2012; Sun *et al.*, 2015; Sun *et al.*, 2017). That route was later extended to waste cooking oil as payload (Su *et al.*, 2015). Calcium-alginate polynuclear capsules of 1 to 7 mm, produced by ionic gelation, were introduced somewhat later (Micaelo *et al.*, 2016; Al-Mansoori *et al.*, 2018; Xu *et al.*, 2019).

Each route carries a specific liability. Porous stones replace part of the aggregate fraction, and they disturb the mineral skeleton of the mixture when they fracture, whereas formaldehyde-based resins involve a potential environmental risk due to the leaking of hazardous compounds, which hampers the application of these capsules in road pavements (Gonzalez-Torre and Norambuena-Contreras, 2020).

Ionic gelation of sodium alginate has become the dominant biobased route. Alginate is a water-soluble polysaccharide extracted from brown algae that crosslinks with divalent cations such as calcium, forming a polynuclear matrix in which the rejuvenator is distributed among multiple internal cavities (Martins *et al.*, 2017). This multi-cavity morphology is not incidental, since it allows a gradual liberation of the healing agent and, consequently, several healing events over the service life of the pavement, which a single-core capsule cannot provide once it has been emptied (Su *et al.*, 2016).

The stiffness and the dissolution behaviour of the gel are governed by the crosslinking conditions (Voo *et al.*, 2016). Size is itself a design variable. Larger capsules have been reported to produce higher healing levels in asphalt mixtures (Ruiz-Riancho *et al.*, 2021).

The process becomes controllable when the oil-in-water emulsion is extruded through a vibrating nozzle. Concha *et al.* (2023) reported capsules of 1.15 to 1.73 mm for biopolymer-to-oil ratios between 1:1 and 1:9, with encapsulation efficiencies above 90 %.

A second family of encapsulants dispenses with the polymeric matrix and uses a natural microcarrier instead. Plant spores are hollow shells of sporopollenin, a chemically inert biopolyester whose molecular structure was only elucidated recently (Li *et al.*, 2019). Their cavities can be emptied and refilled. They have been widely used as microcarriers in drug delivery (Diego-Taboada *et al.*, 2014; Mundargi *et al.*, 2016).

Their transfer to road materials is recent. Alpizar-Reyes *et al.* (2022) reported the first such use, encapsulating a recycled oil rejuvenator in exine capsules obtained from *Lycopodium clavatum* spores by sequential defatting and acid treatment, a route that avoids both the porous stone and the formaldehyde resin of the earlier designs. The treated spores retained an intact microstructure of approximately 28 µm, with an uncovered porous network and an empty core available for loading. Vacuum loading reached an encapsulation efficiency of 93.02 ± 3.71 %, and the microcapsules remained thermally stable up to 204°C. An artificial microcrack of 150 µm width in aged bitumen was completely closed in 50 min.

The loading technology is, in this system, determinant. Vacuum encapsulation reached a significantly higher efficiency of 86.1 % against 59.1 % for passive loading, since the applied pressure gradient forces the rejuvenator into the spore cavities instead of relying on natural diffusion (Alpizar-Reyes *et al.*, 2023). The same carrier logic extends to porous mineral geomaterials, and volcanic pumice saturated with sodium silicate and coated with polyvinyl alcohol has been proposed for self-healing cementitious materials (Alpizar-Reyes *et al.*, 2025). That system was designed for a cementitious matrix, and its transfer to a bituminous one has not been tested. It may nonetheless be relevant for Mexico, where volcanic deposits are widely available.

3.2.3 The processing window: thermal and mechanical survival

An encapsulated rejuvenator is only useful if it reaches the pavement intact. Hot mix asphalt is produced at 150 to 180 °C, and field and laboratory measurements place roller compaction pressures below about 0.7 MPa (Delgadillo and Bahia, 2008). The capsule must survive both stages, and, at the same time, it must rupture only when a crack reaches it. This is, in essence, a two-sided requirement, and it is the reason why the mechanical characterisation of the capsule is reported before and after a heating treatment in most of the studies cited here.

Survival through manufacturing has been verified for several systems. The states of the microcapsules within the binder after mixing have been observed directly (Su *et al.*, 2017), and capsules can be added to an asphalt mixture without compromising its mechanical performance (Al-Mansoori *et al.*, 2017). Thermal stability has been quantified in detail for the alginate route. The biopolymeric matrix alone started to degrade at 168 °C, whereas the capsules containing virgin cooking oil, waste cooking oil

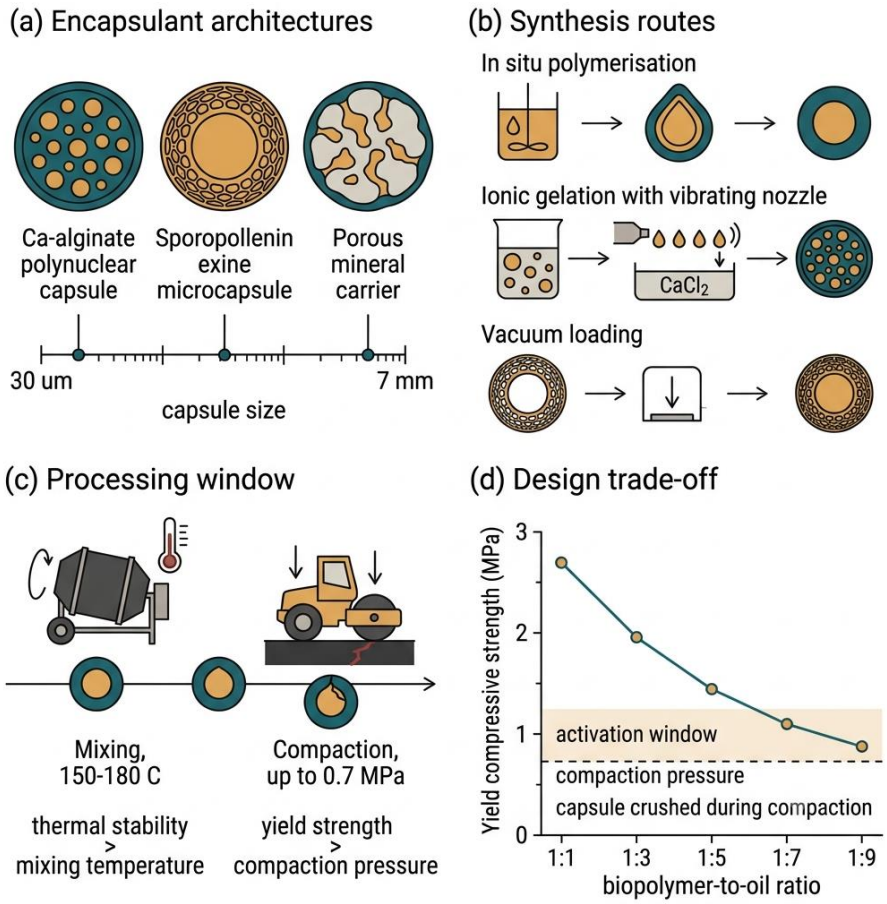
and virgin engine oil kept degradation rates below 1 %/min up to 339, 338 and 209 °C, respectively (Concha *et al.*, 2022).

Mechanical stability follows the opposite trend to the payload. After preheating at 150 °C for 2 h, the yield compressive strength of the same capsules decreased to 2.05, 1.97 and 1.23 MPa, values that remain above the compaction pressure for the two cooking oils. Increasing the encapsulated oil content also weakens the capsule, with strengths falling from 2.71 MPa at a 1:1 ratio to 0.85 MPa at 1:9 (Concha *et al.*, 2023).

The authors believe that this trade-off should be read as a design variable rather than as a limitation. A capsule far stronger than the compaction pressure survives the plant but may never open under service loads, while a capsule close to that threshold activates opportunely. Recent optimisation, in fact, supports the intermediate solution. Capsules of 1.06 mm produced with a 750 µm nozzle and a 2 % wt. calcium chloride hardening solution reached an encapsulation efficiency of 97 %, a compressive strength of 8.23 MPa at 20 °C and a cumulative mass loss of only 5.9 % at 150 °C (Concha *et al.*, 2025; Norambuena-Contreras *et al.*, 2025). The encapsulant architecture available and the processing window that each of them must survive are summarised in figure 1.

Figure 1

Encapsulated rejuvenators for asphalt self-healing. (a) Cross-sections of the three encapsulant morphologies reported for asphalt rejuvenators: calcium-alginate polynuclear capsules, sporopollenin exine microcapsules obtained from Lycopodium clavatum spores, and porous mineral carriers protected by a polymeric coating, spanning three orders of magnitude in size. (b) Synthesis routes: in situ polymerisation of a core-shell wall, ionic gelation of an oil-in-water emulsion extruded through a vibrating nozzle, and vacuum loading of a hollow natural carrier. (c) Processing window that the capsule must survive mixing of hot mix asphalt at 150 to 180 °C and roller compaction at pressures of up to 0.7 MPa. (d) Design trade-off: the yield compressive strength of the capsule decreases as the encapsulated oil content increases, and the activation window lies between the compaction pressure and the strength at which the capsule no longer opens under service loads.



3.2.4 Activation and release kinetics of the healing agent

The release of the rejuvenator is the least characterised stage of the mechanism. It is also the stage that governs how much healing agent reaches the crack, and for how long (Lu *et al.*, 2021). Most reported developments rely on macroscale healing tests, and they treat the release of the capsule as instantaneous.

That assumption is not supported by transport phenomena measurements, however, and it prevents the tailored design of a capsule for a given rejuvenator, which is precisely what a mechanistic description of the release would enable.

Two transport steps have to be separated. They operate on very different scales. The first is the escape of the oil from the fractured capsule matrix. Alpizar-Reyes *et al.* (2024) measured it directly by compressing capsules just below their yield force of 6.14 N, which produced controlled damage without complete rupture, and by quantifying the released oil at intervals between 1 and 120 min. The release followed zero-order kinetics, and the effective diffusion coefficient obtained from Fick's second law in spherical coordinates was 4.80×10^{-6} m²/s.

The second step is the diffusion of the rejuvenator into the aged binder. Ren *et al.* (2023) combined molecular dynamics with experimental validation to describe that interfacial diffusion, and Assaf *et al.* (2024) obtained coefficients between 6.8×10^{-13} and 4.35×10^{-10} m²/s over 240 simulations covering three bitumens, five ageing states and temperatures from 60 to 200 °C.

The two coefficients are not measured on the same basis, and the comparison requires care. The value obtained from a fractured capsule is an effective coefficient that lumps the flow of oil through the damaged biopolymeric matrix, whereas the values obtained by simulation describe molecular diffusion inside the binder. Even allowing for that difference, the gap is too wide to be attributed to the method alone. Hence, the following hypothesis is proposed: diffusion into the aged binder, and not the emptying of the capsule, controls the rate of the healing process.

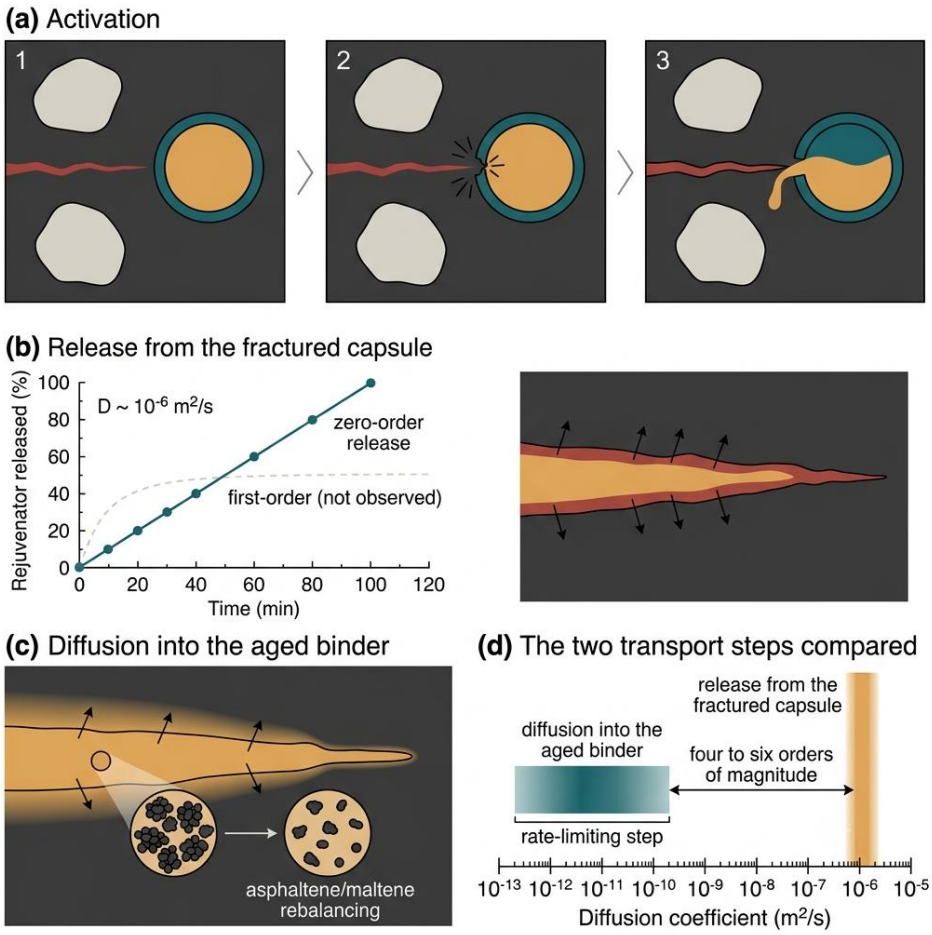
Zero-order behaviour at the capsule scale still matters. The release rate becomes independent of the remaining payload, so that a fractured capsule may sustain the supply of rejuvenator over the whole rest period. In agreement with that reading, healing levels keep increasing between the 6 h and the 24 h rest periods used in cyclic fracture-healing protocols. Wan *et al.* (2025) reached the same conclusion from the loading side, reporting that the released fraction rose from 49.5 % to 61.5 % when the load pressure increased from 0.70 to 1.40 MPa under 64000 cycles.

The subsequent crack closure is governed by the viscosity of the rejuvenator and by the released volume. A rejuvenator, consequently, should be selected for its diffusivity in aged bitumen, and not only for its chemical restoring capacity (Xu *et al.*, 2021).

The release can also be triggered by demand. Mechanical activation of biobased capsules has been proposed to anticipate the healing event, and externally activated systems releasing the rejuvenator under microwave irradiation allow infrastructure managers to heal selected pavement sections before visible damage appears (Pérez Mena *et al.*, 2020). These approaches turn an autonomous mechanism into a manageable maintenance operation, which is a highly attractive feature for a network as extensive as the Mexican one. The complete sequence, from capsule activation to crack closure, is represented in figure 2.

Figure 2

Activation of the capsule and transport of the rejuvenator to the crack. (a) A propagating microcrack in aged bitumen reaches the capsule, the stress concentration at the crack tip fractures its wall and the rejuvenator is released. (b) Release from the fractured capsule follows zero-order kinetics, with an effective diffusion coefficient in the order of 10^{-6} m²/s, so that the release rate is independent of the remaining payload. (c) Diffusion of the released rejuvenator into the aged binder restores the asphaltene/maltene balance and allows capillary flow to seal the crack. (d) The two transport steps compared on a logarithmic scale of diffusion coefficients: the release of the oil from the capsule matrix is four to six orders of magnitude faster than its diffusion into the binder, which identifies the second step as rate-limiting.



3.2.5 Dosage, healing level and mixture performance

The healing benefit of encapsulated rejuvenators is not proportional to the capsule content, as might be assumed. Calcium-alginate capsules modify stiffness, the fatigue life and the rutting resistance of the mixture at the same time as they promote healing (Micaelo *et al.*, 2020).

Healing levels reported at binder and mixture scale appear consistent with those dosages and healing ratios close to 75 % have been measured on beams subjected to 128000 load cycles at 0.7 MPa (Wan *et al.*, 2025). The optimum dosage is a compromise between healing capacity and structural performance, not a maximum, and the determination of that optimum is required for each mixture, for each capsule design and for each expected rest period, since none of those three variables can be transferred from one study to another. Hence, national specifications for smart asphalt materials should prescribe a healing protocol and a dosage range rather than a single capsule content.

3.3 BIOBASED REJUVENATORS AND LOCAL ENCAPSULATING BIOPOLYMERS: AN OPPORTUNITY FOR MEXICO

Biobased rejuvenators restore aged binders by replenishing the light fractions, rebalancing the colloidal structure, deagglomerating the asphaltenes and providing an antioxidant effect. Reported dosages depend on the feedstock and on the degree of ageing. Waste cooking oils restore a 40/50 aged bitumen at 3 to 4 % wt. and are suitable for high-RAP binders at 7.5 to 10 %, whereas virgin vegetable oils require 6 to 8 % for a balanced performance (Hamedi *et al.*, 2026). That dosage range connects the encapsulation route directly with the reclaimed asphalt pavement strategies discussed in Section 7. Sunflower oil has been used as an encapsulated rejuvenator for almost a decade (Shirzad *et al.*, 2016). Both feedstocks are produced by the Mexican agricultural and food service sectors, so the supply of the healing agent is unlikely to be the critical part of the problem. A Mexican implementation should assess the encapsulation process, and not only the healing agent, before an environmental benefit is claimed.

Cost is the argument that usually decides. The conductive additives discussed in Section 7 raise the production cost of the mixture by 30 to 50 %, whereas encapsulated rejuvenators are dosed at 0.125 to 1 % by weight and are manufactured from polysaccharide and a waste oil. Encapsulation is, on that basis, among the least expensive routes towards a smart pavement. The difference is one order of magnitude.

The encapsulating material is the component where the Mexican agro-industry has the clearest opportunity. Hydrocolloids extracted from local crops, and from their residues, have already been characterised as wall materials for the encapsulation of vegetable oils. Tamarind seed mucilage encapsulated sesame seed oil with an efficiency of 91.05 % and produced microcapsules that were thermally stable up to 227 °C, a value well above the mixing temperature of hot mix asphalt (Alpizar-Reyes *et al.*, 2020). Sodium alginate blended with nopal mucilage has been used for the ionic gelation of the same oil, improving its oxidative stability (Velázquez-Gutiérrez *et al.*, 2020); and pectin extracted from red pitaya peel has shown structural and emulsifying properties suitable for oil-in-water systems

(Alpizar-Reyes *et al.*, 2022b). These wall materials are abundant, low cost, biodegradable and non-toxic. They come, moreover, from residues with no competing use.

These hydrocolloids have been validated for food-grade applications, and their transfer to road materials cannot be assumed. The following hypothesis is proposed. Mucilages and pectins of Mexican origin can replace part of the alginate in polynuclear capsules for asphalt rejuvenators, provided that three requirements are verified experimentally, namely a thermal stability above the mixing temperature, a yield compressive strength above the compaction pressure and a release rate compatible with the rest periods of the pavement. The verification of these requirements on Mexican feedstocks constitutes a challenging task for future research. It would also connect the national agro-industrial chains with road infrastructure, paving the way for self-healing technology developed with domestic materials.

3.4 CURRENT DEVELOPMENT STATUS

Although most self-healing technologies remain at the laboratory or pilot scale, full-scale trial sections have been successfully implemented in countries such as the Netherlands. These projects have validated the mechanical durability and healing performance of smart asphalt mixtures under real traffic conditions (Penalva-Salinas *et. al.*, 2024).

For Mexico, self-healing pavements could substantially extend service life while minimizing maintenance-related disruptions.

4 SELF-SENSING ASPHALT MATERIALS

Self-sensing asphalt representes a major technological advance thet enable pavements to function as distributed monitoring systems. Unlike conventional sensors, which are often vulnerable to environmental degradation, self-sensing pavements integrate sensing capabilities directly into the pavement structure.

4.1 ELECTRICAL CONDUCTIVITY AND PIEZORESISTIVE BEHAVIOR

Self-sensing functionality is achieved through the incorporation of conductive carbon-based maerials into asphalt mixtures. The sensign mechanism is bsaed on piezoresistivity, whereby electrical resistance changes in response to applied mechanical loads or structural damage (Lu *et al.*, 2023).

4.1.1 Carbon nanotubes and graphene

Carbon nanotubes and graphene have attracted considerable attention because of their exceptional electrical conductivity and mechanical reinforcement capabilities. These nanomaterials enhance fatigue resistance while providing reliable sensing functionality.

4.1.2 Carbon fibers

Carbon fibers are particularly effective in establishing conductive networks throughout asphalt mixtures thereby improving signal stability and sensitivity to mechanical loading.

4.2 APPLICATIONS FOR TRAFFIC MONITORING

4.2.1 Weigh in motion systems

Self-sensing asphalt can estimate axle loads and vehicle weights in real time. Such information is particularly valuable in freight corridors Where overloaded vehicles significantly accelerate pavement deterioration.

4.2.2 Early damage detection

Variations in baseline electrical resistance can indicate the initiation and propagation of internal cracks before visible surface defects develop, preventing maintenance strategies.

4.2.3 Traffic counting and vehicle classification

Smart pavements can also suport automated traffic monitoring, reducing the need for intrusive sensing systems and improving transportation data collection.

4.3 CHALLENGES ASSOCIATED WITH NANOMATERIAL DISPERSION

Despite their potential, the large-scale implementation of self-sensisg asphalt mixtures remains challanged by the difficulty of achieving uniform nanomaterial dispersion. Particle agglomeration can negatively affect both sensing performance and mechanical properties.

5 ELECTRICALLY CONDUCTIVE PAVEMENTS FOR DE-ICING APPLICATIONS

Ice accumulation poses significant safety rosks in mountainous regions and Northern Mexican states such as Chihuahua and Durango. Conventional de-icing methods based on chemical salts often result in environmental degradation and infrastructure corrosion.

5.1 OPERATING PRINCIPLES

Electrically conductive pavementes function as distribute heating systems. When a low electrical voltage is applied, conductive componentes generate heat through the Joule effect, maintaining pavement temperatures above the freezing point.

Common conductive additives include graphite, carbon fibers, and steel slag, all of which contribute to improve thermal conductivity and heating efficiency.

Some researches have shown that asphalt mixtures containing approximately 1% carbon fiber can achieve temperature increases exceeding 20°C within relatively short heating periods.

5.2 FEASIBILITY AND LIMITATIONS

The principal challange associated with electrically heated pavements is energy consumption. Therefore, deployment in Mexico would be most appropiate in critical locations such as bridges decks, airport runways, tunnel entrances, and steep roadway sections.

6 STRUCTURAL HEALTH MONITORING AND INTELLIGENT TRANSPORTATION INFRASTRUCTURE

The future of road intrastructure lies in integrating smart pavements into broader digital transportation ecosytems. Self-sensing asphalt materials provide continuous data streams that support structural health monitoring and predictive maintenance strategies.

6.1 DIGITAL TWINS

Data collected from smart pavements can be used to develop Digital Twin models that continuously replicate the condition of real world infrastrucutre. These virtual models enable accurate forecasting of pavement deterioration and maintenance requirements.

6.2 INTELLIGENT TRANSPORTATION SYSTEMS

Smart pavement data can be integrated into intelligent transportation systems, allowing communication between infrastructure and connected or autonomous vehicles. Such capabilities can enhance traffic safety by providing real time information regarding pavemente conditions, congestion, or hazardous weather events.

6.3 RENEWABLE ENERGY INTEGRATION

Future developments may combine smart pavements with solar energy harvesting systems, providing sustainable power sources for sensing, communication, and monitoring equipment (Hu *et al.*, 2023).

7 TECHNOLOGICAL CHALLENGES AND FUTURE PERSPECTIVES IN MEXICO

Despite their significant promise, widespread implementation of smart asphalt technologies faces several challenges.

The incorporation of graphene, carbon nanotubes, and carbon fibers can increase mixture production costs by approximately 30% to 50%. However, if life cycle cost analyses indicate that these investments can be offset through reduced maintenance requirments and extended pavemen servisse life.

Another important challenge involves integrating smart materials with reclaimed asphalt pavement Technologies to maximize environmental sustainability and minimize dependence on virgin materials (Mariyappan *et al.*, 2023).

Furthermore, national standars and testing protocols must be developed to evaluate the long-term performance af smart asphalt material unde Mexican climatic and traffic conditions. Collaboration among government agencies, research institutions, and industry stakeholders will be essential for successful implementation.

A specific barrier applies to encapsulated self-healing systems, and it is methodological rather than technological. There is no standardised protocol for quantifying the healing capacity of an asphalt mixture. The reported healing level depends on the rest period, on the conditioning temperature and on the capsule dosage, so that values obtained under different protocols are not comparable with each other (Xu *et al.*, 2018; Li *et al.*, 2021). The release of the rejuvenator, in addition, is rarely measured, and it is usually inferred from the final crack closure.

The definition of a national healing protocol would therefore be a low-cost first step for Mexico. Such a protocol should fix the fracture and healing temperatures, the rest periods and the reporting of the capsule dosage, and it could be developed by the Mexican Institute of Transportation together with the university laboratories already working on asphalt modification. Long-term field validation and life cycle evaluation of the encapsulation stage should follow, as recommended for bio-rejuvenators in general (Hamedi *et al.*, 2026).

7.1 Emerging Research and Development Initiatives in Mexico

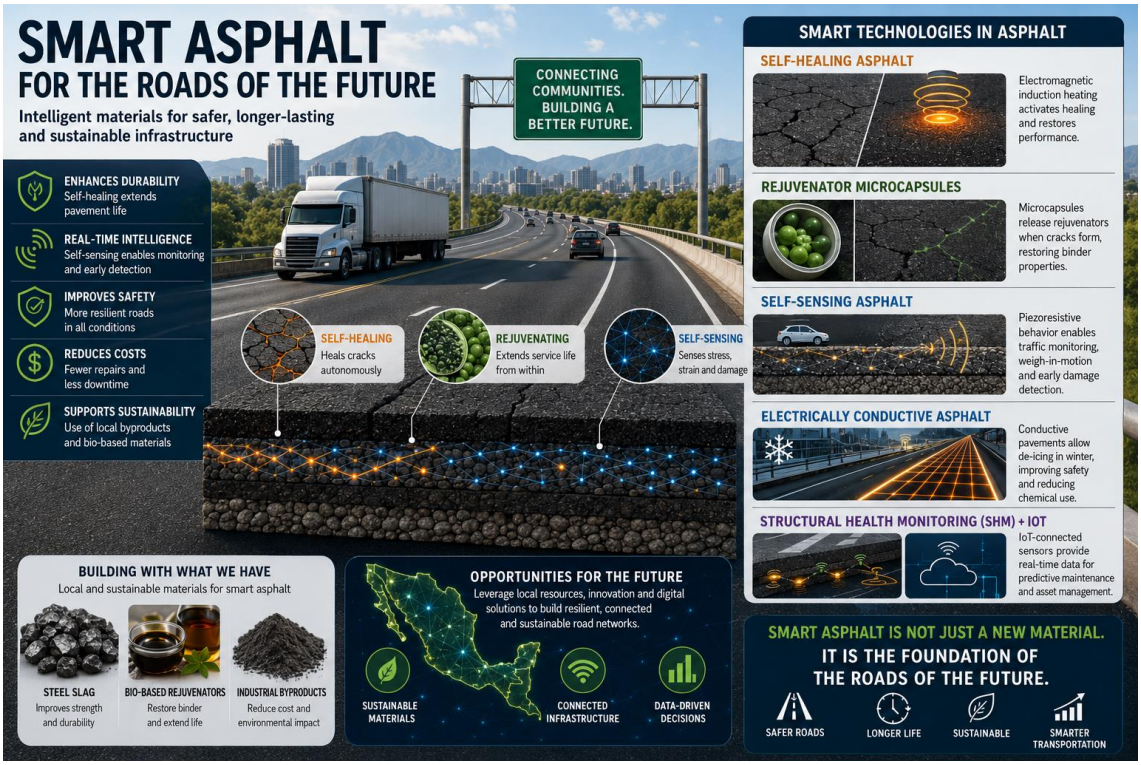
Mexico has begun to establish scientific and technological capabilities that could support the future implementation of smart asphalt pavements. Research conducted at the Institute of Engineering of the National Autonomous University of Mexico (UNAM) has contributed significantly to the understanding of asphalt fatigue, performance modeling, and advanced asphalt modification technologies. Recent collaborations have also explored the incorporation of graphene-based materials into asphalt binders, creating opportunities for the future development of multifunctional and electrically conductive pavements.

Additional research efforts at the Universidad Autónoma de Sinaloa and institutions within the Tecnológico Nacional de México (TecNM) have investigated graphene oxide-modified asphalt mixtures, reporting improvements in rheological and mechanical performance that could support future self-sensing applications (Rondón-Quintana, *et al.*, 2018).

At the institutional level, the Mexican Institute of Transportation (IMT) has promoted innovation in pavement evaluation, infrastructure monitoring, axle-load measurement technologies, and intelligent transportation systems, providing an important foundation for the integration of Structural Health Monitoring (SHM) and digital road infrastructure in Mexico.

Figure 3

Smart Asphalt: From Self-Healing Materials to Intelligent Road Networks



8 CONCLUSIONS

Smart asphalt materials represent one of the most significant innovations in modern transportation infrastructure. Self-healing technologies offer the possibility of pavements capable of autonomously mitigating damage, while self-sensing systems provide real-time intelligence for traffic management and structural monitoring.

Although economic and technical barriers remain, the strategic use of domestic industrial byproducts such as steel slag, together with bio-based rejuvenators and advanced sensing technologies, creates a unique opportunity for Mexico to accelerate the transition toward resilient, sustainable, and digitally connected road networks.

Ultimately, smart asphalt materials should not be viewed merely as an emerging technology but as a critical component of future infrastructure development, enabling safer, longer lasting, and more sustainable transportation systems.

Among the self-healing Technologies discussed here, encapsulated rejuvenators present the lowest entry barrier for Mexico, since they require no modification of the paving equipment and they can be produced from agro-industrial residues and from locally available biopolymers. Their performance, however, is governed by three quantities that must be measured rather than assumed: the thermal and

mechanical stability of the capsule under mixing and compaction, the release kinetics of the healing agent once the capsule has been activated, and the dosage beyond which the healing gain no longer compensates the loss of stiffness of the mixture.

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