infrastructures

Concept Paper

A Review of the Contribution of Mechanomutable Asphalt Materials Towards Addressing the Upcoming Challenges of Asphalt Pavements

Paulina Leiva-Padilla [1,*], Fernando Moreno-Navarro [1], Guillermo Iglesias [2] and Maria Carmen Rubio-Gamez [1]

1 Laboratory of Construction Engineering of the University of Granada (LabIC.UGR), 48-18071 Granada, Spain; fmoreno@ugr.es (F.M.-N.); mcrubio@ugr.es (M.C.R.-G.)
2 Department of Applied Physics of the University of Granada, 18071 Granada, Spain; iglesias@ugr.es
* Correspondence: pleiva@ugr.es

Received: 1 December 2019; Accepted: 25 February 2020; Published: 28 February 2020

Abstract: In the coming years, asphalt materials will face significant challenges due to the demand for smart multifunctional materials in transportation infrastructures, designed under sustainability criteria. Asphalt pavements will not only have to contribute towards the provision of an adequate surface for the transportation of different types of vehicles, but will need to do so considering the increased loads that they will have to support, as well as the extreme weather conditions resulting from climate change. These pavements will also need the capacity to interact with autonomous vehicles and provide information to the users and maintenance agencies regarding traffic data or performance levels. This paper describes how mechanomutable asphalt materials (MAMs) could enhance the properties of asphalt materials, enabling their use as a solution for smart infrastructures.

Keywords: mechanomutable asphalt materials; MAMs; smart materials; smart roads; magnetic fields

1. Introduction

Over the years, engineers have worked on developing solutions to meet the needs of society, including housing, basic services and communications. In the area of transport infrastructure, there is an identifiable process of development, which began with Roman roads and continually evolved to produce the improved paved roads that allow for the driving of motorized vehicles. These roads were later transformed into the high-capacity roads (the roads that we know today) that have recently begun to incorporate more sustainable and smarter materials and practices of building and design.

Therefore, roads are beginning to be regarded as more than simply a means of transporting goods and services between cities; they are required to provide extra value for the investments made to build them and the spaces that they use. In particular, new trends have emerged in the design and production of advanced materials with the capacity to overcome the challenges associated with recent technological advances, as well as the effects of extreme weather resulting from climate change. One example is the implementation of methodologies for evaluating the environmental impact of traditional processes of production and construction, and for the definition of strategies to make these processes cleaner and more sustainable (e.g., low temperature manufacturing technologies, the use of waste as a substitute for natural resources and LCA studies). A further example is the design of new materials capable of dealing with extreme temperature changes and the associated problems, including permanent deformations produced at high temperatures, aging generated by high exposure to UV rays and chemical pollutants, fatigue cracking produced by freeze-thaw cycles and thermal cracking caused by the retraction of the material at low temperatures.

In general terms, this new generation of roads could be built using resilient and smart materials that have the capacity to extend the life of the pavement, improve sustainability, reduce maintenance costs and improve road safety, in addition to avoiding the traffic disruptions that lead to significant economic losses and, therefore, the slower development of countries. Additionally, these roads could contribute towards meeting the requirements established by recent technological advances in the autonomous vehicle industry.

Therefore, some of the main characteristics of the materials developed to be included in this new generation of roads include the capacity to self-heal the cracks developed as a result of traffic-induced fatigue, to show more visible colors at night in order to enhance road safety, to register the level of pressure and strain experienced by the effect of vehicle loads, to capture energy from the environment (wind, solar, hydraulic) in order to feed other components of the traffic system, to communicate with autonomous vehicles to assist in their guidance, as well as to send traffic signals to generate an integral system of communications.

Included among this new generation of materials are mechanomutable asphalt materials (MAMs), which are composed of a bituminous matrix with magnetically susceptible materials activated by the effect of external magnetic fields, if needed. MAMs can be used in three main potential applications [1,2]: (1) the mechanical control of the modulus of the bituminous matrix, to improve the performance of specific areas of the road; (2) the generation of thermal changes in order to propose alternative solutions for road maintenance and (3) the construction of encoded roads to assist self-guided vehicle systems.

The present paper presents a general description of MAMs, the mechanisms associated with their functioning and use, as well as the specific areas in which they could be most conveniently placed, in order to consider their use as a potential solution for the construction of smart pavements.

2. Mechanomutable Asphalt Materials

Mechanomutable asphalt materials can be defined as a bituminous matrix modified with ferromagnetic materials, which can modify mechanical performance using the effect of magnetic fields produced in permanent magnets [3–7]. As shown in Figure 1, this concept can be extended to thermomutable materials due to the thermal changes produced by the effect of magnetic fields generated in induction coils, which can also allow for the construction of encoded roads for smart cities (communication with self-driving vehicles, cars, scooters, bikes people with limited mobility, traffic signals and for collecting traffic count data, among other uses) [2].

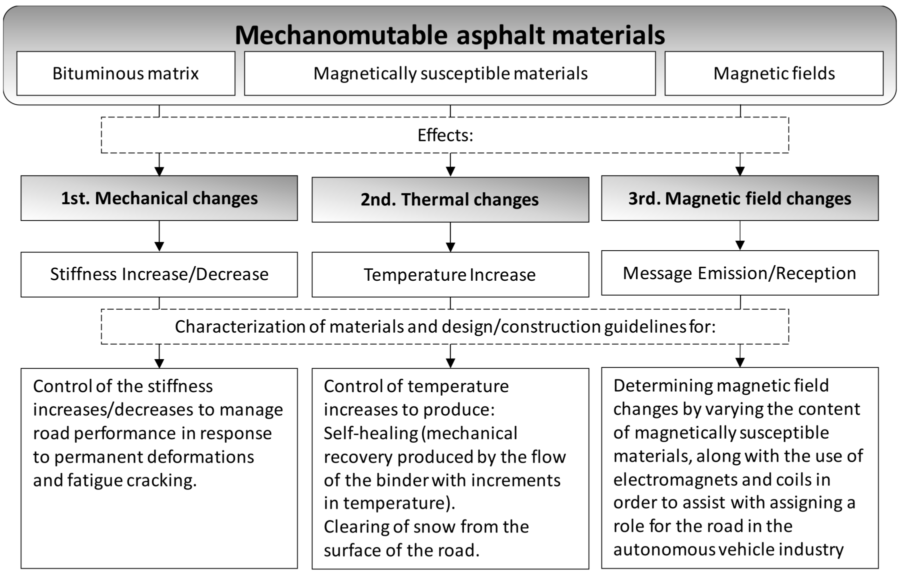

Figure 1. Mechanomutable asphalt materials.

Table 1 displays the materials with ferromagnetic properties that have been used until now in the construction of asphalt materials. These can be summarized as: steel slag, steel grit, ferrite fillers, fibers (carbon, steel, steel wood and carbon nanofibers), magnetite (tailings and powered), carbonyl iron powder, graphene, graphite, carbon nanotubes and carbon black. Depending on the type of material, these can serve as total or partial substitutes for the fine/coarse aggregate. The main parameters evaluated in previous studies are associated with the typical distresses developed in the material during practice, but without the application of magnetic fields (Table 1). These are: cracking (dynamic and quasi-static tests to represent fatigue and fracture), permanent deformation (Marshall stability and rutting) and moisture damage (stiffness loss).

More recent studies (Table 1) have also evaluated the changes produced by magnetic fields in terms of dynamic modulus values, phase angle and the healing capacity of these materials (understood as the mechanical recovery of the material following the application of heat and resting periods), as well as susceptibility to detection by magnetic field sensors, a characteristic that makes these materials a viable option for the encoding of the roads that is needed for the autonomous vehicle industry.

Table 1. Ferromagnetic materials used in the construction of asphalt materials.

Material	Parameters studied	Reference
Steel slag (coarse aggregate and powdered), steel grit.	Permanent deformation, fracture energy, moisture damage, Marshall stability.	[8–12].
Ferrite fillers.	Permanent deformation, healing, moisture damage, Marshall stability	[13–16].
Fibers (carbon, steel, steel wood and carbon nanofibers)	Fracture energy, moisture damage, Marshall stability.	[2,16–23].
Magnetite (tailings and powdered)	Moisture damage, Marshall stability.	[24–26]
Carbonyl iron powder	Permanent deformation, fatigue cracking, complex modulus and phase angle.	[4,5]
Carbon (carbon fiber, flake graphite and exfoliated graphite, graphene, carbon black and carbon nanotubes)	Electrical resistivity, healing, rheology, electrical conductivity, temperature changes.	[18,27–34]

2.1. *Mechanomutable Asphalt Materials as Improved Materials for Constructing Pavements*

Mechanomutable asphalt materials were born from the principle of the functioning of the magneto-rheological (MR) fluids applied to asphalt binders [4,5]. As shown in Figure 2, the characteristics of magneto-rheological fluids provide a medium (in this case a bituminous matrix) in which to magnetically suspend active particles during the absence of magnetic fields. However, when magnetic fields are present, these materials have the capacity to behave as a quasi-solid material, increasing the apparent viscosity of the material [35,36], modifying its rheological behavior from Newtonian to viscoelastic [37] and impeding the movement of the magnetically active particles, which produce an internal stress tensor in the mixture [5].

Research studies that have specifically focused on mechanomutable asphalt materials have confirmed that, at the binder scale (Figure 3, MAB1, MAB2, MAB3), the higher intensity of the magnetic field and higher quantities of magnetically active particles can increase the modulus and decrease the phase angle of the mechanomutable binder [5]. Related studies that have simulated the dynamic demands of traffic (creep and recovery tests) have revealed that the cumulative deformations in these materials are due to a decrease in their propensity to deform rather than an increase in their recovery capacity (which is more strongly influenced by the penetration grade of the bitumen) [4]. In order to scale those findings to practice, later studies at the mortar scale (Figure 3, MAM1) confirmed the increase in modulus values, depending on the increase in the intensity of the magnetic field and the quantity of magnetically susceptible materials [6].

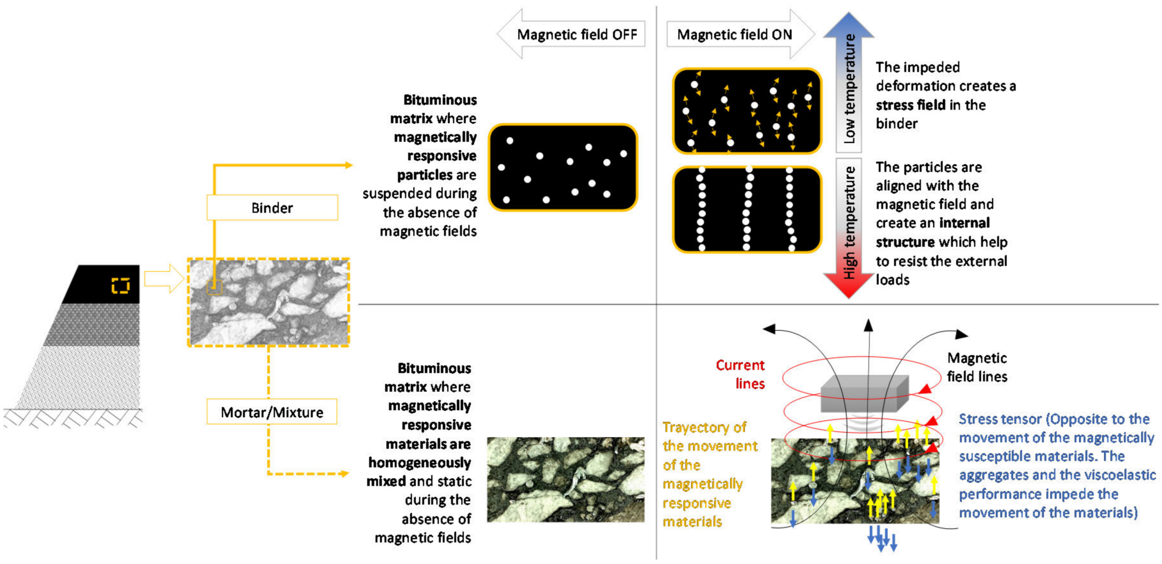

Figure 2. Functioning mechanism of mechanomutable asphalt materials (MAMs) as improved materials for pavements.

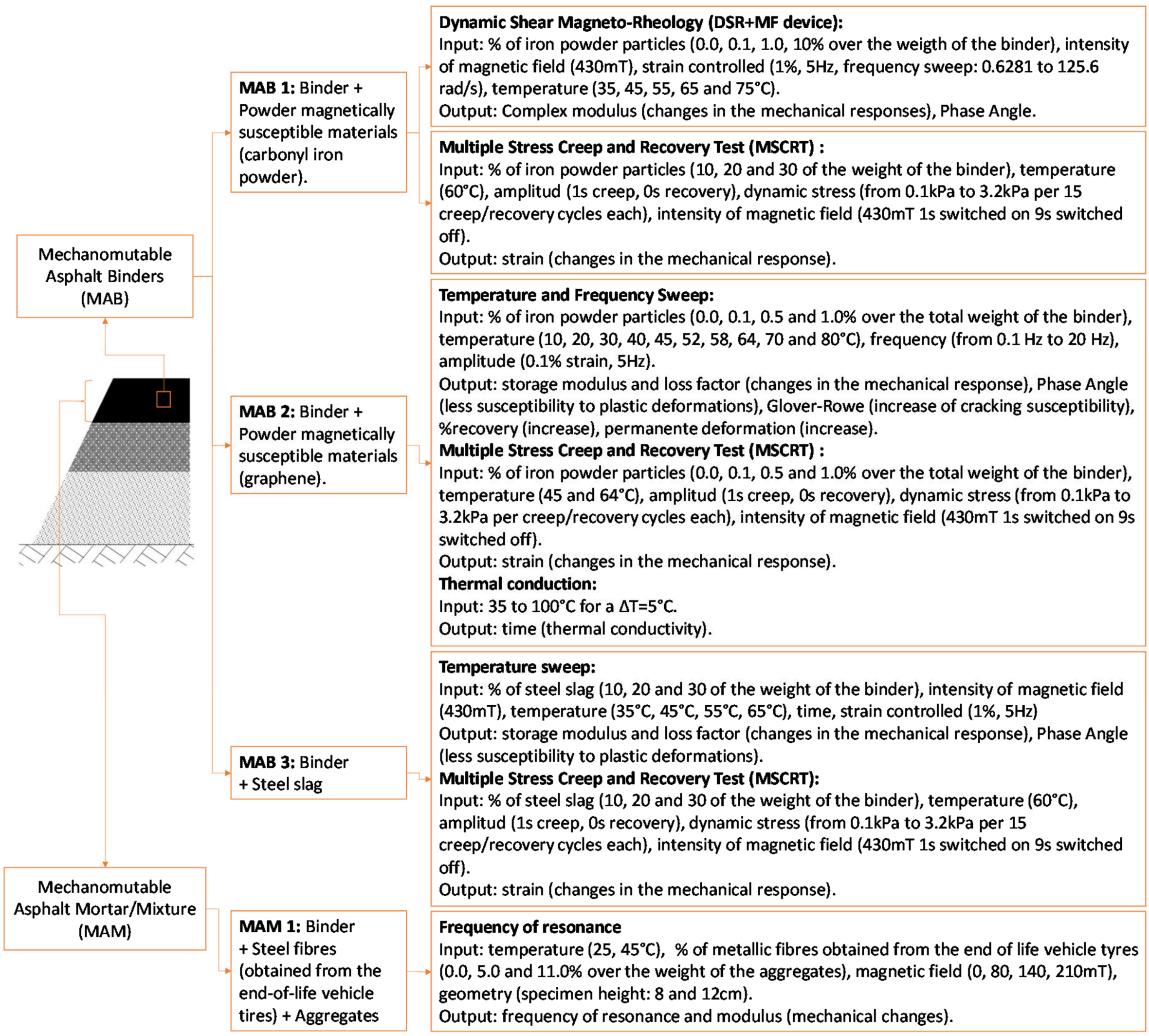

Figure 3. Key studies regarding the structural applications of MAMs in pavements [3–6,38].

Finally, studies regarding the piezoresistivity of electrically conductive asphalt base composites reveal that there is a correlation between this parameter and the stress–strain responses of the pavement, which could be useful for weighing, traffic monitoring, border monitoring and structural vibration control [39,40]. Therefore, the aforementioned capacities of these materials point to their potential use in the construction of airport runways, the high loading areas of airports, ports and parking lots, bus stops and exclusive lanes for heavy traffic.

2.2. Mechanomutable Asphalt Materials for Improving Road Safety and Service Conditions

Mechanomutable asphalt materials are electroconductive; thus, they have the capacity to produce and conduct Foucault currents generated from the effect of magnetic fields (Figure 4). In turn, these currents are the source of the energy losses transformed into heat through the Joule effect. Thus, mechanomutable asphalt materials can also be regarded as thermomutable asphalt materials, which makes them ideal for two types of road maintenance operations: 1) clearing ice and snow from the surface of the road (Figure 4), and 2) healing the cracks produced from the dynamic loads of traffic, temperature and moisture changes (Figure 5).

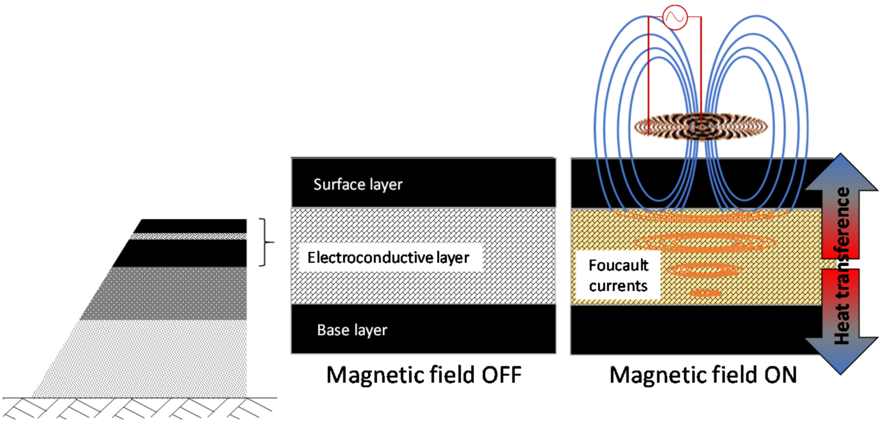

Figure 4. Schema of the thermomutable asphalt materials under magnetic fields for use in de-icing and producing anti-snow roads.

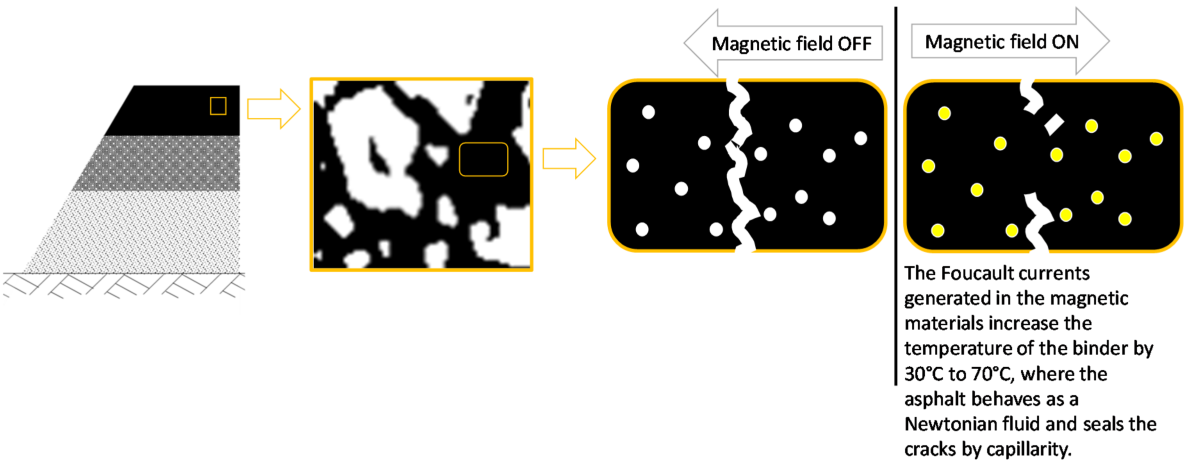

Figure 5. Schema of the healing capacity of thermomutable asphalt binders.

To achieve the first type of maintenance activity, the temperature of the electroconductive layer is increased with the goal to heat up the whole pavement system though conduction. This has the effect of melting possible snow and ice on the road and increasing user safety. For the second maintenance activity, a magnetic field is applied to the MAM to produce a controlled increase in temperatures between 30 °C and 70 °C, via induction [19,41] and microwaves [19], which is the interval of temperatures between which the binder flows as a Newtonian fluid and is then able to seal potential cracks in the pavement [22].

To achieve both aforementioned maintenance operations, an electroconductive smart layer can be placed inside the bituminous layers of the pavement. As shown Figure 4, the surface course would be applied on top to protect vehicle tires from possible damage caused by magnetically responsive materials in the mechanomutable asphalt layer; these materials, such as steel fibers obtained from end-of-life tires, typically have sharp edges. This surface layer would be an ultra-thin layer, to ensure the structural performance of the pavement and resist the temperature increase produced in the electroconductive layer by the activation of a magnetic field.

Table 2 describes recent strategies for managing snow- and ice-related maintenance activities on road pavements. These strategies have considered the use of electroconductive materials, as in this study, as well as other alternative systems. For example, the use of infrared heating, hydronic heating systems and embedded heating wires to melt the snow and ice in various public areas, such as pedestrian walkways, emergency entrances, loading dock ramps, hotel lobby entrances, bridge decks, sidewalks and pavements. These snow-melting systems are each composed of an energy source (which can be electric, geothermal and/or magnetic), heat exchanging elements, sensors (for measuring actual weather conditions) and a system control. The power consumption of these strategies varies depending on the current development of the system, which demonstrates that these solutions still require further research in order to optimize their performance and, finally, bring their use into practice.

Given that hazardous weather conditions can increase the susceptibility of traffic accidents, especially with snowfall being a particularly high risk factor in road accidents [42], these solutions can be used as environmental-friendly and smart alternative strategies for traditional "de-icing salts". While these salts have been shown to be economically accessible and effective, they affect the roadside soil, underground and surface water and vegetation integrity [43,44], as well as the long-term structural performance of the road infrastructure and vehicle health [45].

Table 2. Strategies for managing snow and ice in road surfaces.

System	Components	Performance	References
Infrared heating	Energy source, sensors, infrared heaters and control system.	Power consumption: 75 W/m^2. Areas of application: pedestrian walkways, emergency entrances, loading dock ramps and hotel lobby entry.	[46–48]
Hydronic heating systems	heat source, heat exchanging tubes usually embedded in the pavements (floor heating), heat transfer fluid, sensors and a system control.	Power consumption: 473 W/m^2. Areas of application: bridge decks, sidewalks, inclined pavements.	[48–51]
Embedded heating wires	energy source, sensors, heating element (cables and electric mats) and system controllers.	Power consumption: 323 to 3430 W/m^2. Areas of application: railroad, bridge deck, pavements.	[48,50,52]
Electrically conductive materials	heat source (induction, microwave, electricity), sensors, magnetically susceptible materials and system controllers.	Power consumption: 516 W/m^2 Areas of application: pavements, bridge decks.	[30,48,53]

With respect to the second type of maintenance operation, with the aim to transform roads into more resilient structures through self-healing, recent research efforts have designed and evaluated the use of encapsulated healing agents (oily rejuvenators) [54–56] and the effect of resting periods [57]. As it stands, this area is somewhat newer and has undergone less research.

2.3. Mechanomutable Asphalt Materials for the Guidance of Autonomous Vehicles

According to the levels established by the US National Highways Traffic Safety Administration (NHTSA), there are five levels, ranging from zero (no automation) to four (full self-driving automation) for classifying the autonomy of vehicles [58]. Due to the fact that the majority of the new conventional vehicles have one or more specific control functions that are automated, it can be assumed that Level 1 and Level 2 are now being implemented in real life. Ongoing research by the major vehicle manufacturers is being carried out with the aim of reaching Level 3, where the drivers can concede full control of the safety-critical functions of the vehicle under certain traffic or environmental conditions. Finally, some researchers [2,59,60] consider that to fully achieve Level 3 and Level 4, that is, full self-driving automation, it will be essential to incorporate the necessary infrastructure.

If the benefits of assigning a multifunctional character to the road are also considered, the use of mechanomutable asphalt materials can be extended to encoding the road [2] (Figure 6). Encoding the road entails assigning, alongside it, a type of language that is easily read by magnetic field sensors, with the aim of processing this signal so that it can be converted into specific functions for the vehicles and the rest of the traffic signals in the road infrastructure. Therefore, studies [2] in this field have addressed this issue by evaluating the performance of MAMs to allow for encoded roads, with the aim of establishing design methodologies and guidelines for their real-life implementation.

Figure 6 shows the potential areas of application, such as tunnels (where the GPS signal can be weak) and intersections (where the interaction can also involve traffic signals, pedestrians and personal mobility vehicles).

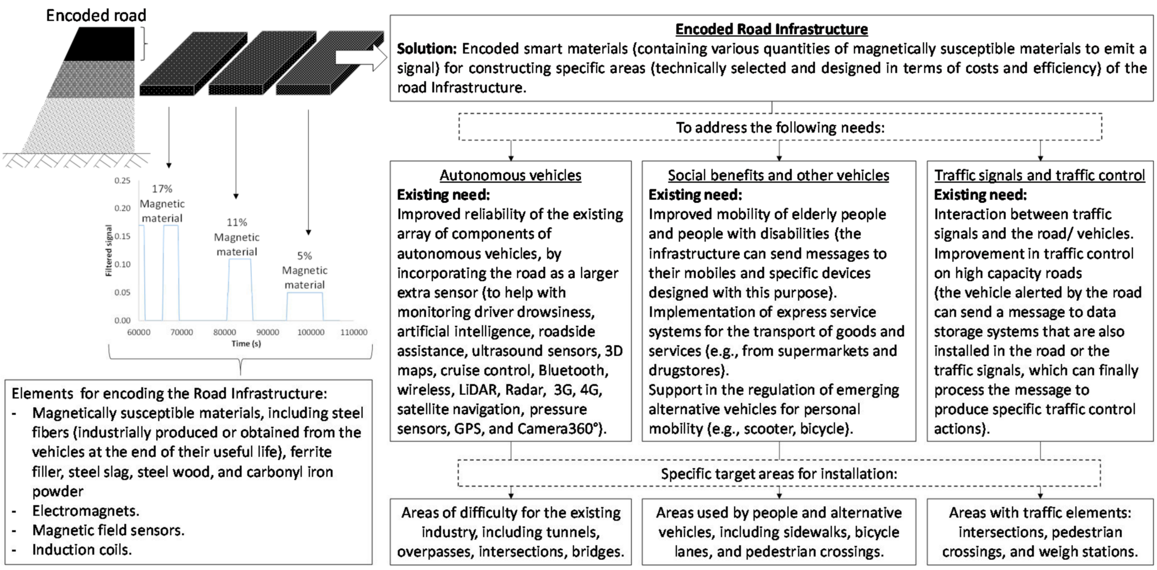

Figure 6. Schema of the applications of the encoded roads.

In addition, it is important to note that, with the emerging concept of smart cities, the mentioned benefits of MAMs would greatly benefit and be used in harmony with already existing smart systems. These other systems include smart sensors (both in the road and on vehicles and traffic signals), artificial intelligence (based on machine learning), image processing, big data and computer vision, to develop better traffic management systems and manage the road network in real time [61–66] (Figure 7).

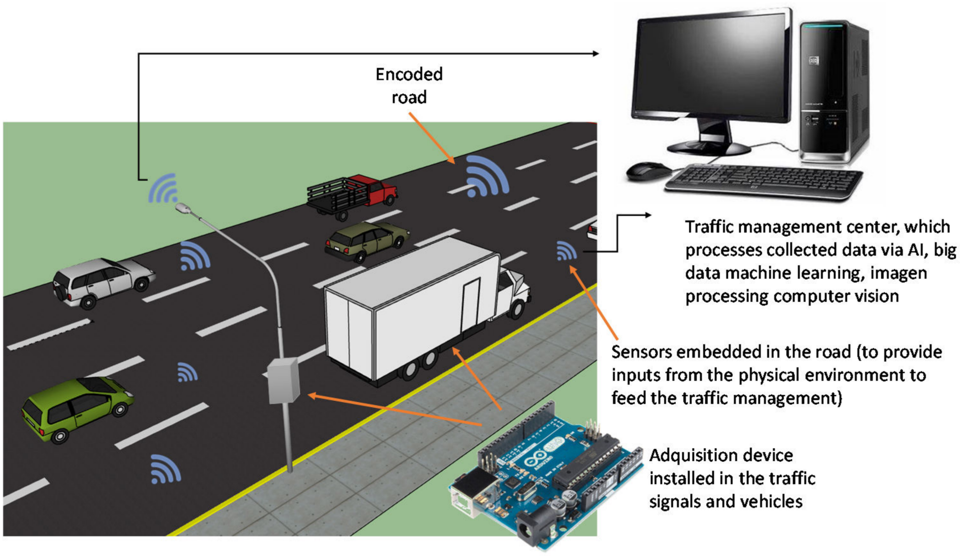

Figure 7. Schema of a novel traffic management system using encoded roads.

3. Conclusions

The aim of this paper was to describe how mechanomutable asphalt materials (obtained by modifying conventional asphalt materials with magnetically susceptible particles) could contribute towards meeting the challenges faced by asphalt roads. The main conclusions can be summarized as follows:

- The first potential application in which MAMs aim to improve the mechanical performance of asphalt pavements showed that the magnetically susceptible materials used in their manufacture tended to be aligned to the forces of activated magnetic fields. This movement improves the mechanical properties of these materials, which depends on the temperature, the amount of magnetically susceptible materials and the intensity of the magnetic field. The mechanisms of action involved in the process are associated with: (1) the development of an internal structure in the material at high temperatures and (2) the generation of a stress field inside the bituminous matrix at low temperatures;
- In the case of the second application, the concept of MAMs can be extended to their use as thermomutable materials. The electrical properties of the magnetically susceptible materials used in their manufacture allow for the production of parasite currents which produce energy losses and increments in the temperature of the material and the surrounding layers. This thermal capacity could be taken into account when proposing new strategies for improving the safety and service conditions of the road;
- With regard to the third application, the development of a better means of transportation means that the road infrastructure should be prepared to respond to the associated advances in technology, and mechanomutable asphalt materials provide a tool for developing roads that can be used for the guidance of autonomous vehicles;
- Finally, it should be noted that further research is required with regard to the development of these materials. In particular, there is a need is to replicate the results obtained in the laboratory in a real-scale study. More results are needed to provide inputs for validating numerical models, which can be useful in the parametrization—and, therefore, the extrapolation—of the uses of MAMs in practice. This will allow for validating and adjusting the tested designs, a step that is necessary for the future implementation of MAMs as smart materials that can be used in the construction of smart pavements.

Author Contributions: Conceptualization, P.L.-P., F.M.-N., G.I. and M.C.R.-G.; writing—original draft preparation, P.L.-P.; writing—review and editing, P.L.-P. and M.C.R.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon 2020 Programme under the Marie Skłodowska-Curie actions for research, technological development and demonstration, grant n.721493.

Acknowledgments: The research presented in this paper was carried out as part of the H2020-MSCA-ETN-2016. This project has received funding from the European Union's H2020 Program for research, technological development and demonstration under grant agreement number 721493.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Moreno-Navarro, F.; Rubio-Gámez, M.C. Development of new smart materials for the pavements of the future. *Carreteras* **2018**, *4*, 56–65.
2. Moreno-Navarro, F.; Iglesias, G.R.; Rubio-Gámez, M.C. Encoded asphalt materials for the guidance of autonomous vehicles. *Autom. Constr.* **2019**, *99*, 109–113. [CrossRef]
3. Moreno-Navarro, F.; Iglesias, G.R.; Rubio-Gámez, M.C. Experimental evaluation of using stainless steel slag to produce mechanomutable asphalt mortars for their use in smart materials. *Smart Mater. Struct.* **2016**, *25*, 115036. [CrossRef]
4. Moreno-Navarro, F.; Iglesias, G.R.; Rubio-Gámez, M.C. Mechanical performance of mechanomutable asphalt binders under cyclic creep and recovery loads. *Constr. Build. Mater.* **2016**, *113*, 506–512. [CrossRef]
5. Moreno-Navarro, F.; Iglesias, G.R.; Rubio-Gámez, M.C. Development of mechanomutable asphalt binders for the construction of smart pavements. *Mater. Des.* **2015**, *84*, 100–109. [CrossRef]
6. Leiva-Padilla, P.; Moreno-Navarro, F.; Iglesias, G.R.; Rubio-Gámez, M.C. Analysis of the mechanical response of asphalt materials manufactured with metallic fibres under the effect of magnetic fields. *Smart Mater. Struct.* **2019**, *29*, 015033. [CrossRef]
7. Moreno-Navarro, F.; Iglesias, G.R.; Rubio-Gámez, M.C. Ligante modificado con propiedades mecánicas controlables por campos magnéticos. International Patent Application No. PCT/ES2014/071002, 31 December 2014.
8. Skaf, M.; Manso, J.M.; Aragón, Á.; Fuente-Alonso, J.A.; Ortega-López, V. EAF slag in asphalt mixes: A brief review of its possible re-use. *Resour. Conserv. Recycl.* **2017**, *120*, 176–185. [CrossRef]
9. Chen, Z.; Wu, S.; Wen, J.; Zhao, M.; Yi, M.; Wan, J. Utilization of gneiss coarse aggregate and steel slag fine aggregate in asphalt mixture. *Constr. Build. Mater.* **2015**, *93*, 911–918. [CrossRef]
10. Wan, J.; Wu, S.; Xiao, Y.; Chen, Z.; Zhang, D. Study on the effective composition of steel slag for asphalt mixture induction heating purpose. *Constr. Build. Mater.* **2018**, *178*, 542–550. [CrossRef]
11. Gómez-Meijide, B.; Ajam, H.; Garcia, A.; Vansteenkiste, S. Effect of bitumen properties in the induction healing capacity of asphalt mixes. *Constr. Build. Mater.* **2018**, *190*, 131–139. [CrossRef]
12. Gómez-Meijide, B.; Ajam, H.; Lastra-González, P.; Garcia, A. Effect of air voids content on asphalt self-healing via induction and infrared heating. *Constr. Build. Mater.* **2016**, *126*, 957–966. [CrossRef]
13. Zhao, H.; Zhong, S.; Zhu, X.; Chen, H. High-efficiency heating characteristics of ferrite-filled asphalt-based composites under microwave irradiation. *J. Mater. Civ. Eng.* **2017**, *29*, 04017007. [CrossRef]
14. Nabiun, N.; Khabiri, M.M. Mechanical and moisture susceptibility properties of HMA containing ferrite for their use in magnetic asphalt. *Constr. Build. Mater.* **2016**, *113*, 691–697. [CrossRef]
15. Zhu, X.; Cai, Y.; Zhong, S.; Zhu, J.; Zhao, H. Self-healing efficiency of ferrite-filled asphalt mixture after microwave irradiation. *Constr. Build. Mater.* **2017**, *141*, 12–22. [CrossRef]
16. García, Á.; Schlangen, E.; van de Ven, M.; van Vliet, D. Induction heating of mastic containing conductive fibers and fillers. *Mater. Struct. Constr.* **2011**, *44*, 499–508. [CrossRef]
17. Pamulapati, Y.; Elseifi, M.A.; Cooper, S.B.; Mohammad, L.N.; Elbagalati, O. Evaluation of self-healing of asphalt concrete through induction heating and metallic fibers. *Constr. Build. Mater.* **2017**, *146*, 66–75. [CrossRef]
18. Pan, P.; Wu, S.; Xiao, F.; Pang, L.; Xiao, Y. Conductive asphalt concrete: A review on structure design, performance, and practical applications. *J. Intell. Mater. Syst. Struct.* **2015**, *26*, 755–769. [CrossRef]

19. Norambuena-Contreras, J.; Garcia, A. Self-healing of asphalt mixture by microwave and induction heating. *Mater. Des.* **2016**, *106*, 404–414. [CrossRef]
20. Dai, Q.; Wang, Z.; Hasan, M.R.M. Investigation of induction healing effects on electrically conductive asphalt mastic and asphalt concrete beams through fracture-healing tests. *Constr. Build. Mater.* **2013**, *49*, 729–737. [CrossRef]
21. García, A.; Norambuena-Contreras, J.; Partl, M.N. Experimental evaluation of dense asphalt concrete properties for induction heating purposes. *Constr. Build. Mater.* **2013**, *46*, 48–54. [CrossRef]
22. García, Á.; Schlangen, E.; van de Ven, M.; Liu, Q. A simple model to define induction heating in asphalt mastic. *Constr. Build. Mater.* **2012**, *31*, 38–46. [CrossRef]
23. Liu, Q.; García, Á.; Schlangen, E.; van de Ven, M. Induction healing of asphalt mastic and porous asphalt concrete. *Constr. Build. Mater.* **2011**, *25*, 3746–3752. [CrossRef]
24. Wang, Z.; Xu, C.; Wang, S.; Gao, J.; Ai, T. Utilization of magnetite tailings as aggregates in asphalt mixtures. *Constr. Build. Mater.* **2016**, *114*, 392–399. [CrossRef]
25. Wang, Z.; Wang, H.; An, D.; Ai, T.; Zhao, P. Laboratory investigation on deicing characteristics of asphalt mixtures using magnetite aggregate as microwave-absorbing materials. *Constr. Build. Mater.* **2016**, *124*, 589–597. [CrossRef]
26. Patti, F.; Mansour, K.; Pannirselvam, M.; Giustozzi, F. Mining materials to generate magnetically-triggered induction healing of bitumen on smart road pavements. *Constr. Build. Mater.* **2018**, *171*, 577–587. [CrossRef]
27. Zhang, K.; Gao, X.; Zhang, Q.; Li, T.; Chen, H.; Chen, X. Preparation and microwave absorption properties of asphalt carbon coated reduced graphene oxide/magnetic CoFe2O4 hollow particles modified multi-wall carbon nanotube composites. *J. Alloys Compd.* **2017**, *723*, 912–921. [CrossRef]
28. Yoo, D.Y.; Kim, S.; Kim, M.J.; Kim, D.; Shin, H.O. Self-healing capability of asphalt concrete with carbon-based materials. *J. Mater. Res. Technol.* **2019**, *8*, 827–839. [CrossRef]
29. De Melo, J.V.S.; Trichês, G.; de Rosso, L.T. Experimental evaluation of the influence of reinforcement with Multi-Walled Carbon Nanotubes (MWCNTs) on the properties and fatigue life of hot mix asphalt. *Constr. Build. Mater.* **2018**, *162*, 369–382. [CrossRef]
30. Arabzadeh, A.; Ceylan, H.; Kim, S.; Sassani, A.; Gopalakrishnan, K.; Mina, M. Electrically-conductive asphalt mastic: Temperature dependence and heating efficiency. *Mater. Des.* **2018**, *157*, 303–313. [CrossRef]
31. Jahanbakhsh, H.; Karimi, M.M.; Jahangiri, B.; Nejad, F.M. Induction heating and healing of carbon black modified asphalt concrete under microwave radiation. *Constr. Build. Mater.* **2018**, *174*, 656–666. [CrossRef]
32. Wang, Z.; Dai, Q.; Porter, D.; You, Z. Investigation of microwave healing performance of electrically conductive carbon fiber modified asphalt mixture beams. *Constr. Build. Mater.* **2016**, *126*, 1012–1019. [CrossRef]
33. Chen, B.; Li, B.; Gao, Y.; Ling, T.C.; Lu, Z.; Li, Z. Investigation on electrically conductive aggregates produced by incorporating carbon fiber and carbon black. *Constr. Build. Mater.* **2017**, *144*, 106–114. [CrossRef]
34. Wang, Z.; Dai, Q.; Guo, S. Laboratory performance evaluation of both flake graphite and exfoliated graphite nanoplatelet modified asphalt composites. *Constr. Build. Mater.* **2017**, *149*, 515–524. [CrossRef]
35. Iglesias, G.R.; Ahualli, S.; Otero, J.E.; Ruiz-Morón, L.F.; Durán, J.D.G. Theoretical and experimental evaluation of the flow behavior of a magnetorheological damper using an extremely bimodal magnetic fluid. *Smart Mater. Struct.* **2014**, *23*, 085028. [CrossRef]
36. Zubieta, M.; Eceolaza, S.; Elejabarrieta, M.J.; Bou-Ali, M.M. Magnetorheological fluids: Characterization and modeling of magnetization. *Smart Mater. Struct.* **2009**, *18*, 095019. [CrossRef]
37. Skalski, P.; Kalita, K. Role of magnetorheological fluids and elastomers in today's world. *Acta Mech. ET Autom.* **2017**, *11*, 267–274. [CrossRef]
38. Moreno-Navarro, F.; Sol-Sánchez, M.; Gámiz, F.; Rubio-Gámez, M.C. Mechanical and thermal properties of graphene modified asphalt binders. *Constr. Build. Mater.* **2018**, *180*, 265–274. [CrossRef]
39. Liu, X.; Wu, S. Study on the graphite and carbon fiber modified asphalt concrete. *Constr. Build. Mater.* **2011**, *25*, 1807–1811. [CrossRef]
40. Liu, X.; Wu, S.; Ye, Q.; Qiu, J.; Li, B. Properties evaluation of asphalt-based composites with graphite and mine powders. *Constr. Build. Mater.* **2008**, *22*, 121–126. [CrossRef]
41. Vila-Cortavitarte, M.; Jato-Espino, D.; Tabakovic, A.; Castro-Fresno, D. Optimizing the valorization of industrial by-products for the induction healing of asphalt mixtures. *Constr. Build. Mater.* **2019**, *228*, 116715. [CrossRef]

42. Eisenberg, D.; Warner, K.E. Effects of snowfalls on motor vehicle collisions, injuries, and fatalities. *Am. J. Public Health* **2005**, *95*, 120–124. [CrossRef] [PubMed]
43. Willmert, H.M.; Osso, J.D.; Twiss, M.R.; Langen, T.A. Winter road management effects on roadside soil and vegetation along a mountain pass in the Adirondack Park, New York, USA. *J. Environ. Manag.* **2018**, *225*, 215–223. [CrossRef]
44. Rivett, M.O.; Cuthbert, M.O.; Gamble, R.; Connon, L.E.; Pearson, A.; Shepley, M.G.; Davis, J. Highway deicing salt dynamic runoff to surface water and subsequent infiltration to groundwater during severe UK winters. *Sci. Total Environ.* **2016**, *565*, 324–338. [CrossRef] [PubMed]
45. Shi, X.; Akin, M.; Pan, T.; Fay, L.; Liu, Y.; Yang, Z. Deicer impacts on pavement materials: Introduction and recent developments. *Open Civ. Eng. J.* **2009**, *3*, 16–27. [CrossRef]
46. Mensah, K.; Choi, J.M. Review of technologies for snow melting systems. *J. Mech. Sci. Technol.* **2015**, *29*, 5507–5521. [CrossRef]
47. Endoh, Y.; Yoneda, Y.; Mori, K. *Far-Infrared Ray Snow Melting System*; West Nippon Expressway Facilities Company Limited: Osaka, Japan, 2000.
48. Yehia, S.; Tuan, C.Y. Bridge Deck Deicing. In Proceedings of the Transportation Conference Proceedings, Des Moines, IA, USA, 19–20 August 1998.
49. Wang, H.; Liu, L.; Chen, Z. Experimental investigation of hydronic snow melting process on the inclined pavement. *Cold Reg. Sci. Technol.* **2010**, *63*, 44–49. [CrossRef]
50. Zhao, H.; Wu, Z.; Wang, S.; Zheng, J.; Che, G. Concrete pavement deicing with carbon fiber heating wires. *Cold Reg. Sci. Technol.* **2011**, *65*, 413–420. [CrossRef]
51. Chen, M.; Wu, S.; Wang, H.; Zhang, J. Study of ice and snow melting process on conductive asphalt solar collector. *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 3241–3250. [CrossRef]
52. Kim, M.S.; Jang, D.-U.; Hong, J.-S.; Kim, T. Thermal modeling of railroad with installed snow melting system. *Cold Reg. Sci. Technol.* **2015**, *109*, 18–27. [CrossRef]
53. Abdualla, H.; Ceylan, H.; Kim, S.; Mina, M.; Cetin, K.S.; Taylor, P.C.; Gopalakrishnan, K.; Cetin, B.; Yang, S.; Vidyadharan, A. Design and construction of the world's first full-scale electrically conductive concrete heated airport pavement system at a U.S. airport. *Transp. Res. Rec.* **2018**, *2672*, 82–94. [CrossRef]
54. Wang, X.-Y.; Xie, X.-M.; Wang, L.-Q.; Su, J.-F.; Guo, Y.-D.; Mu, R. Rheological behaviour of bitumen blending with self-healing microcapsule: Effects of physical and chemical interface structures. *Colloids Surf. A Physicochem. Eng. Asp.* **2020**, *586*, 124212. [CrossRef]
55. Su, J.F.; Guo, Y.D.; Xie, X.M.; Zhang, X.L.; Mu, R.; Wang, Y.Y.; Tan, Y.Q. Smart bituminous material combining anti-icing and self-healing functions using electrothermal graphene microcapsules containing oily rejuvenator. *Constr. Build. Mater.* **2019**, *224*, 671–681. [CrossRef]
56. Norambuena-Contreras, J.; Yalcin, E.; Hudson-Griffiths, R.; García, A. Mechanical and self-healing properties of stone mastic asphalt containing encapsulated rejuvenators. *J. Mater. Civ. Eng.* **2019**, *31*, 04019052. [CrossRef]
57. Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C. Exploring the recovery of fatigue damage in bituminous mixtures: The role of healing. *Road Mater. Pavement Des.* **2015**, *16*, 75–89. [CrossRef]
58. National Highway Traffic Safety Administration (NHTSA) Preliminary Statement of Policy Concerning Automated Vehicles. 2013. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=2ahUKEwiZ2J3g6qDoAhWMKqYKHRbPD28QFjAAegQIAhAB&url=https%3A%2F%2Fwww.nhtsa.gov%2Fstaticfiles%2Frulemaking%2Fpdf%2FAutomated_Vehicles_Policy.pdf&usg=AOvVaw1kzgMhDIOOc-olHnCFb4os (accessed on 27 May 2018).
59. Wang, K.; Akar, G. Effects of neighborhood environments on perceived risk of self-driving: Evidence from the 2015 and 2017 Puget Sound Travel Surveys. *Transportation (Amst)* **2019**, *46*, 2117–2136. [CrossRef]
60. Litman, T. Autonomous vehicle implementation predictions: Implications for transport planning. In Proceedings of the Transportation Research Board Annual Meeting, Washington, DC, USA, 8–12 January 2017.
61. Jain, S.; Kumar, A.; Priyadharshini, M. Smart city: Traffic management system using smart sensor network. In Proceedings of the International Conference on Physics and Photonics Processes in Nano Sciences, Eluru, India, 20–22 June 2019; Volume 1362.
62. Fernández-Isabel, A.; Fuentes-Fernández, R.; de Diego, I.M. Modeling multi-agent systems to simulate sensor-based Smart Roads. *Simul. Model. Pract. Theory* **2020**, *99*, 101994. [CrossRef]

63. Pundir, S.; Wazid, M.; Singh, D.P.; Das, A.K.; Rodrigues, J.J.P.C.; Park, Y. Intrusion detection protocols in wireless sensor networks integrated to internet of things deployment: Survey and future challenges. *IEEE Access* **2020**, *8*, 3343–3363. [CrossRef]
64. Vasudev, H.; Das, D.; Vasilakos, A.V. Secure message propagation protocols for IoVs communication components. *Comput. Electr. Eng.* **2020**, *82*, 106555. [CrossRef]
65. Gade, D. ICT based smart traffic management system 'iSMART' for smart cities. *Int. J. Recent Technol. Eng.* **2019**, *8*, 3920–3928.
66. Nallaperuma, D.; Nawaratne, R.; Bandaragoda, T.; Adikari, A.; Nguyen, S.; Kempitiya, T.; De Silva, D.; Alahakoon, D.; Pothuhera, D. Online incremental machine learning platform for big data-driven smart traffic management. *IEEE Trans. Intell. Transp. Syst.* **2019**, *20*, 4679–4690. [CrossRef]