

Development of Innovative Pothole Repair Materials Using Induction Heating Technology

By

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Dedicated to

My Family and My Husband

Thank you for your love, support and encouragement

Abstract

Millions are spent by authorities to maintain and repair the world's potholes. In addition to the direct costs, they can also lead to damaged vehicles and an accelerated deterioration of the road system. The potholes create traffic risks that lead to the daily loss of hundreds of work hours for drivers and passengers. Many road crews are not familiar with the proper materials and methods for pothole repair. Correct selection of pothole patching materials and proper application of repair procedures can greatly increase the longevity of pothole repairs, lead to fewer driver frustrations, and lower road maintenance budgets.The present study aims to develop innovative materials to repair of potholes by using induction heating technology.

Three innovative patching materials to repair potholes are proposed, assessed and compared with conventional pothole patching materials. The first material is a combination of a prefabricated asphalt tile and a bonding layer that can be placed into a sanitised pothole and bonded by applying electromagnetic induction heating. The second material involves using prefabricated asphalt pellets to directly fill a pothole and then heated by induction. The third material comprises (1) prefabrication of binder pellets containing bitumen and steel wool that has been coated with a shell to avoid them sticking to each other; (2) the development of a mobile induction heating mixer that can mix the binder pellets with cold aggregate on-site before directly filling a pothole and compacting the mixture.

In this research, their tensile and shear strength properties were assessed and demonstrated by repairing simulated potholes on testing slabs and subjected them to wheel tracking tests. The innovative patching materials showed excellent durability higher than a road repaired with cold mix asphalt.

Furthermore, the innovative patching materials have been evaluated from economic and environmental standpoints and compared results with conventional hot mix and cold mix. These proposed patching materials have been applied by different raw materials and procedures, and have importance of properties that performed by laboratory tests. Based on the results of loaded wheel test, the service life of each patching materials has been calculated. An inventory was prepared to help quantify the energy requirements, material inputs, and emissions produced during production of raw materials, prefabrication of each product and their final installation. The requisite data was obtained from various sources in the literature. Two maintenance hypothesis were considered. The results showed that three innovative patching materials may be more sustainable and could reduce cost, energy usage and CO_2 emissions over time in agreement with hypothesis 1. However, they may cause to increase the economic and environmental impacts over time in agreement with hypothesis 2.

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Declaration

This is to declare that the contents of this thesis are my own work and were performed at the University of Nottingham from 2015 to 2018. This thesis has not been submitted to any other institution for another degree.

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Chapter 1
Introduction

1.1. Overview and research motivation

Nowadays, potholes are a widespread problem affecting all countries in the world. Most departments of road maintenance suffer from this type of road failure every year. Potholes can be specified according to their dimensions (length, width, depth) and location on the road. They can be found anywhere on the road surface and there can be a number of potholes closely spaced in different parts of the road system. The method and material of pothole repair can vary based on the road type (high capacity or local roads). This variation can be attributed to the pothole features because high capacity roads tend to have smaller and shallower holes than local roads, as reported by Blaha (1993).

It has been reported in the literature that there are key factors that might contribute to pavement deterioration and then cause the formation of potholes on the road surface (Wilson and Romine, 2001, Munyagi, 2007, Rahman and Thom, 2012, Agzenai et al., 2015, Nicholls et al., 2016). Generally, the flexible pavement structure comprises several layers: surface, base, subbase and subgrade layers (from top to bottom) which have a particular degree of bonding at their interfaces. Theoretically, the pavement structure is designed to be fully bonded together between the adjacent layers, and to behave as a single layer that does not produce any relative slip (Collop et al., 2003, Sangiorgi et al., 2003). This has an effect on the stability of asphalt mixtures in terms of cohesion and internal friction which are based on the aggregate gradation, density and quantity of asphalt mix (McHale et al, 2016).

The pavement strength is based on the strength and durability of each individual layer. In addition to this, the interlayer bonding of the multi-layered pavement system plays an important role in determining the long-term performance of a pavement. The distribution of stress and strain between the pavement layers is dependent on the adhesion at the interfaces between the various layers, and this bonding then influences the pavement life (Mohammad et al., 2005). If the bond is insufficient at the interface layer, there could be increased strains through the pavement under the applied traffic loads (Collop et al., 2003). The pavement deterioration is a developing process of distress as determined by the effects of pavement materials, the condition of the subgrade soil, traffic and the environment (Mobasher et al., 1997, Zborowski and Kaloush, 2011).

Surface distresses of asphalt pavement are classified into various categories of deterioration such as cracking, rutting, ravelling and pothole. The last is one of the most common deteriorations of pavements that occur, usually in regions of cold weather. The development of potholes can be caused by water penetrating through cracks in the surface layer of the asphalt pavement. Cycles of freezing–thawing increase the speed of the formation of potholes. This type of deterioration is a bowl-shaped depression of different sizes that can reach all the way from the surface layer down to the base course. This probably occurs on the surface of flexible pavements (Miller and Bellinger, 2003). Several researchers have reported on this mechanism of pothole formation: Maher et al. (2001), Miller and Bellinger (2003), Homji and Adi (2006), Munyagi (2007). They describe how potholes are created as different sized holes in the pavement surface. These are formed by distress that progresses through existing cracks in the pavement,

or through corrosion of the aggregate base and asphalt layer. They can also occur due to traffic loads that cause structural cracking in the wheel paths.

Therefore the formation of potholes increases the need for road maintenance in order to maintain the working life of the pavement (Maher et al., 2001). There are number of key factors affecting the acceleration of pothole formation such as the pavement structure type, pavement materials and thickness, traffic loads, unsuitable maintenance of pavement failures, pavement age and the weather (Paige-Green et al., 2010).

1.2. Problem statement

One of the most significant pothole repair approaches is the pothole patching, a maintenance remedial action for the asphalt pavement structure. The performance and durability of the pothole repair depend on two main factors: the repair materials selection and the repair method. For example, patching in winter can receive immediate stress from freezing temperatures and the patch then has a shorter survival period than patching in summer (Wilson and Romine, 2001). This can lead to the same potholes having to be repaired several times, increasing the overall pothole repair cost (Marcus and Elizabeth, 2001).

Most of the background studies have shown that the materials used for pothole repair can be either hot or cold asphalt mixture, but that the use of hot mix can be considered of limited applicability owing to its requirements, such as high application temperature (Bailey, 2011). Cold mix has the advantage that it can be applied at ambient temperature, but it is generally a lower-quality solution owing to the lower stiffness and required curing time (Gomez-Meijide and Perez, 2015, Gomez-Meijide et al., 2016). Recently, a series of polymeric materials and resins have been used as a pothole repair

material to produce high-quality repairs (Yuan et al., 2012), albeit at a relatively high cost (Krauss and Wyman, 2010).

Parts of the UK and other mainland European countries are located within regions of cold climatic conditions. The pothole is considered the most serious distress of asphalt pavement in these areas. This is not only expensive in terms of maintenance but also creates hazardous conditions for road users. Statistical reports show that, over the past decade, about 17.9 million potholes have needed to be repaired in the UK at a cost of more than a billion pounds. In 2016/17, the number of potholes repaired by local authorities was 2267 in London (Asphalt Industry Alliance, 2017).

There are various methods of pothole repair that have been used by different maintenance agencies such as throw-and-roll, semi-permanent and spray injection. Temporary repair methods as throw-and-roll are only appropriate when weather conditions are too poor or when the road is due to be rehabilitated soon. For other reasons, contemporary maintenance techniques, such as inlay/overlay or hot-on-hot paving processes are often expensive, involving high consumption of energy and posing significant health risks to operators owing to the high work temperatures and hazardous fumes and conditions (Read and Whiteoak, 2003). These methods increase the costs associated in terms of labour, materials and equipment, and traffic delays. For instance, according to London First Road Sense (2012), the congestion costs of roadworks can be around £2000 per roadwork hour at the busiest places on the transport road London network (TRLN).

The research problem tackled in this thesis was defined as a result of a critical appraisal of the literature. Therefore, there is a significant need to carry out intensive scientific

research in order to address the maintenance of potholes in the UK, more precisely to consider the contributory factors causing the potholes formation. This demands innovative and sustainable pothole repair material products using newer technologies applied to previous maintenance practices. The properties of these materials and the use of this technology should be similar to or better than the conventional materials and methods, in order to justify their broader application.

1.3. Research contribution

Over the past several years, different techniques have been used for paving and for repair of the pavement road, such as rollpave and asphalt pellets.

The rollpave technique is a prefabricated asphalt mixture layer that can be spread over an old road surface and fixed by means of a bituminous membrane – containing a steel mesh – which can be heated and melted using induction heating technology (Morgan, 2008, Naus et al., 2010).

Moreover, asphalt pellets, which are a combination of bitumen and aggregates with maximum size of approximately 20–40 mm, can be heated in an oven and used to manufacture small amounts of asphalt mixture to patch roads; they have similar durability and mechanical properties to HMA, at a lower energy cost (Artamendi et al. 2014, 2016). Asphalt pellets can be stored and transported at ambient temperature and heated on site, which reduces the heating needs and binder ageing (Saeed and Hammons, 2009; Bailey, 2011).

Despite extensive research into different pothole repair methods, to date there is no evidence in the literature that the induction heating technology is effective for pothole repair. The use of induction heating technology could help to achieve a good bond

between asphalt concrete layers; since it plays an important role in pavement performance. This can be applied quickly and easily to activate the bond between pavement layers through transfer of heat to the bitumen, leading to melting and the creation of a strong bond between them. Furthermore, the current research has been designed in order to identify innovative pothole repair materials. These materials would be for use with the induction heating technology and would address the drawbacks of conventional materials, providing excellent performance. Accordingly, it is hoped that wider use of induction heating with the innovative pothole repair materials could be derived from the current research. Therefore, this research contributed to the development and comparison of novel materials for repairing potholes through a combination of prefabrication and on-site induction heating. The innovative materials with induction heating should (1) be suitable for use in any environmental condition, (2) create a patch of comparable quality and durability to the original road material, (3) reduce the production of debris materials, (4) improve the work conditions for operators, as there is no need for heating elements and noxious fumes, (5) minimise traffic disruption, thanks to a higher time/cost efficiency and (6) have comparable life-cost to current asphalt patching methods, based on information obtained from Wilson and Romine (2001).

1.4. Aim and objectives

The present study aims to develop innovative materials that target the medium- or long-term repair of potholes by using induction heating technology. The evaluation of these new materials and methods will be based on laboratory tests that are commonly used to

determine the durability of conventional pavement materials. Therefore, the specific objectives of this study include:

1. To design and manufacture innovative materials to repair potholes by using induction heating.
2. To evaluate the properties of the interface bonding between the new repair materials and the interior surface of the potholes.
3. To evaluate the resistance to permanent deformation of potholes repaired by these materials.
4. To assess the new materials economically and environmentally.
5. To compare the properties of these innovative materials with the traditional materials commonly used in pothole repairs.

1.5. Thesis outline

This thesis is organised into eight chapters as follows:

- **Chapter One: Introduction**

This chapter contains an overview of maintenance and rehabilitation of asphalt pavement, the main objectives of this research and the thesis organisation.

- **Chapter Two: Literature review**

This gives general information about the asphalt pavement structure and presents the factors that affect the state of the bond at the interfaces between asphalt layers. It then gives a definition of the term ‘pothole’, including causes and repair methodology and offers a choice of material and procedure for the repair of potholes. There is then a description of the induction healing concept in general as a solution to pavement

maintenance problems and an evaluation of different methods of determining the mechanical properties of the interface bond.

- **Chapter Three: Materials and experimental works**

This chapter reviews the materials and test methods that have been used and applied to achieve the objectives of this research. It presents in detail the characterisation of raw materials used in innovative patching materials to repair potholes in asphalt roads. It also assesses the bonding properties of each innovative material using different mechanical testing and examines the performance requirements of these materials by using a wheel track test. It finally examines the effect of moisture on the bonding properties of each material used and the functionality observed using wheel track test.

- **Chapter Four: Mechanical assessment of asphalt tile and bonding layer**

This contains a brief description of the asphalt tile and bonding layer for repairing potholes in asphalt roads using induction heating by high frequency electromagnetic fields to heat up the fibres and melt the bitumen. This chapter also gives a full description of all results that have been found for this proposed technique.

- **Chapter Five: Mechanical assessment of asphalt pellets**

This chapter shows the effect of asphalt pellets under the action of electromagnetic induction, in terms of the different mechanical properties of the material resulting after compaction. These results were obtained for assessing the proposed technology and comparing it to hot and cold mix asphalt. This chapter also shows all the results that have been found using asphalt pellets technique.

- **Chapter Six: Mechanical assessment of binder pellets**

In this chapter, an innovative patching material to repair potholes is developed, evaluated and compared to current maintenance materials. Mechanical properties of the resulting material are assessed after checking the heating temperature that has been reached under the action of electromagnetic induction during mixing, and the volumetric properties of the binder pellet mixtures resulting after compaction. It also shows the results of this technique that related to durability and performance and compared with conventional asphalt materials.

- **Chapter Seven: Economic and environmental assessment of the innovative materials**

Here, the effect of a range of variables on the performance and cost effectiveness of various patching materials and procedures for repairing potholes are studied. These variables include a comparison of the material costs, labour costs, equipment costs, productivity and timings of each activity when using asphalt tile, asphalt pellets or binder pellets materials are used. The assessment of a value for the quantity of carbon dioxide and energy consumption emitted per unit of production and implementation for each alternative approach is analysed.

- **Chapter Eight: Conclusions and recommendations**

This chapter summarises the findings and suggests areas for further research.

Finally, Figure 1.6 shows details of the plan followed in performing the present research.

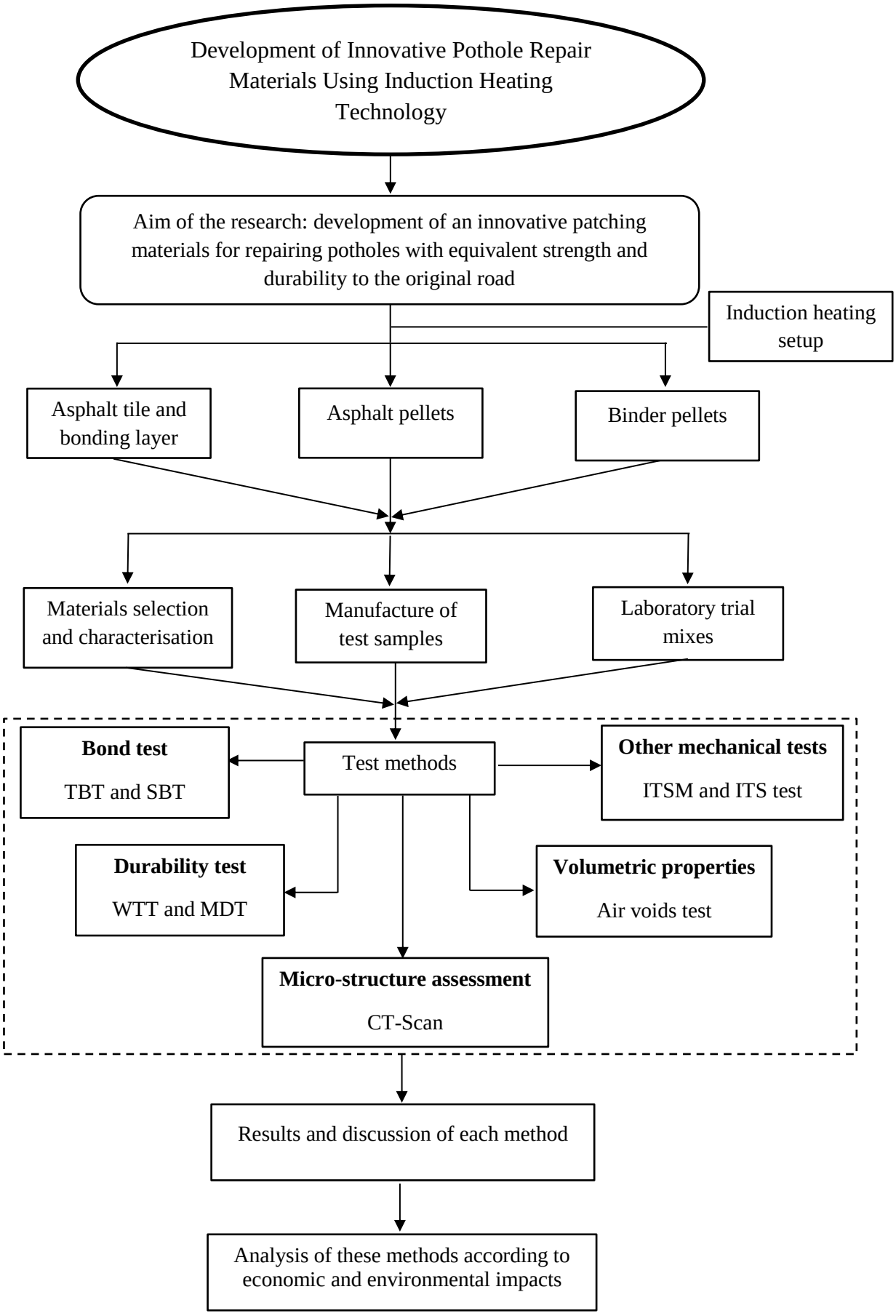


Figure 1.1 Flowchart of the research methodology

1.6. List of publications

The majority of findings obtained in this PhD project have been published or are under review, as follows:

- Obaidi, H., Gomez-Meijide, B. and Garcia, A., 2017. A fast pothole repair method using asphalt tiles and induction heating. *Construction and Building Materials*, *131*, pp.592-599. **(Published)**

- Gomez-Meijide, B., Obaidi, H. and Garcia, A., 2017. Induction heatable asphalt tiles and pellets. New approaches in road maintenance, International Conference on Advances in Construction Materials and Systems (ICACMS-2017), India. **(Published)**

- Obaidi, H., Gomez-Meijide, B. and Garcia, A., 2018. Induction-Heatable Asphalt Pellets as a New Material in Road Maintenance. *Journal of Materials in Civil Engineering*, *30*(11), p.04018300. **(Published)**

- Obaidi, H., Gomez-Meijide, B. and Garcia, A., 2018. On-site manufacture of hot mix asphalt using pellets that can be melted by induction energy, *Powder Technology*. **(Under review)**

Chapter 2

Literature review

2.1. Introduction

This chapter provides an overview of the literature which is related to pothole repair techniques and the current practices for pothole patching. This chapter also investigates the causes of pavement deterioration, pavement evaluation and pavement maintenance. This investigation is important as it provides a baseline for evaluation of current road maintenance methods by assessing different experiences around the world. Some research background of induction healing in asphalt mixes and literature review are given in order to define the gaps needing to be filled in this research. The literature review also deals with economic issues in pavement maintenance problems when comparing conventional methods currently being used.

2.2. Distresses of flexible pavement structure

Flexible pavement layers are exposed to deformations and distresses resulting from several factors such as traffic loading, the design of pavement structure and the site climate in terms of the temperature distribution (Miller et al., 1993, Roberts et al., 1991). Most pavements throughout the world, in terms of raw materials, design methods and construction procedures, have surface and base layers to produce more stable and durable structures of pavement. It is important to clarify the types of pavement failure that may affect the state of the bond between asphalt layers. The following section provides basic information on the most common distresses which have occurred in asphalt pavement (Miller and Bellinger, 2003, Adlinge and Gupta, 2013). Cracking can develop in asphalt pavements due to repeated traffic loading. The repair is based on the shape and location of the cracks categorised into different types of cracks.

Deformation of the surface can be classified as 1) rutting 2) shoving. Surface defects have been found on pavement surfaces such as bleeding and ravelling. The last type is responsible for patching deterioration and potholes. Patching deterioration is defined as the removal and the replacement of the pavement surface part and addition of a new asphalt patching material that will be applied on the pavement after the original construction. Furthermore, the full description and definition of potholes will be presented in the next section because it can be regarded as the main topic in this thesis.

2.3. Description of potholes

Potholes can be considered the most common form of deterioration of the pavement surface (Figure 2.1), and one of the most significant because of the risk they pose to the travelling public and the general damage that may be caused to vehicles (Clifton, 2012). In spite of procedures taken by transportation agencies, pothole development is considered an inevitability, representing a significant challenge for all local highway agencies contributing to pavement maintenance. A pothole is a bowl-shaped hole in one or more layers of the pavement structure that leads to significant influence on vehicle tyres and handling (Miller et al., 1993, Jassal, 1998). Several factors should be considered when selecting the best method to patch a pothole, including the size of the pothole, crew size required, productivity rates, and life cycle costs (Homji and Adi, 2006).

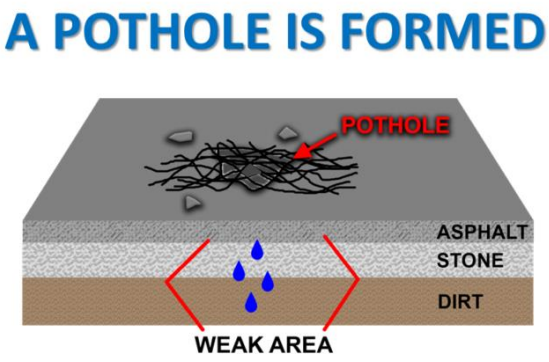


Figure 2.1 High-severity pothole (Miller et al., 1993)

Paterson (1987) defined a pothole as due to the failure and loss of asphalt surface material leading to depression of the base material, and further defined that a pothole was a hole in the pavement surface which was 150mm or more in diameter and 25mm or more in depth. Conversely, Roberts et al. (1996) describe a pothole as a small bowl-shaped deterioration in the surface of pavement that penetrates the road from the hot mix asphalt layer down towards the base layer. There are likely to be sharp edges and vertical sides close to the upper part of the hole. The dimensions of potholes probably appear in the road surface of thin HMA between 25-50mm. Sometimes they are either 100mm or deeper in HMA surface.

However, Clifton (2012) stated that a report for Federal Highway Administration (2003) pointed out through its program that related to a Distress Identification manual for long-term Pavement Performance that potholes were classified into three types dependent upon the level of severity. For high severity the depth of hole is greater than 50mm, for moderate severity the depth is between 25-50mm, while, if the pothole depth is less than about 25mm that is low severity. Meanwhile, Nazzal et al. (2014) reported that the Ohio Department of Transportation (2008) defined a pothole as a hole which occurs in the surface layer of pavement that exceeds 50mm in depth and 93000mm² in area. In all of these definitions mentioned above, it will be assumed that a pothole is a deeper hole occurring in the surface of the pavement road that influences the safety of the pavement structure and the essential requirements of maintenance.

2.4. Mechanism of potholes formation

2.4.1. Initiation of potholes

The formation of potholes is based on two major factors: water and traffic loads (Nazzal et al., 2014). The occurrence of potholes is the least expected but these are most severe outcome of pavement distresses. Although, this is a fact and they need high costs of maintenance, limited research has been provided about pothole formation (Jassal, 1998, Maher et al., 2001, Miller

and Bellinger, 2003) with the majority of research related to the repair and maintenance of the potholes (Wilson and Romine, 2001, Munyagi, 2007, Atkins, 2010, Rahman and Thom, 2012, Bennett and Velinsky, 2014, Nicholls et al., 2016, Mchale et al., 2016).

Kerali (2000) stated that the Highway Data Management report (2000) prepared investigations that help to predict the pothole modelling and study the effects of potholes on vehicles to get an economic evaluation tool to determine the results of delayed or neglected maintenance. This model was based on the principle that the pothole was formed as a result of losing the cohesion within the asphalt surface materials, then the base materials. The findings showed that the main factor affecting the pothole formation is the shape and size of holes. That leads to influence the bond between the surface and the base of asphalt layers especially, the base layer having the greatest impact. It also reported the use of prime or tack coat can improve the bond between asphalt layers which may lead to reducing the probability of potholes' occurrence. The report also suggested approaches or properties that can enhance the initiation of pothole formation as given below:

- The existence of fine materials at the top of the base of asphalt layer which leads to easy separation of the entire surface layer after the presence of a crack.
- The materials of the base layer are non-treated under high compaction which leads to easy deterioration of the surface layer when subjected to traffic loading and the presence of water.

Biswas (2016) reported the findings from Michigan Department of Transport (2004) suggesting that potholes are created as a result of water penetration through the formed cracks in the surface of pavements into the asphalt base layer or the foundation of the pavement as shown in Figure 2.2. These cracks appeared as a result of fatigue on the top layer of asphalt concrete due to asphalt ageing and traffic loading. Meanwhile, when water seeps through the

asphalt layer it is trapped as a result of insufficient drainage and the low temperature of pavement. In particular at night, the water is frozen leading to expansion in the top layer of asphalt pavement, and an increase in volume of the surface layer of about 9% because of water volume which can increase the size of crack. Moreover, the development of freeze-thaw cycles can enable configuration of voids in the subgrade layer, thus forming the potholes during continuous increase in traffic stresses

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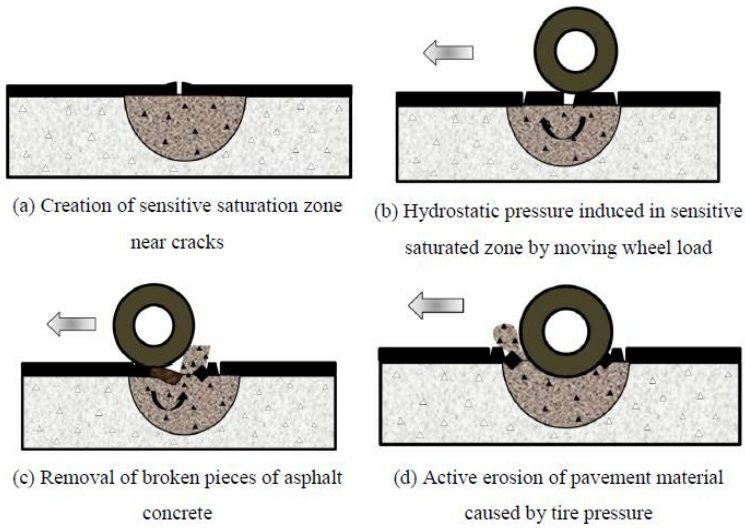


Figure 2.2 How a pothole are formed (Biswas, 2016)

There are additional mechanisms to the formation of potholes that may occur in the direction either from bottom to top or from top to bottom. Moreover, the potential mechanism is likely on either thick or thin types of road structure. Freitas et al. (2003) reported that the mechanism of top-down occurs principally as a result of the surface material condition characteristics, while the mechanism of bottom-up is accelerated by the flexural weakness or the water pressure accumulation between road pavements layers that lead to the sudden appearance of a pothole. The deterioration of pothole has occurred with different severity levels. Two different mechanisms for forming a pothole have been identified such as fracture and attrition of potholes (Atkins, 2010).

- **Pothole fracture**

Potholes are characteristically circular or elongated very close to vertical edges and form in what may seem to be an otherwise competent material (Kringos and Scarpas, 2007). The mechanics of pothole fractures (Figure 2.3) are periodic hydrostatic pressures due to the pressure or suction from tyres of passing vehicles. The pothole formation is caused by the displacement and progression of a material block and is usually fairly limited. The dislodged block of the pothole base is dependent on the nature of the material under it that makes the base impermeable with existing water in Figure 2.4. This is consistent with Kringos et al. (2008).

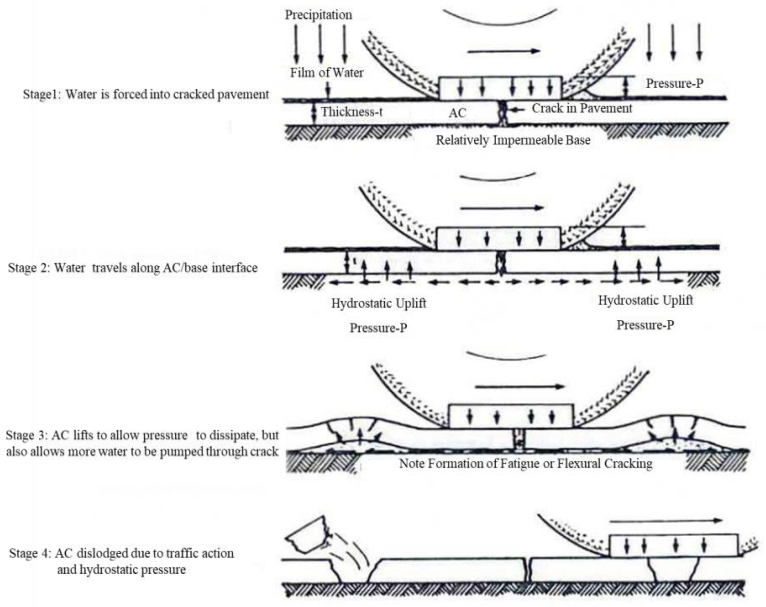


Figure 2.3 Fracture mechanics of pothole formation (Gerke, 1979)



Figure 2.4 Fracture pothole (Asphalt Institute Alliance, 2017)

- **Pothole attrition**

This mechanism is basically relevant in the direction from top to down (Kringos and Scarpas, 2007). Its occurrence depends on the relative state and thickness of the bond surface, see Figure 2.5. Attrition potholes happen on any type of road and can evolve rapidly to being important features, especially on road pavements so that the road surface is relatively thin. Beyond a critical distress point caused by ageing binder, adhesion of particles at the contact points of interlock is compromised and the previously bound material is degraded to unbound particles that can be removed by the shearing forces from passing traffic tyres (Kringos, 2007).

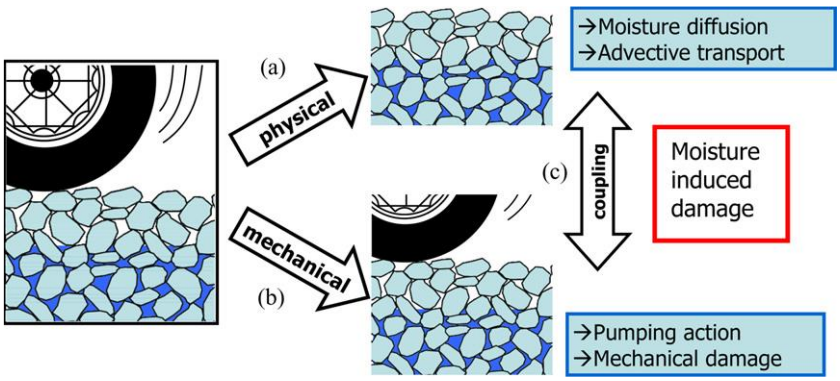


Figure 2.5 Attrition mechanics of pothole formation (Kringos, 2007)

Attrition potholes characteristically have round edges that can easily be abraded to make the base permeable and can be easily dislodged by traffic when reaching a critical size. In spite of the fact that the base may become permeable, these potholes can be filled with water leading to increasing accelerated progression, see Figure 2.6 (Atkins, 2010).



Figure 2.6 Attrition pothole (Atkins, 2010)

2.5. Factors affecting the bonding properties of flexible pavement structure

Potholes typically form in weak areas of the pavement structure that result from various problems that increase the pavement deterioration. In order to improve the bonding between the pavement layers, it is necessary to understand the factors that affect the state of the bond between pavement layers. Some of these factors are discussed briefly in this section.

- Water

Water is considered an important factor which negatively affects asphalt pavement structure by decreasing the adhesion of bitumen (Santucci, 2002, Jahromi, 2009, Nejad et al., 2012, Adlinge and Gupta, 2013). The majority of research on water damage in asphalt mixtures states that it affects negatively the performance of pavement. For example, a report of ADEPT (2010) states that the existence of additional water and poor systems of drainage cause damage of the pavement leading to the formation of potholes. Raab and Partl (2004), Sutanto (2009), and Yilmaz and Sargin (2012) found that the presence of water at the surface of the lower layer leads to a reduction in the shear strength of the interface. They studied the influence of water permeability at the interface layer by pumping pressurised water through a small hole to the

interface and submerging core samples in water before the shear test. The results indicated that water penetration at the interface reduces the interface shear strength by about 15-27%.

- Aggregate gradation

Aggregate gradation has an influence on the bonding between the upper and lower layers of asphalt pavement that affects the interface shear strength (Jaskula and Rys, 2017). Pos et al. (2001) found that asphalt mixtures which contain fine and coarse-grained materials lead to sufficient inter-particle friction at the interface, thus obtaining high interface shear strength. They reported that the bond at the interface of an asphalt mixture with the same materials is highly influenced by bitumen content and the adhesive properties of the bitumen. Another study conducted by Oke (2011) showed that aggregate gradation plays a main role in the performance of bituminous patching mixtures that affect the workability and stability of the mixtures. He concluded that the selection of proper gradation, shape and other properties related to aggregate that must be done carefully because of its effect on the performance of bituminous patching mixtures.

- Construction quality

This category includes factors influencing the performance and bonding of the asphalt pavement layers such as the compaction level, quality of materials used during construction, and thickness of pavement layers (after compaction) to ensure a strong bond between asphalt concrete layers (Adlinge and Gupta, 2013). An appropriate compaction level of the top layer can be considered of significant importance in achieving a good bond and quality of the lower layer. More studies done by Canestrari et al. (2005) and Miro Recasens et al. (2005) concluded that the best compaction results ensure a good interlock for aggregates in the asphalt concrete layers to achieve good contact between the upper and lower layers as well as the impact the compacting method has on the interface bond. Chatterjee et al. (2006) and Nazzal et al. (2014)

reported that patching mixture should more stable after placement and compaction to resist vertical and horizontal displacement due to traffic load especially immediately after compaction when the material is still hot or uncured.

- Traffic loading

Traffic loading is also considered an important factor affecting the bond and performance of asphalt pavement. This performance has a relationship with the interface bond between asphalt concrete layers in terms of the applied vertical load on the pavement structure (Raab and Partl, 2004, Raab and Partl, 2009, Ogundipe, 2013). This load will be generated as a normal force at the interface between layers that leads to an increase in the shear strength at the interface with increases in the loading magnitude (Adlinge and Gupta, 2013). West et al. (2005) showed that the normal load has a reduced impact at low temperatures because the friction between aggregate particles at the interface depends on the interface shear strength at high temperatures. As the result, the resistance of friction between aggregate particles is proportional to the normal load. Paige-Green et al. (2010) and Biswas (2016) have discussed that when the traffic loading has exceeded the loading of pavement design it could lead to the failure of the road resulting from surface cracks of the pavement structure. These cracks allow water to penetrate into the layer underneath and cause material loss, which creates potholes.

To sum up, it should be noted that the factors mentioned above commonly affect the pavement structure. However, further investigation is required to study different influential factors that cause an increase in pavement deterioration.

2.6. Pavement Maintenance

Maintenance works of pavement are carried out from time to time to maintain the pavement against the effects of normal traffic and natural forces, as far as possible in their condition as constructed (Ann, 2000, Gedafa, 2006, Girmay, 2016). The idea of maintaining pavements in

full service is to reduce expenditure, and lessen inconvenience to the road users. Poor maintenance is commonly worse than nothing at all. There is not a construction of pavement that does not require maintenance. Many community associations have found too late that appropriate maintenance can prevent costly replacements (Ann, 2000). The objective of maintenance is to retain the roads with a better service through their design life leading to increasing driving safety and reducing costs (Donnges et al., 2007).

In general, maintenance of pavement can be classified into three types regarding the frequency, intensity, and costs for maintenance such as preventive maintenance, corrective maintenance and emergency maintenance (Ann, 2000). Figure 2.7 explains the differences between these three types of pavement maintenance operations. From the graph, the main difference is the pavement status when applying the treatment.

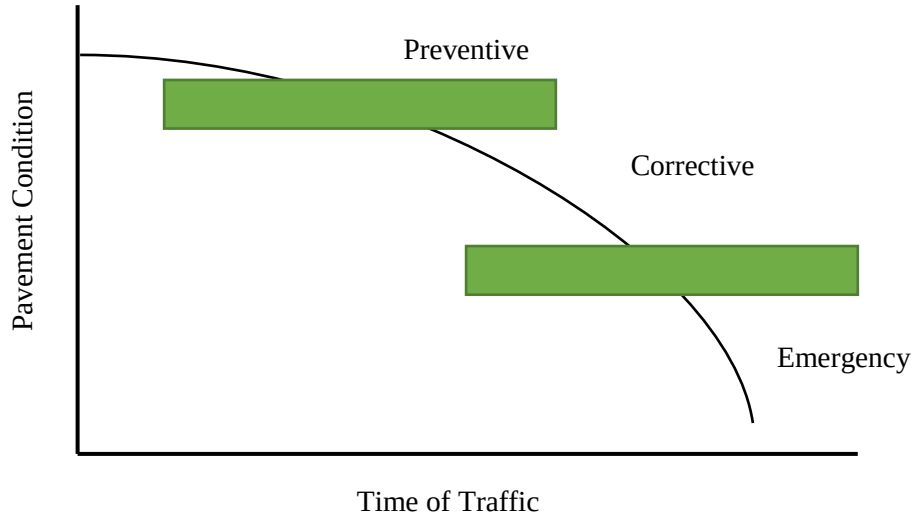


Figure 2.7 Types of Pavement Maintenance (Ann, 2000)

Furthermore, routine maintenance carried out depends upon the required frequency of maintenance that has the treatment regularly every one or two years. Typical routine maintenance includes sealing cracks and filling, pothole repair, and drainage work (Symons, 1999, Hand et al., 2000). To decrease the deterioration and maintain the road within the limits

of acceptable standards, engineering research has identified preferred strategies for the different levels of deterioration (Wilson and Romine, 1993, 2001, Qiao, 2015).

The literature reports that the common strategy has two major components that must be taken into account to determine quality maintenance, however, its durability cannot be ensured. Most deteriorations evolve from either poor repair material or inappropriate procedure of maintenance after deterioration within a short period of time. Therefore quality maintenance is based on (Sainz, 2016, Nicholls et al., 2016):

1. Selection of patching material.
2. Techniques of repair.

2.7. Pothole patching materials

Generally, different patching materials are used to repair various types of potholes such as shallow, small and large areas for potholes (Maher et al., 2001, Clifton, 2012). It is easy to place and compact them so that the adhesion of these materials improves the condition of the potholes (Wilson and Romine, 2001). Recently, patching materials need to improve significantly. There is a lack of standard specification to the use of new types of material by a number of highway agencies. Although, some patching materials can be used in adverse weather conditions for emergency works, the materials must be selected carefully to ensure a high quality of pothole repair. Therefore, the following section will describe conventional patching materials that have been reported in the literature.

2.7.1. Hot mix asphalt (HMA)

It has been reported that Hot Mix Asphalt (HMA) has high quality among the patching materials which are obtainable in the market (Sainz, 2016). HMA produced in plants and applied directly after production has more durability than other mixtures (Maher et al., 2001,

Chatterjee et al., 2006, Pimentel, 2007). Clifton (2012) stated that hot mixes are normally prepared by mixing aggregates with bitumen binder at 180-250 °C and at 160 °C respectively prior to placing on the road surface as the increase in the temperature of the mix leads to a reduction in the viscosity of bitumen. Mchale et al. (2016) have reported that HMA has good workability and easy compaction while it is hot, and directly hardens once it cools down. They mentioned that the temperature of the hot mix can be changed depending on the type of bitumen because heavier bitumen needs a higher temperature of mixing to improve its workability. However, the temperatures used are relatively high and large amounts of fuel are needed to heat up the aggregates and the bitumen (Skolnik et al., 2013, Sullivan and Moss, 2014). This is another limitation of using this mixture especially in cold conditions where it has to be used hot. Furthermore, the operation of patching of potholes may be slow and if it takes a long time to finish the repair the mix becomes cold prior to being completely used. Therefore, small hot boxes can be used to solve this problem (Roberts et al., 1996, Paul Teng, 2001, Mchale et al., 2016). Improvement of hot asphalt mixtures depends on the mixture properties, affecting the stability, durability, flexibility, fatigue resistance, skid resistance, permeability, and workability (Roohi Sefidmazgi, 2014).

2.7.2. Cold mix asphalt (CMA)

Cold mix asphalt (CMA) is commonly applied for pothole patching in cold regions, especially in winter weather. It has less environmental impact, less energy consumption and cheaper processes of production but it is mostly used as a temporary repair (Clifton, 2012, Hasan et al., 2016). CMAs are manufactured using emulsified or cutback asphalt to obtain more workability in cold climates, and antistripping agents to decrease moisture damage (Maher et al., 2001). The binder is either cutback bitumen or bitumen emulsion. It is difficult to deal with cutback bitumen at low temperatures unlike bitumen emulsion because it requires some time to warm

in the sun prior to its use (Munyagi, 2007, Nazzal et al., 2014). CMA can be prepared by using facilities of hot mix asphalt then filled up and stored until later use. But they have the lowest quality compared to other asphalt patching mixtures (Prowell and Franklin, 1996). Furthermore, the main drawback for cold mix is that it cannot normally be compacted to the same level as hot mix asphalts because the latter has higher cohesive strength (Munyagi, 2007). However, the advantage of cold mixes is that the time for application is short and they can be applied in severe winter conditions (Nicholls et al., 2016, Sainz, 2016). Pimentel (2007) has reported that CMAs can be used and tested with dynamic loads to simulate traffic load. He applied the freeze-thaw test to understand the behaviour and efficiency of this mix which is influenced by weather conditions. He found that particle size distribution or gradation affected the performance of pavements.

Therefore, the quality of patching materials is considered a very important parameter in terms of a durable patching repair. These materials must have some special properties to provide long-term patching repair. Most of the properties of bituminous patching materials are explained below (Maher et al., 2001, Chatterjee et al., 2006, Pimentel, 2007).

The properties of patching mixes need to maintain the workability and durability of patching materials as they can be considered the two main challenges that may be faced. Marcus and Elizabeth (2001) reported on the properties of patching mixtures with different variables of their properties. Table 2.1 clarifies that the mixtures containing different shapes of aggregates (open graded, rounded and fines) with low viscosity of binder have appropriate workability with poor durability. Otherwise, the mixture used is dense graded, angular and fines with high viscosity of binder leading to good durability and less workability.

Table 2.1 Characteristics of patching mixture for repairing potholes with different parameters of material properties (Marcus and Elizabeth, 2001)

Property	Parameter	Workability	Durability
Gradation	Open gradation	Good	Poor
	Dense gradation	Poor	Good
	One size	Good	Poor
Aggregate Shape	Angular	Poor	Good
	Round	Good	Poor
Aggregate size	Larger gradation	Poor	Good
	Finer mix	Good	Good if depth < 76mm
Binder viscosity	Low viscosity	Good	Poor
	High viscosity	Poor	Good

2.8. Conventional methods of pothole repair

The remedy of repairing a pothole is generally referred to as patching. Patching can be described as the filling of a hole or a depression in a road surface with an appropriate asphalt mixture (Chehovits and Parkison, 2002). The goal of patching is to return the pavement to a working condition that will not deteriorate under the traffic load and temperature cycles. Blaha (1993) reported on the project supported by SHRP (Strategic Highway Research Program). He indicated that the basic condition for the domain of pothole repair in the flexible pavement was about 25-150 mm, either close or far space that has to be repaired in any condition of the weather.

The quality of pothole repair is based on selecting the material for patching and producing repair methods that have been used in various seasons (Wilson and Romine, 1999, Maher et al., 2001). There are different methods to perform pothole patching such as 1) throw-and-roll, 2) semi-permanent, and 3) spray injection. These are traditional methods for repairing the

pothole depending on the repair processes and the equipment used for the repair operation a (Maher et al., 2001, Wilson and Romine, 2001). There are a number of factors that must be evaluated when selecting the best patching materials and methods to use. These factors have included, but are not limited to (Wilson and Romine, 1993, Nazzal et al., 2014, Marasteanu et al., 2018):

- The size of the pothole
- The required time of patching
- Distancing between potholes
- Traffic flow, traffic control measures
- Required materials and equipment
- Equipment costs
- Number of potholes
- Crew size required
- Productivity rates
- Transportation of materials

Below is a brief description about the traditional methods for repairing the pothole.

2.8.1. Throw-and-roll

This approach consists of placing patching material directly into the pothole, see Figure 2.8. As this may or may not be filled with water and debris, a compressed air lance can be used to partially clean and dry the hole in order to increase the patch performance and compact these materials slightly between 3 and 6 mm. This method allows the road to remain open to traffic, and the equipment can be left in the roadway (Anderson et al., 1988, Griffith, 1998, Wilson and Romine, 1999).

The throw-and-roll method is considered an effective procedure, having a low cost and being usable in adverse weather because it can be implemented quickly. If this repair is used for potholes with depths of more than 100 mm, the patching material should be placed and compacted in lifts not exceeding 80 mm each. In order to improve performance in cold conditions, the patching material should be stored indoors and/or in heated truck boxes (Wilson and Romine, 1993). This method can be applied for small and shallow potholes. If this method is implemented appropriately, the service life for the pothole repair can be expected to be about 1 year. This pothole repair method is recommended as a temporary measure used for reasons of safety (Clifton, 2012).



Material placement Compaction of patch

Figure 2.8 Throw-and-roll pothole repair (Wilson and Romine, 1999)

2.8.2. Semi-Permanent

This method can be used for repairing the pothole as a partial-depth, see Figure 2.9. This also needs less time and effort in order to perform pothole patches successfully (Wilson and Romine, 1999, Maher et al., 2001). The results of this method can give the longest life for the pothole patch because of good compaction on the sides, however, it requires more labour and equipment (Wilson and Romine, 1993). Previous studies showed that the semi-permanent method is superior compared with other methods such as the throw-and-roll because it increases the performance of the patches by improving the surrounding support. However,

some studies showed that high-quality of mixes can be more effective than the throw-and-roll, but the latter is less labour intensive (Wilson and Romine, 1993, Maher et al., 2001).



Cutting edges using pavement saw



Compaction using vibratory compactor

Figure 2.9 Semi-permanent pothole repair (Wilson and Romine, 1999)

2.8.3. Spray injection

This is to some extent similar to the throw-and-roll method, but there is a significant difference in that the materials used should be cold-blended and then sprayed into the hole which is being repaired, see Figure 2.10 (Homji and Adi, 2006, Paige-Green et al., 2010, Sainz, 2016). Generally, the materials used for spray patching are emulsified or cutback asphalts and local aggregates; these materials are then compacted. Workers are able to start to apply this method and leave the equipment in the roadway, and consequently the road is open to traffic (Wilson and Romine, 1999, Maher et al., 2001, Clifton, 2012). The spray injection method was found to be a more effective method for pothole repair in asphalt pavements as reported in the SHRP project (Wilson and Romine, 1993) This method has advantages compared to the throw-and-roll method as the spray hose is easy to handle meaning the user is not in the line of traffic for an extended period of time (Chatterjee et al., 2006). This repair does not require more compaction after spraying because of the fine sizes of the materials used. The use of these materials allows the patch to reach deeper into the cracks of the pothole (Paige-Green et al.,

2010). One of the disadvantages of this method that the big machine is exposed to traffic (Chatterjee et al., 2006).



Figure 2.10 Spray-injection pothole repair (Manas, 2012)

Wilson et al. (2001) carried out an extensive experiment of pothole repair as part of the SHRP project. The most commonly used materials were cold mix asphalt patching materials tested during winter and spring seasons to repair potholes. The aim of this project was to determine the most cost-effective materials and methods that showed a significant impact on the durability of the patches. The throw-and-roll method has the same effectivity as the semi-permanent method when using the same type of patching materials, while the throw-and-roll and spray injection methods produced the highest quality of repairs and were found to be the most cost-effective.

2.9. Assessment of existing techniques of pavement maintenance

The development of pavement maintenance techniques aims to increase the durability of maintenance and decrease the maintenance costs. Therefore, researchers and road engineers have attempted to replace conventional repair techniques in terms of materials and equipment to ensure the best performance. A practical solution to increase the quality of the pavement repair was discovered in the Netherlands through cooperating with the Dutch Ministry of

Transport. They carried out the first trial of the rollable road surface in 2001 (see Figure 2.11) in the project called Roads to the Future (Wang et al., 2014).



Figure 2.11 Rollpave technique in the Netherlands (Wang et al., 2014)

This technique consists of a prefabrication of asphalt wearing course as a thin layer of porous asphalt that can be adhered with bituminous membrane as a bonding layer with some metal particles placed between them for the purposes of induction heating (Naus et al., 2010, Pasquini, 2009). The thickness of the bonding layer was approximately 3 mm and was made of an SBS polymer (Naus et al., 2010, Pasquini, 2009). The next stage of applying this technique is to use the induction heating. The latter is done by a machine that generates an electromagnetic field which is induced in the metal particles in the bonding layer (Naus et al., 2010), see Figure 2.12. Further details of induction heating will be discussed in section 2.10. The role of these particles is to transfer the heat from them to the bitumen in which they are embedded. Thus, the bitumen is melted which results in a strong bond between the new layer of asphalt and the old pavement. Therefore, the main advantage of this idea is to obtain the repair quickly and it is easily bonded during construction phase and un-bonded when the asphalt must be replaced or removed for any reason (Naus et al., 2010).

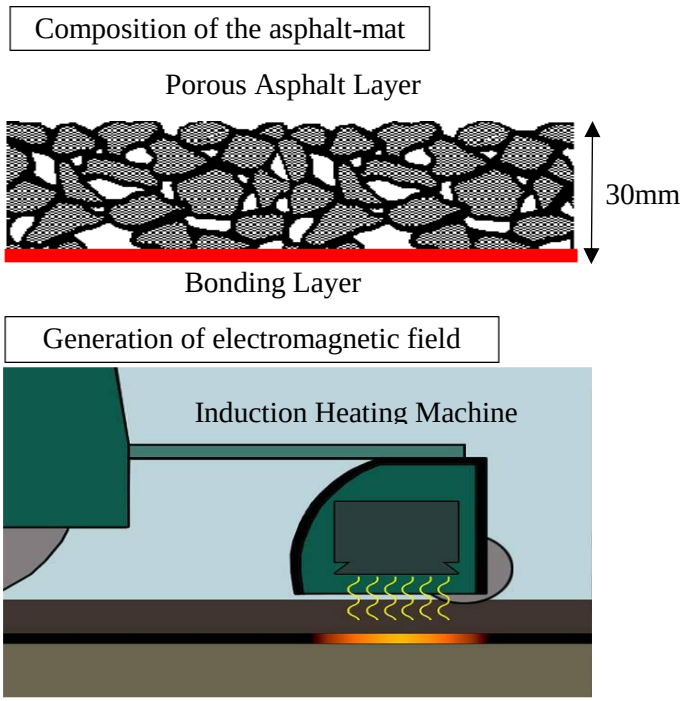


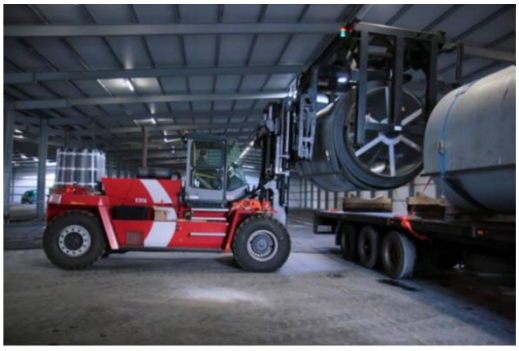
Figure 2.12 Principle of heating the bonding layer by means of induction (Naus et al., 2010)

The expectation of service life of the surface was around 10 years depending on the durability of the surface of porous asphalt. Rollpave has a high performance of skid resistance compared to single layer porous asphalt. However, the initial costs of it (labour, equipment and the material, etc.) are high compared to conventional asphalt (Pasquini, 2009).

The first implementation of rollpave was successfully performed on a road section in the Netherlands in November 2001, see Figure 2.13 (Houben et al., 2004). Further research has been carried out at Delft University of Technology to try a second experiment in September 2002 (Houben et al., 2004).



After production the asphalt mat is rolled on the reel



The asphalt-mats ready for transport



The operator controls the movement of the asphalt-mat and places it very precisely

Figure 2.13 Processes of Rollpave (Naus et al., 2010)

Other test trials were performed on other road sections and in different cities in the Netherlands to achieve the main scope from this technique and increase the chances of technical success (Naus et al., 2010, Goubert and Sandberg, 2010).

Other researchers have paid attention to the discovery of another technique that was aimed at increasing the performance and reducing the costs in the implementation of a trillion paving applications. For instance, Nitech Corporation focused on the development of new processes and products. They have specialised in finding new innovative technologies for the plastics and asphalt industries for over 40 years. This company presented their patent about pelletised asphalt technology allowing the asphalt to be stored as free flowing asphalts at ambient temperature, thus the energy can be saved to keep asphalt as a molten liquid during storage. The asphalt pellets can then be mixed with stone aggregate heated on-site on demand, to create

hot mix as shown in Figure 2.14 (NiTech, 2007). From tests, they found that pellets can provide the equivalent quality of conventional asphalt hot that have bought these as a batch or drum from the plants.

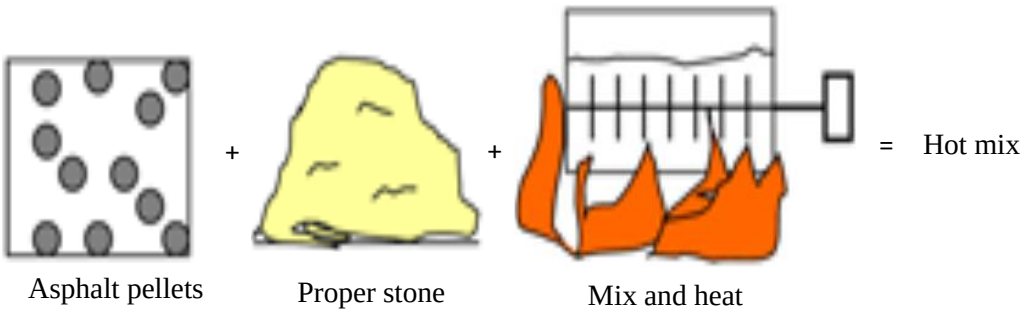


Figure 2.14 NiBlock - Technology for Pelletized Asphalt (NiTech, 2007)

The production of these pellets has been carried out by encapsulating the bitumen with a shell of modified polymer, then coated with fine material as a powder to prevent them sticking to each other, see Figure 2.15. In this case, they used fine clay or other fine materials as available. However, the use of clay led to increasing the moisture damage of asphalt mixes. Therefore the selection of the coating powder can be considered a very important issue because it impacts on the performance (Saeed and Hammons, 2009).

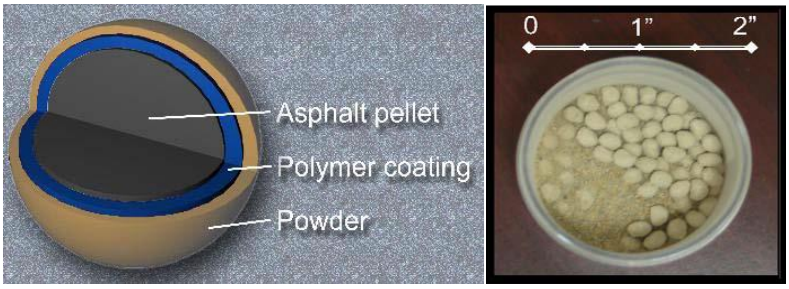


Figure 2.15 Composition of Asphalt Pellets (Saeed and Hammons, 2009)

Billian International Company has specialised in the production of asphalt pellets that minimise effects on environment impacts through finding the solutions for multiple aspects. They are dealing with waste recycled material such as ground tyre rubber and focus on the production

and supply of paving pellets to the road paving industry in the UK (King, 2016). Billian pelleting technology has used mineral fillers of high quality to prevent agglomeration of the pellets instead of using thicker layers of coating. They use hydrated lime because it is the best option to minimise moisture damage as well as clearly increasing the resistance of rutting (Bailey, 2010). So far, Billian pelleting technology has improved pelletisation for the combination of bitumen, hydrated lime, and crumb rubber. The main advantage of this technology has been the use of different applications for repairing pavement such as utility cut repairs, pothole patching, and small residential roads etc. leading to a reduction in their dependence on the production of hot mix in terms of using their equipment. The use of pellets to pave the roads provides cost-saving through repairing the potholes (Bailey, 2011). This process will reduce the energy consumption and CO_2 emissions because it does not need too much energy during transporting and storing hot asphalt (Saeed and Hammons, 2009). In the UK, most pothole repairs cost £65-90/ton for small quantities of hot mix while the repair of the pothole with asphalt pellets has cost £47/ton with no waste (King, 2016).

2.10. Induction heating

An induction heating machine generates the currents leading to heating the induced material by means of electromagnetic induction; it is a non-contact heating process (Hellier and Shakinovsky, 2001, Haimbaugh, 2001, Rudnev et al., 2002). Induction heating technology is widely used as means to overcome environmental issues and is used in many industrial processes (United Induction Heating Machine, 2013) since traditional heating devices such as burner heating furnaces need higher energy than induction heating. Therefore, the use of induction heating in the hot forging plants diminishes pollution of air and water (Avitzur, 1996). Induction heating is a method where an alternating magnetic field is generated to heat a conductor or workpiece. When a conductor is positioned near an alternating magnetic field this

field transmits energy into the conductor, hence heating it up (Rudolf et al., 2000, Ahmed et al., 2006).

Electromagnetic induction was discovered by Michael Faraday in the middle of the 1800s. When a conductor was placed in an alternating magnetic field, he observed it became heated and this is the same principle used today in induction heating to melt metals (Agzenai et al., 2015). This process has the ability to rapidly heat only in certain areas, meaning that the heat is generated inside the part itself, rather than by an external heat source, transferred by heat conduction (Agzenai et al., 2015).

An induction heating system includes an induction power supply which converts line power to an alternating current and delivers it to a work-head (tank circuit) and an induction coil creating an electromagnetic field (Takau, 2015). The coil is placed around or adjacent to the workpiece. It does not touch the workpiece; the heat is only generated by the induced current flowing in the workpiece. It should also be accompanied by a quenching media device. Quenching machines can be divided into standard and special machine tools: the former applies to the general workpiece which is suitable for mass production (United Induction Heating Machine, 2013, Ambrell, 2015). The material of the workpiece can be a metal, for example steel, copper, aluminium or brass, or it can be a semiconductor, for example carbon, graphite or silicon carbide. In the case of non-conductive materials such as plastic or glass, induction can heat an electrically-conductive susceptor such as graphite, which then transfers the heat to the non-conducting material.

However, it is preferable to use metals such as steel as conductive materials, especially in terms of the rate of heating and power, because it has a high resistance to the electric current so that when an electric current is passed through it, substantial heat is produced. In addition, steel has the ability to absorb more heat as the temperature increases; more energy is needed to heat the steel when it is hot than when it is cold (Stutz and Semiatin, 1986).

2.10.1. Factors affecting induction heating

Induction heating technology is widely used in all fields of life. This technology can be used to heat material locally by focusing only on the part of the material's surface with which it is in direct contact, directly heating the material. High frequency induction heating technology is considered very important in terms of its high heating efficiency of metallic materials. A number of essential factors affect the implementation of induction heating (GH Induction Atmospheres, 2015) as follows:

- Metal or Plastic

Induction heating uses only conductive materials such as metals while non-conductive materials can be heated indirectly via heating a conductive metal susceptor which transfers heat to the non-conductive material.

- Magnetic or Non-magnetic

Magnetic materials can be more easily heated. These materials can produce heat through the hysteresis effect. This effect will cease when temperatures have surpassed the Curie point. At these temperatures, the magnetic material will lose its magnetic properties.

- Thick or Thin

The heating occurs on the surface of conductive materials; the heating intensity reduces with increased distance from the surface. As a result, the heat rises more quickly in small or thin parts rather than large or thick parts, particularly when the larger parts can be heated all the way through.

- Resistivity

Resistivity increases with temperature, therefore, steel will be very hot when using induction heating. Steel has high electrical resistivity because it strongly resists the current

flow, and so heat builds up quickly. Other metals such as brass and aluminium have low resistivity; they take a longer time to heat.

- Power supply capacity

The size of the induction power supply required for heating a particular part can be easily calculated. The amount of energy that needs to be transferred to the workpiece must be determined. This depends on the mass of the material being heated, the specific heat of the material, and the rise in temperature required. Heat losses from conduction, convection and radiation should also be considered.

- Degree of temperature change required

The efficiency of induction heating for a specific application depends on the temperature change required. A wide range of temperature changes can be accommodated. In general, more induction heating power is utilised for each degree of temperature increase.

To investigate more about the new mixtures of asphalt concrete with using induction heating, it is essential to gain an in-depth understanding of the mechanism between the conductive particles and other asphalt components. The fact leads to improve macroscopic response of an asphalt pavement that is a directly related to the durability of the bonding components in the asphalt mixtures. To evolve mixtures of conductive asphalt as a suitable for induction heating purpose, much research was focused on the addition of conductive material to increase the durability of mixtures and to improve the efficiency of induction heating as shown in the next section.

2.11. Conductive asphalt concrete

Induction heating has been utilised in road engineering. Principally, the induction heating process is used to remove the cracks in asphalt pavement (Harakawa et al., 2009, Soeda et al.,

2007, Koji et al., 2007, Garcia et al., 2009, Garcia et al., 2012; Garcia et al., 2013), arising from the need of road engineers to find new methods to treat pavement cracks.

Asphalt conductive concrete has been investigated using induction heating technology in pavement engineering. Electrically conductive asphalt concrete is a functional material developed to reach good electrical conductivity (Huang et al., 2009, Zhang, 2010, Pan et al., 2015). The use of induction heating on asphalt pavement helps by increasing the temperature and closing the cracks by high temperature self-healing of bitumen. To apply this technology to asphalt concrete it has to be made electrically conductive, since only conductive materials are heated with induction energy (Garcia et al., 2009, Garcia et al., 2010, Andriopoulou, 2012, Liu et al., 2012, Ayar et al., 2016). It is based on the phenomenon of electromagnetic induction, and can be applied by using electrically conductive and magnetically susceptible materials such as fillers and fibres mixed into the asphalt mixture (Liu et al., 2012, Agzenai et al., 2015). Different types of electrically conductive materials, whether fillers or fibres, have been used for the purpose of making asphalt concrete conductive such as graphite (Baranikumar, 2013), carbon black (Liu and Wu, 2011), steel fibres (Obaidi et al., 2017), steel wool (Garcia et al., 2013), steel grits (Menozzi et al., 2015) and steel slag (Pan et al., 2015).

For induction heating methods to heal a material there are two main requirements: firstly, it should be conductive, which can be achieved by adding a certain volume of conductive fillers or fibres into the asphalt mixes; secondly, these materials should be connected in closed loop circuits (Agzenai et al., 2015). When this method is employed an alternating electrical current applied across the conductive material will form closed loop circuits around all the micro cracks which have appeared, see Figure 2.16. Then, if a magnetically susceptible and electrically conductive material is located within the magnetic field, eddy currents will be induced in the materials with the same frequency as the magnetic field (Ahmed et al., 2006).

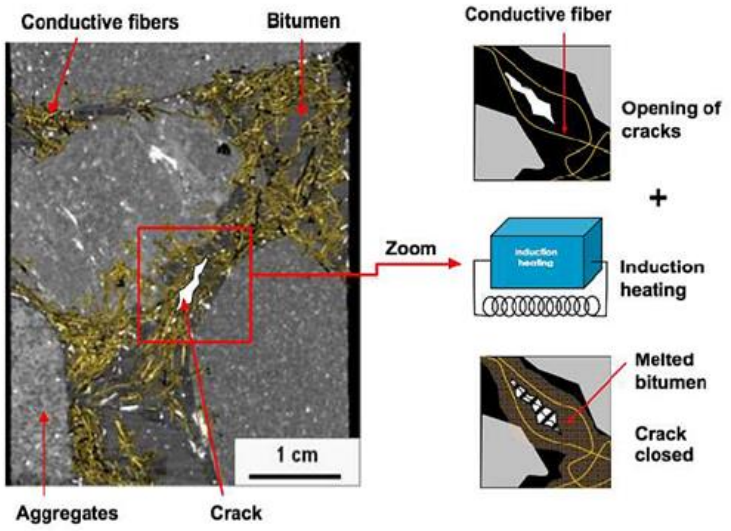


Figure 2.16 The mechanism of induction heating (Garcia et al., 2010)

This resulting generated heat will lead to the bitumen melting and the cracks closing. Induction heating has advantages in terms of improvements in the self-healing properties of the asphalt concrete or mastic. The induction heating system can convert 90% of the energy consumption to useful heat and as such is considered very efficient. In addition, it gives better working conditions by avoiding emissions, open flames and loud noise (Liu et al., 2012).

The first trial of producing electrically conductive asphalt concrete to control snow melting and ice accumulation dates back to the 1960s. Graphite as a conductive material was added to asphalt concrete mixture (Minsk, 1968). Induction heating has a wide array of potential applications in developed countries, and this method was used for the first time on a Dutch motorway in 2010. The experiment was conducted on specimens which were taken from the road and the results of this experiment were compared with the previous results from the laboratory. The field results showed good particle loss resistance, high strength and high induction healing capacity (Liu et al., 2013) following the installation of the induction heating asphalt pavement, and it showed that the increased temperature of bitumen had led to self-healing and closing of the cracks.

Many researchers have successfully prepared conductive asphalt concrete. Ahmed et al. (2006) examined different types of healing mechanisms of doped asphalt such as dielectric hysteresis heating and contact resistance healing, finding that the best one used fibre heating. In addition, they observed that the amount of heat generated in the sample coincided with the amount of induction energy deployed. They stated that the resistivity can be increased with a small increase in the fibres volume, but the induction heating will behave differently, concluding that the length of healing time for the pavement depends on the maximum temperature it reaches. For example, they found that after one cycle of healing the resistance of the samples was about 90% of the original samples, and that the resistance reached about 70% of the original samples after the fifth healing cycle. They found also that the induction system could be useful to close cracks in order to avoid water freezing in the asphalt concrete pavement. They considered the sand-bitumen ratio an important factor in the design of a conductive asphalt mixture as conductive materials. The sand-bitumen ratio can be increased by adding graphite as filler to sand.

Garcia et al. (2011) examined the asphalt mastic using induction heating and adding electrically conductive material (graphite and steel wool) in order to prove that these materials can be healed with induction energy. They found that the optimum content of fibres for each s/b ratio did not allow any further increase in heating of the mastic and that the maximum temperature had a strong relationship with the s/b ratio and the volume of fibre over a certain period of time, in spite of the fact that the effect of heating still existed due to local conductivity. The mastic may heat when the volume of conductive fibres is very low. Therefore, the mastic can be heated well depending on certain factors: the types of aggregate, sand-bitumen ratio, type of conductive fibres, length and diameter of these fibres, and type of conductive fillers.

Other studies, such as Garcia et al. (2013), focused on the environmental conditions which influence the durability of the pavement structure over time. They added steel wool fibres as

an electrically conductive material for the purposes of induction heating to study the mechanical and physical properties of dense asphalt concrete. In this study 25 mixtures with the same gradation of aggregates and amount of bitumen were used while two different fibre lengths (2.5-7 mm), three different percentages (2, 4, and 6%), and four different diameters of fibres (0.028, 0.036, 0.083 and 0.155 mm) were used. They also exposed the test specimens to different types of damage and studied the effect of different temperatures on the flexural strength of the dense asphalt concrete which contained the steel wool fibres. They concluded that this type of fibre does not contribute to improving the mechanical properties and damage resistance of dense asphalt concrete. They noted that the different fibre content percentages can change the distribution of air voids in the asphalt concrete mix, even if it decreases its particle loss resistance. It can therefore be assumed that the use of short fibres with large diameters is useful in terms of the induction heating process. Finally, it seems that the original properties of the dense asphalt concrete were not changed due to the use of these fibres.

Menozzi et al. (2015) used induction heating to heat the asphalt mixture by adding electrically conductive and magnetically susceptible materials such as steel particles into the mixture. The maximum temperature after heating in this study was very different. It can be stated that the optimum temperature is a mix-dependent value. This research was evaluated on Marshall Specimens damaged by indirect tensile fatigue tests and healed by induction heating. In addition, 6% steel grits by volume were added to the asphalt mixture. They showed that the lifetime of specimens exposed to fatigue test may extend by up to 31% by using induction heating, while this process only healed the cracks with a certain width. This study also indicated the optimum time for cracks to heal themselves was at 55 ºC and the healing capacity reduced at temperatures above 55 ºC. With more heating during the induction process the bitumen is degraded, which has an impact on the capacity of the mixture to heal.

Recently, Gomez et al. (2016) explored four types of conductive particles used for asphalt induction heating. Steel grit, steel wool, steel fibres tyres and steel shavings were added to asphalt mixtures. The test results indicate that maximum contents of steel of about 0.45% produced acceptable results of heating and healing. They found that steel fibres from old tyres gave rates of healing higher than other types of steel. The healing ratio is related to the content of metal particles and the applied healing energy. The healing results of steel grit and wool were very similar, whereas the results of steel shavings were significantly lower. They recommended that fibres from old tyres were used in base layers compared with the use of steel wool or grit which were used close to the surface to get great heating potential that led to convert higher ratios of healing.

With regard to the different materials, procedures, and mixtures offered in the previous studies concerning technology of induction heating, most of the results are not consistent across laboratory experiments. Moreover, the impacts of induction heating on the bitumen structure should be analysed. Until now, a comprehensive body of research regarding the induction method has not yet been conducted. Recently, the use of induction heating in researches of asphalt pavement is to improve self-healing in asphalt pavements. In contrast, to date, there have been no attempts in the scope of using induction heating to activate repairing the potholes by using new asphalt patching mixes.

2.12. Economic evaluation of pothole repair

Generally, when the deterioration reaches a certain point, maintenance must be applied in order to eliminate the defects. Any delay in road maintenance leads to increasing the total failure rate until reaching the end of road design life. This is referred to as the deterioration cycle of the road (Paterson, 1987) as illustrated in Figure 2.17.

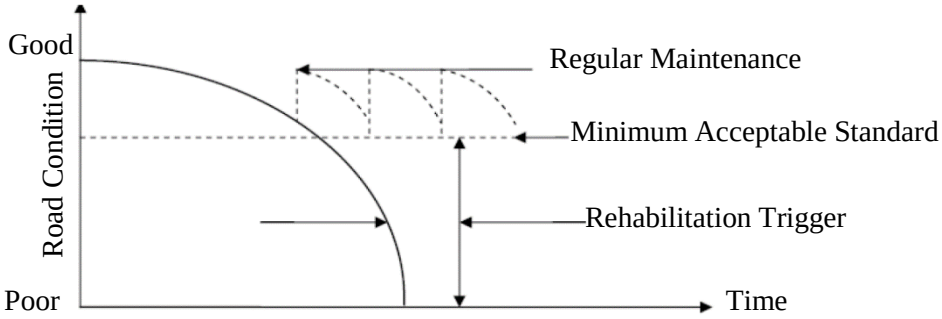


Figure 2.17 Pavement deterioration with time or traffic loading (Paterson, 1987)

To reduce the process of deterioration and sustain the road within the proper standard limits, engineering studies have identified the strategies that are used to treat the different levels of deterioration (Vishwanath et al., 2013). The selection of maintenance strategy is dependent upon pavement age, condition, availability of funding and the amount of deterioration increases (Ismail et al., 2009). If the pavement condition is good, the cost-effectiveness of the road maintenance is relatively inexpensive, while if the pavement has reached the end of its design life that leads to expensive reconstruction (Girmay, 2016).

Technically, pavement condition measures for example rutting, roughness and cracking considered the most common types of deterioration for starting maintenance. An unacceptable level of pavement condition indicates these types of distress have exceeded values of threshold as shown in Figure 2.17, known as trigger values. These values are the indicators of maximum acceptable level of distress that indicate the highest tolerable levels of distress for pavements. Once the indicator of distress as a roughness leads to exceeding the trigger values due to performance deterioration of pavement, strategies of intervention are required as a rehabilitation to repair the road to be a better condition (Kerali et al., 2006).

Table 2.2 presents the treatment suggestion of pavement maintenance related to the PCI (Pavement Condition Index) to evaluate the network segments. If the PCI of a segment is 70-100, this is considered excellent or very good condition. In this case, the routine maintenance includes small patching and sealing crack whereas reconstruction is required to sections that have failed or are in very bad condition (Shah et al., 2013).

Table 2.2 Suggestion of Pavement Maintenance Treatment with PCI Ranges (Shah et al., 2013)

PCI Range	Pavement Condition	Condition Class	Suggested Maintenance
70-100	Excellent/ Very good	I	Routine Maintenance
55-70	Good / without effect of loads	II	Routine Maintenance
55-70	Good / with effect of loads	III	Thin Asphalt Overlay layer
25-55	Fair/ Poor	IV	Double Asphalt Overlay layer
0-25	Very Poor/ Failed	V	Reconstruction

Furthermore, local road authorities in the UK have used another system that is more efficient to assess local road network conditions and to manage the maintenance for all roads, the United Kingdom Pavement Management System (UKPMS) (Phillips, 1994, Cartwright, 2005, Alfar, 2016). The UKPMS is used for the assessment of highway condition, inventory data, treatment selection type and budget predictions based on whole life costs (UK Roads Liaison Group, 2011). Figure 2.18 displays the road condition indicator through representing three categories (green, yellow and red) as suggested by UKPMS.

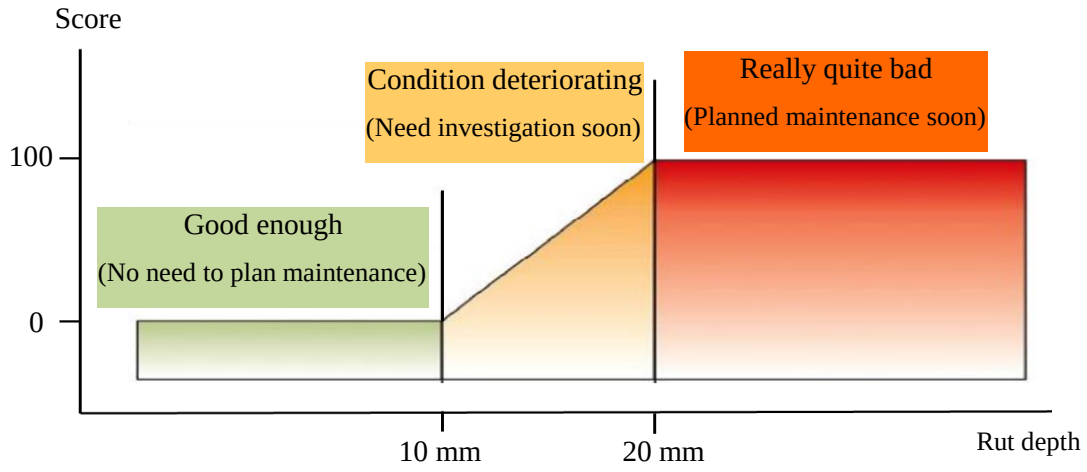


Figure 2.18 Suggestion of road condition indicator (Alfar, 2016)

In the UK, roads with asphalt surface account for 95% of the paved road network. Increased volumes of traffic and heavy loads associated with repeated bad weather cause significant deterioration (Rahman and Thom, 2012). As a result, the distresses when exceeding threshold values lead to the creation of unacceptable levels of pavement condition. This leads to the formation of millions of potholes and areas of failure such as cracking and rutting. These areas not only diminish the quality of the ride but are likely to create dangerous conditions of driving and increased costs for the road users. The situation has led to widespread dissatisfaction of significant public causing media coverage (Kerali et al., 2006). For that reason, maintenance is required at this stage to give the best service to road users. In 2012, the bill to repair for cars damaged by the potholes may reach £1bn. To treat this huge problem nationwide, the government gave £871m in the same year to cover maintenance of roads by road authorities (Rahman and Thom, 2012, Qiao, 2015).

In 2017, the survey shows a decline in the average number of potholes patched. In England the numbers show a 19% decrease while London shows the biggest drop at about 43%. A large difference has been shown in the cost between patching potholes that is part of a planned road repair programme and the cost of reactive repair which may reach almost a third more. The

average cost for patching a pothole in each area reached £102.3 million spent in England and Wales in 2017 (Asphalt Industry Alliance, 2017).

The costs of pothole patching can be divided into three different categories: materials, labours and equipment. Moreover, cost effectiveness of traffic delays has identified by the rate of patch survival. These repairs have to be monitored for at least one year. Monitoring involves checking the repair's presence and noting the survival or failure of each pavement section (Wilson and Romine, 1999).

Therefore, a durable pothole repair is very important and is based upon the combination of material and the selected procedure. Accordingly, an overview of the associated repair and durability of materials is provided in Table 2.3 which combines the general types of materials with an estimation of their durability according to corresponding remediation procedures (Kubanek, 2013).

In all of these types, there is more than one type can be estimated durability that is shown in it. That leads to massive variation in the durability of a material, based on the procedure used, so, in addition, it is important to show the used procedure when a pothole is repaired. Consequently, the durability of pothole repair materials depends on different categories as follows (Kubanek 2013):

1. Short-term durability (less than one year): the objective of emergency repairs of potholes is for the repair to last until the conditions of weather can allow the application of a more durable repair material.
2. Medium-term durability (between one and three years): the objective of the pothole repair is to change the layer of pavement surface to last for 1-3 years
3. Long-term durability (more than three years): the objective of this repair is to place new surfaces relatively with a durability of 3-7 years.

Effective cost analysis is the same as the Life Cycle Cost Analysis (LCCA) to assess the cost-effectiveness of patches. Wilson and Romine (2001) estimated the actual cost depended on predictable time of patch service and analysis period. They also found that throw-and-roll method was more effective on the cost than patching with the semi-permanent due to reduced labour and equipment.

Dong et al. (2014) applied the evaluation of the cost-effectiveness to two methods of pothole patch, throw-and-roll and semi-permanent, with different material compositions. The survey time was about 14 months to evaluate the performance of patching on pavement sections which measured different conditions of weather and traffic. They observed 70% of throw-and-roll patches failed before the end of survival time. The total cost of labour costs was about 50% to 60% whereas material costs were only 20% for cold mixes and 2-5 % for semi-permanent patches. The throw-and-roll patches were highly cost-effective in the short term because of the reduction of equipment and labour costs.

Furthermore, there are two cases of repair that can be distinguished: immediate repair – the potholes are always repaired directly after their occurrence, the period between pothole occurrence and repair is very small and can be neglected; deferred repair – the period between the pothole occurrence and repair is long enough to be not neglected (Hartmann, 2013). Therefore, the highway agency has to decide either to repair potholes immediately or defer their repair. The delay until repairing potholes can be different and may be of the order of 3-9 months and this difference was calculated by the LCCBA (Hartmann, 2013).

2.13. Summary

The aim of this chapter is to provide general information about a solution to pavement maintenance problems, when compared to the conventional methods currently being used. In addition, it is necessary to understand the factors that affect the state of the bond at the

interfaces between asphalt layers. As mentioned previously, asphalt pavements are composed of several layers. This research is interested in studying the bond between the base and surface layers of pavement structures. This is considered one of the most important properties that influence the performance of the pavement that can be summarised as follows:

- Section 2.2 focuses on distresses of flexible pavement, and bonding between asphalt layers that is not always achieved; there are many reasons for this bond failure, such as an increased traffic load and environmental conditions.
- Sections 2.3 and 2.4 present the different types of failure that have occurred in pavements. It is well known that potholes are one form of deterioration in asphalt pavements.
- Section 2.5 presents the important factors contributing to the deterioration of the pavement layers, which lead to a reduction in their durability and loss of adhesion between the binder and aggregates.
- Section 2.6 explains maintenance works of pavement that are carried out from time to time to maintain the pavement. Sections 2.7 and 2.8 display different conventional methods that are used to repair the asphalt interfaces of the different layers of asphalt pavements, and proposed techniques to heal the top layer of asphalt.
- Section 2.9 focuses on the development of techniques of evaluating pavement repair materials to determine if these materials will meet performance expectations.
- Section 2.10 and 2.11 discuss induction heating technology that can be applied to rehabilitate pavements that have deteriorated. Induction heating can be an efficient technique for self-healing by using conductive materials within the binder to induce heating, which leads to a decrease in the binder viscosity near cracks. The existing induction heating technique and knowledge about the conductive asphalt concrete make it possible to use induction heating to heat an asphalt layer and to heal the cracks through high-temperature self-healing of the bitumen.

- Section 2.12 reviews the economic aspects which are offered by previous authors to assess the cost-effectiveness of patches.

Chapter 3

Materials and experimental works

3.1. Introduction

This chapter describes the materials and the methodology were used and followed in this research in order to achieve the aims and objectives which were mentioned previously. The pothole repair materials are the asphalt tile and bonding layer, asphalt pellets and binder pellets. The procedure of prefabrication for each technique is presented as well as the asphalt materials that are used for comparison purposes. Furthermore, this chapter also describes the importance of the mechanical properties to evaluate the bond and performance of these materials using standard tests such as tensile bond test, shear bond test indirect tensile stiffness modulus test (ITSM), water sensitivity test and wheel tracking test. The tests were carried out in accordance with British standards.

3.2. Asphalt tile and bonding layer

3.2.1. Materials

The top layer (the tile) was made of the most suitable kind of asphalt mixture depending on the properties of the road where the pothole (or set of potholes) is going to be repaired. For the experimental assessment of the technology, the present investigation was carried out with hot mix asphalt, dense gradation and limestone aggregates, in compliance with British standards (BSI 13108-1:2006). The limestone aggregate was used for the study and provided by a local quarry (Tunstead Quarry, Derbyshire, UK) to NTEC at the University of Nottingham. The selection of limestone aggregate is based on commonly use in the UK and cheap. The gradation

of limestone aggregate which was used to manufacture the asphalt tile in compliance with British standards is shown in Table 3.1. The bitumen used was 40/60 pen provided by Shell. The selection of this grade of bitumen is because it is widely used in asphalt pavement engineering. The properties of the bitumen used in this study according to European Standard EN 12591:2009, the specific gravity and penetration index at 25 °C, were found to be 1.03 and 58 respectively.

Table 3.1 Asphalt tile composition

Sample	Cumulative aggregate weight % passing
10 mm	100
6.3 mm	80
Dust	50
Binder content (by mass of total mix)	5%
Target air void content	5%

In addition, the materials for the bonding layer were prepared by mixing 96% in mass of bitumen 40/60 pen and 4% of styrene-butadiene-styrene (SBS) during 2 hours at 170 °C, using a high shear mixer, see in Figure 3.1. The SBS was added during prefabricating membrane as a bonding layer to make it more flexible that can easily be wrapped the tile. This study also proposed the concentration of SBS polymer that is 4% by mass of binder. Although, SBS is considered an expensive type of polymer, it is probably the most appropriate polymer for asphalt modification as recommended by Yildirim (2007). The typical properties of utilized SBS-modifier are a solid, white colour particles (Figure 3.2), essentially odourless (after mixing there is almost an odour) with density 880-950 kg/m^3 and it is soluble in water (specific gravity <1).

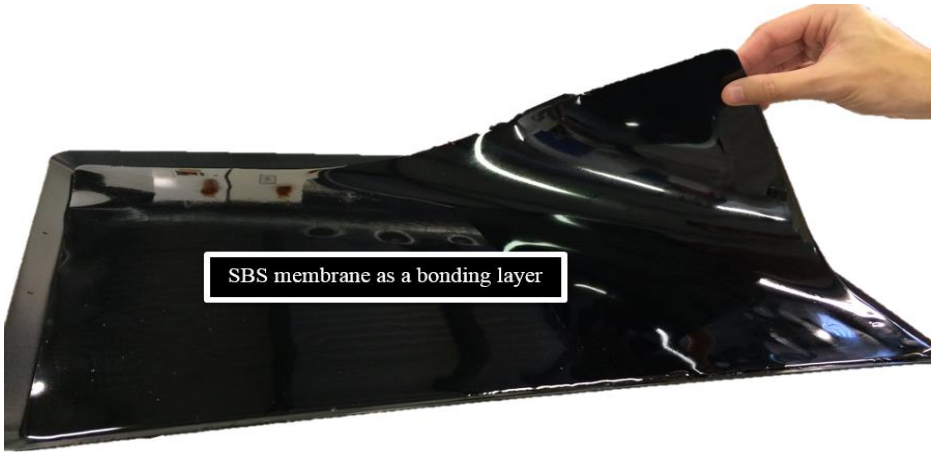


Figure 3.1 SBS Membrane



Figure 3.2 Styrene-Butadiene-Styrene (SBS)

Conductive material was added to increase the durability of mixtures and to improve the efficiency of induction heating. Therefore, stainless steel fibres in two different configurations were assessed. First, fibres were obtained from recycled tyres, with average diameter 0.34 mm with the size distribution shown in Figure 3.3. The use of steel fibres require an effort to disperse steel fibres uniformly because this type was a little bit long and sharp that lead to inhomogeneity distribution. Second, chicken wire was obtained from Mesh Company with approximate diameter 0.36 mm and four different apertures, as shown in Table 3.2.

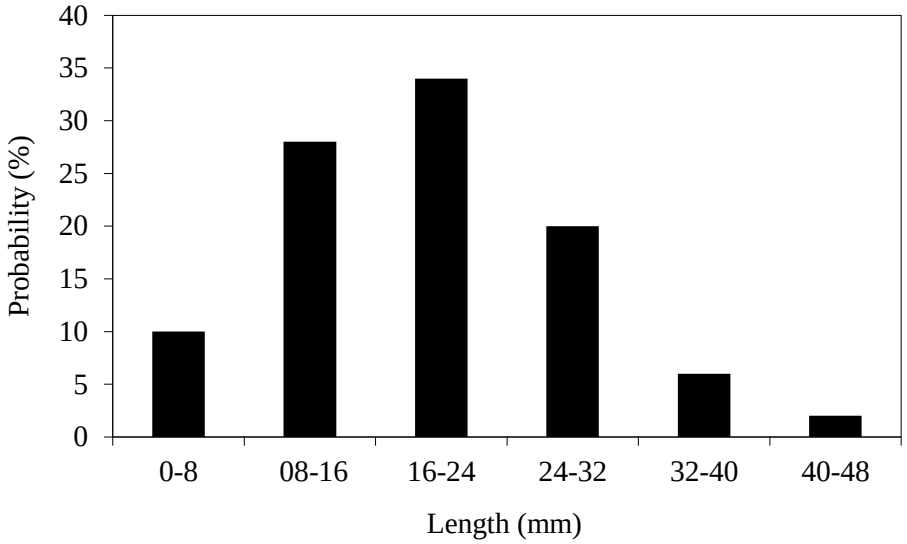


Figure 3.3 Steel fibres size distribution

Table 3.2 Specifications of steel mesh wire

Aperture	0.552mm	0.91mm	1.233mm	2.18mm
Wire Diameter	0.36mm	0.36mm	0.36mm	0.36mm
Open Area	37%	51%	60%	74%

3.2.2. Construction of asphalt tile and bonding layer

The bonding layer was built by pouring the modified bitumen at 170 °C into a tray of (360*470) mm^2 until it reached a thickness of 3 mm, to form a bituminous membrane. Then, the membrane was let to cool down at a temperature of 5 °C for 2 hours. Later, the membrane was cut into (100*100) mm^2 sections.

Moreover, asphalt tiles were assessed using asphalt mixture prismatic test samples of (100*100*20) mm^3. The tiles were cut from a bigger test sample of (305*305*20) mm^3, compacted at 140 °C using the roller compactor method to a target air void content of 5%.

Besides, loose fibres were uniformly spreaded or the chicken wire was placed on the hot asphalt mixture right after compaction, while the mixture was still hot. Asphalt tiles with 26 g, 53 g, 106 g and 133 g of loose fibres were prepared, corresponding to 80%, 60%, 20% and 0% of open area left by the fibres in surface of the test specimens.

These values were assessed visually using ImageJ. Note that 0% open area did not correspond to a solid sheet of steel over the asphalt, but the loose nature of fibres allowed bitumen to pass through. Finally, the membrane was placed on top of the fibres while asphalt mixture was still hot. To evaluate the effect of the membrane thickness on the adhesive properties of the tiles, samples with 1, 2, 3, 4 and 5 membranes were fabricated.

Finally, careful pressure was manually applied to guarantee the adhesion of the membranes to the tile and the metallic particles. See Table 3.3 for an overview of the asphalt tiles fabricated and their composition.

Table 3.3 List of asphalt tiles studied

Number of membranes; thickness of composed membrane	Open area of loose fibres				Open area of chicken wire			
	0%	20%	60%	80%	37%	51%	60%	74%
1; 3 mm	X	X	X	X				
2; 6 mm		X						
3; 9 mm		X						
4; 12 mm		X			X	X	X	X
5; 15 mm	X	X	X	X				

3.3. Asphalt pellets

3.3.1. Materials

Induction-heating pellets were composed of limestone aggregate, bitumen 40/60 pen and steel grit. The limestone had continuous gradation with maximum size 2 mm, while the steel grit had uniform size between 0.425 and 1 mm. It was characterised rounded shape hence did not

face any problem during using and mixing. It was behaved as a normal fine aggregate. Hence, the maximum size of the granular material is considerably lower than that used by other authors (e.g. 20 to 40 mm by Artamendi et al., 2014, Artamendi et al., 2016) who heated pellets into mixers. For the present approach, the objective was to heat the pellets directly inside the pothole, removing the need of a heating mixer. In order to ensure good distribution and compatibility, smaller pellets were used (8*8*8) mm^3, which limited the aggregate maximum size. In order to assess the effect of bitumen and steel grit on the pellets performance, two groups of mixes were prepared. Group 1 had 10% of bitumen and variable amounts of steel grit and aggregates, ranging from 5 to 45% and from 85 to 45%, respectively. Group 2 had 35% of steel grit and variable amounts of bitumen and aggregates, ranging from 15 to 25% and from 50 to 40%, respectively. For a more detailed overview of the composition of the pellets, see Table 3.4.

Table 3.4 Composition of asphalt pellets used for the present investigation (% of total volume)

<table>
<tr><th></th><th>Mix number (MN)</th><th>Bitumen</th><th>Steel Grit</th><th>Aggregates</th></tr>
<tr><td rowspan="5">Group 1
Constant bitumen</td><td>1</td><td rowspan="5">10%</td><td>5%</td><td>85%</td></tr>
<tr><td>2</td><td>15%</td><td>75%</td></tr>
<tr><td>3</td><td>25%</td><td>65%</td></tr>
<tr><td>4</td><td>35%</td><td>55%</td></tr>
<tr><td>5</td><td>45%</td><td>45%</td></tr>
<tr><td rowspan="3">Group 2
Constant steel grit</td><td>6</td><td>15%</td><td rowspan="3">35%</td><td>50%</td></tr>
<tr><td>7</td><td>20%</td><td>45%</td></tr>
<tr><td>8</td><td>25%</td><td>40%</td></tr>
<tr><td rowspan="5">Limestone aggregate gradation</td><td>Sieve size</td><td colspan="3">Cumulative aggregate weight passing (%)</td></tr>
<tr><td>0.5/2 mm</td><td colspan="3">100</td></tr>
<tr><td>0.125/0.5 mm</td><td colspan="3">52.2</td></tr>
<tr><td>0.063/0.125 mm</td><td colspan="3">33.5</td></tr>
<tr><td>0/0.063 mm</td><td colspan="3">27.1</td></tr>
</table>

3.3.2. Manufacture of asphalt pellets

First, dried aggregates and bitumen were heated in an oven at 170 ºC for 1 and 3 hours respectively. Then, aggregates and steel grit were blended in a 5 litre planetary Hobart mixer at 1725 rpm, for 2 min before the corresponding amount of bitumen was added and all the materials were mixed for 3 min at 1725 rpm. The mixture was used to make pellets, by introducing it into silicone moulds with inner dimensions (8*8*8) mm^3 and compacting it by hand. Subsequently, the material was cooled down for 3 hours at 5 ºC and demoulded, obtaining the pellets shown in Figure 3.4 (a). The shape of the pellets was cubical due to the easiness of fabrication. In the future, they could be made spherical if that is required. The internal structure of the pellets can be observed in Figure 3.4 (b). Finally, pellets were stored in plastic bags at ambient temperature until they were used for testing, several days later.

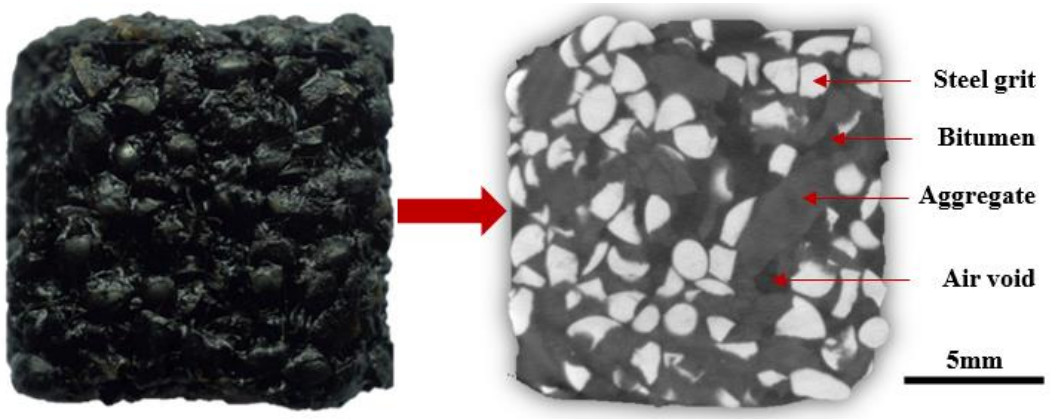


Figure 3.4 Induction-heating asphalt pellet. External view (a) and internal structure obtained by CT-Scan (b)

3.4. Binder pellets

3.4.1. Materials

Binder pellets were composed of bitumen 40/60 pen with a density of 1.03 gm/cm^3 and steel wool with a diameter between 16 and 72 μm and a length of 0.15-5 mm. This type of fibre, with small size, produces uniform and homogeneous distribution within the mix, avoiding the formation of clusters. In order to produce a protective shell, the following components were used: (a) sodium alginate ($C_6H_7O_6Na$), which is an anionic polysaccharide, widely distributed in the cell walls of brown algae; (b) a calcium source, provided by Sigma-Aldrich as anhydrous, granular pellets of calcium chloride ($CaCl_2$), of 7 mm diameter, and 93% purity; and (c) limestone filler. The aggregate used was limestone with continuous gradation and maximum size of 2 mm.

In order to optimise the asphalt mixture made with pellets, three variables were investigated, (see Table 3.5).

1. Type of protective shell. Four types of pellets were produced: (a) with no protective shell, (b) covered in mineral filler, (c) encapsulated into an alginate-calcium chloride shell and (d) encapsulated into an alginate-calcium chloride shell and then covered in mineral filler. All these pellets were manufactured with 50% bitumen and 50% steel content.

2. Amount of steel in the pellets. Four asphalt mixtures were manufactured by fixing the pellets content at 15% but changing the steel content in the pellets (20%, 35%, 50% and 65%).

3. Amount of pellets in the mix. Four asphalt samples were manufactured by fixing the type of pellets (encapsulated into an alginate-calcium chloride shell and covered in mineral filler) and their steel content (50%), while changing the amount of pellets in the mix (5%, 10%, 15% and 20%).

Table 3.5 Composition of asphalt mixtures made with binder pellets

Mix number	Pellets Content	Aggregates	Bitumen/Steel wool Content in Pellets	Type of Shell
1	5%	95%	50% / 50%	Alginate + Calcium Chloride + Limestone Filler
2	10%	90%		
3	15%	85%		
4	20%	80%		
6	15%	85%	35% / 65%	Alginate + Calcium Chloride + Limestone Filler
7			50% / 50%	
8			65% / 35%	
9			80% / 20%	
10	15%	85%	50% / 50%	No Shell
11				Filler
12				Alginate + Calcium Chloride
13				Alginate + Calcium Chloride + Limestone Filler
Limestone aggregate gradation	**Sieve size**		**Cumulative aggregate weight passing (%)**	
	0.5/2 mm		100	
	0.125/0.5 mm		52.2	
	0.063/0.125 mm		33.5	
	0/0.063 mm		27.1	

3.4.2. Manufacturing of binder pellets

A summary of the steps carried out to manufacture the pellets can be seen in Figure 3.5.

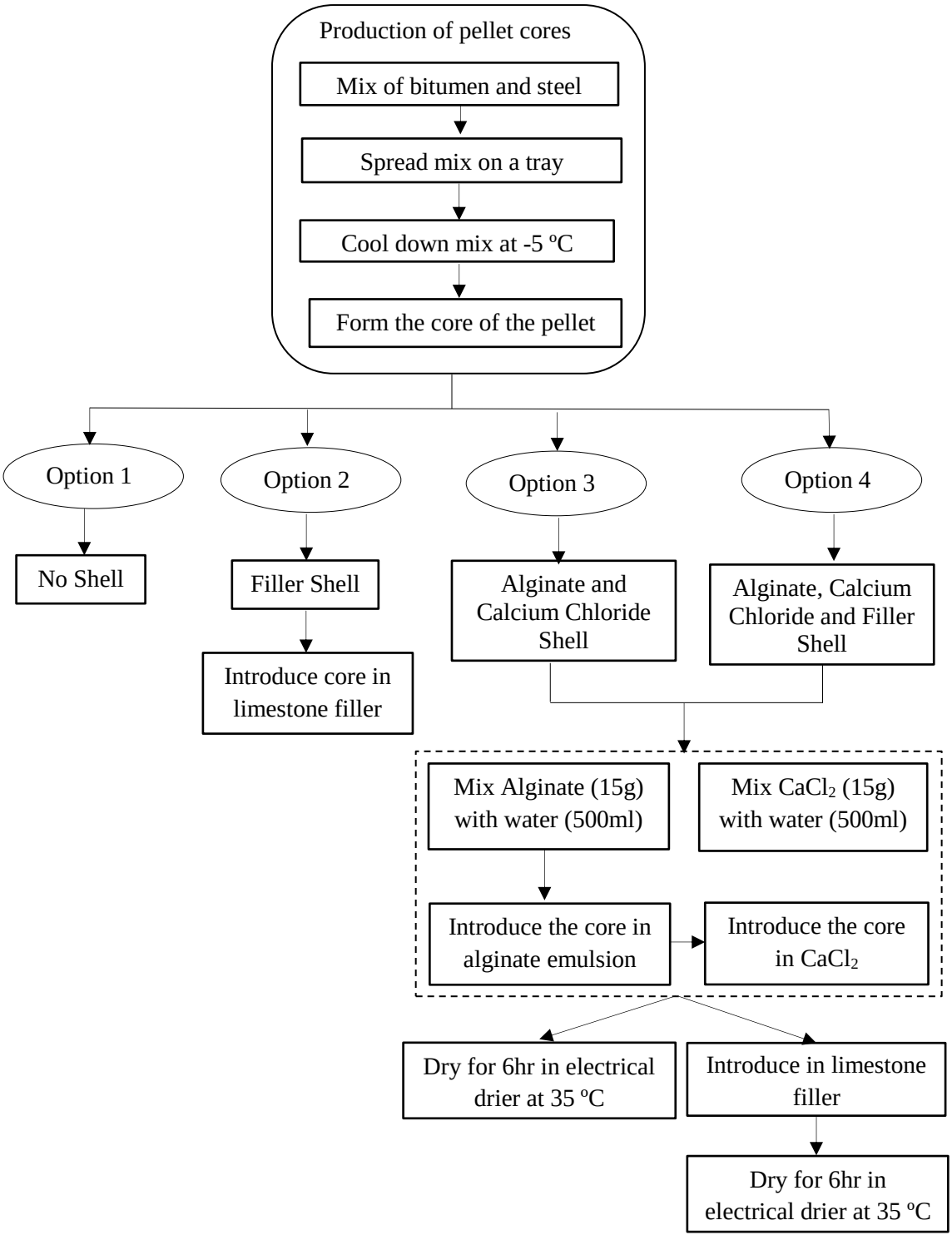


Figure 3.5 Steps for pellets manufacturing

First, the core of binder pellets was manufactured by mixing bitumen 40/60 pen and steel wool in four different contents (65%, 50%, 35% and 20% by weight of total mix). The blending was

carried out at 170 ºC for 2 min, time enough to ensure homogeneous mixing. Then, the loose mix was spread in a tray and cooled down at -5 ºC to facilitate its removal from the tray. The non-compacted layer was then broken into small irregular pieces, which formed the core of the pellets. These were stored in plastic containers at 3 ºC to maintain the properties of bitumen and avoid them sticking to each other.

In order to reduce the adhesion between pellets at ambient temperature, the first modification was to sieve the cores with limestone filler, which produced a cover of dry material.

A second method consisted of encapsulating the pellets into a protective shell. For that, 500 ml of tap water and 15 g of alginate were introduced into a 1-litre glass container. Both components were mixed by using a laboratory gear drive mixer at 400 rpm for 10 min, which created a homogenous emulsion, where the alginate acts as the emulsifier. Simultaneously, a calcium chloride solution was prepared by mixing 500 ml of tap water with 15 g of calcium chloride ($CaCl_2$) in another 1-litre glass container. The cores were introduced first into the alginate emulsion and then into the calcium chloride solution, producing the reaction between both components over all the surface of the pellets, which remained as a polymeric protective shell. Finally, they were introduced into an electrical drier at 35 ºC for 6 hours to remove the moisture and produce the hardening of the shell.

One last type of pellet was produced by a combination of previous methods. Hence, the cores were first encapsulated into an alginate-calcium chloride polymeric shell and then sieved with limestone filler to cover the shell with an extra layer of mineral powder before drying in the electrical drier. This type of pellet can be seen in Figure 3.6.

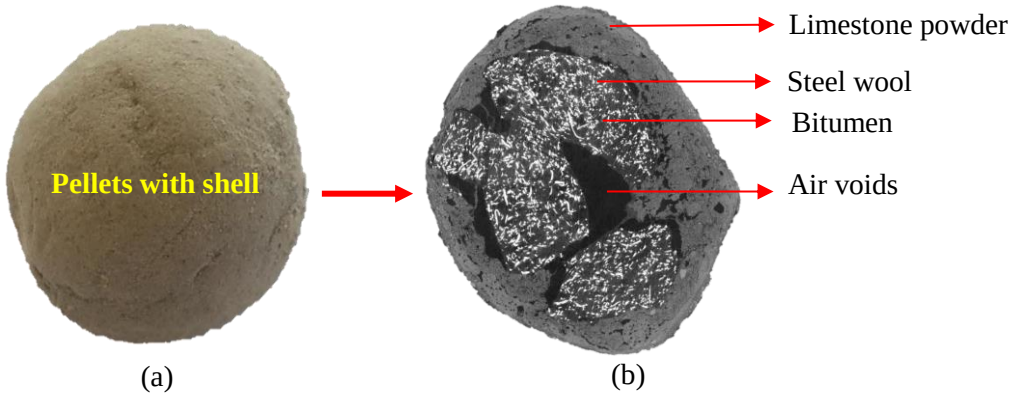


Figure 3.6 Images of pellets: (a) pellets with alginate-calcium chloride and filler shell; (b) internal structure of pellets obtain by CT-Scan.

3.5. Materials and sample preparation of asphalt blocks and slabs to simulate the bottom surface of a pothole

The road materials to which all proposed ideas (tile, asphalt pellets and binder pellets) would adhere were simulated by means of asphalt blocks or slabs. These were manufactured with a dense asphalt mixture, composed of limestone aggregates, 20 mm maximum size and bitumen 40/60 pen. The mass composition was 95%, and 5%, respectively. To simulate the bottom surface of a pothole, the dense asphalt mixture specifically designed for this was roller compacted at 140 ºC, to have 5% target air void content, in compliance with the Standard BSI 13108-1:2006 and used to manufacture (300*300*50) mm^3 asphalt slabs. These were used as the base for Hamburg wheel-tracking tests, placing on top another layer of the material to be tested. Moreover, specific batches of these slabs were cut with a radial saw blade, suitable for concrete and stone materials, into prismatic (100*100*50) mm^3 asphalt blocks. These test samples were used as the base to do tensile and shear strength tests.

3.6. Samples preparation for tensile and shear tests

3.6.1. Bonding the tiles to asphalt blocks using induction heating

Asphalt tiles were bonded to the asphalt blocks by means of induction heating at room temperature, 20 °C. The setup of induction heating was applied during the present investigation by means of a flat, 3-turns coil connected to a 6 kW induction generator (EASYHEAT LI 5060), with working frequency 348 kHz. The current was set to 100 A, and the power to 2800 W during the experiments. The distance from the surface of the tiles to the coil was 5 mm and the test specimens were exposed to induction heating for times that ranged between 1 second and 1 minute, depending of the type of specimen used. The maximum heating time was decided as the time when test specimens started smoking. The surface temperature was registered using a 320*240 pixels, full colour, infrared camera, thermo IMAGER TIM 160. Right after induction heating, a weight of 5 kg was placed on top of the tile for 1 min, to guarantee the quality of the bonding, see Figure 3.7 for an scheme of the asphalt tiles

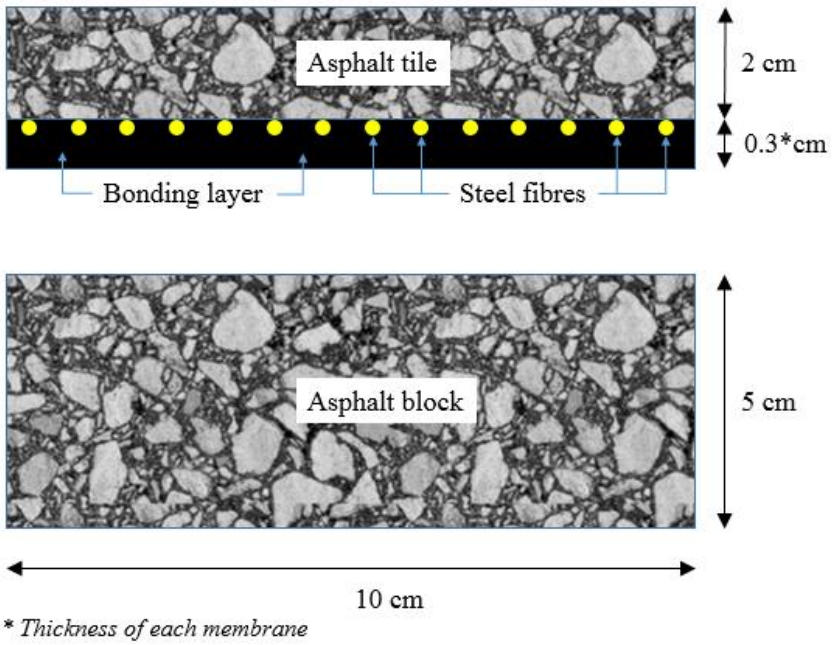


Figure 3.7 Asphalt tiles scheme

3.6.2. Manufacture of asphalt test samples with asphalt pellets

The test samples for tensile and shear tests were manufactured in two stages. First, asphalt blocks (described in section 3.5) were introduced into concrete moulds with inner dimensions (105*105*85) mm^3, see Figure 3.8, and topped with enough pellets to fill the mould at ambient temperature. Concrete was used for the moulds to prevent them from being heated by electromagnetic induction. The setup of induction heating was applied during the present investigation by means of a flat, 3-turns coil connected to a 6 kW induction generator (EASYHEAT LI 5060), with working frequency 348 kHz. The current was set to 100 A, and the power to 2800 W during the experiments. The surface temperature was registered using a (320*240) pixels, full colour, infrared camera, thermo IMAGER TIM 160.

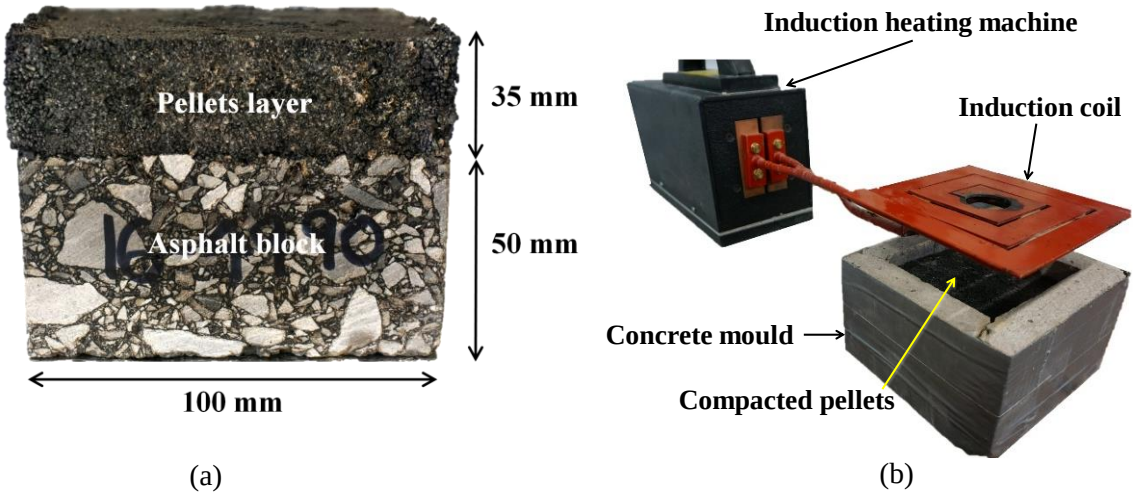


Figure 3.8 Test specimen (a) and heating of asphalt pellets by electromagnetic induction (b)

The mould containing the block and pellets was placed under the induction coil and exposed to induction heating for 2 min. Then, the material was compacted with a vibrating hammer Humboldt H-4115.3 for 1 min and another thin layer of pellets was added to fill the volume that had reduced due to compaction. Immediately after, the test samples were induction heated

for 1 min and compacted again for 1 min until the surface was flat and levelled. Finally, the samples were left to cool down at room temperature, (20 ± 2) ºC, to simulate road conditions.

3.6.3. Manufacture of asphalt test samples binder pellets

The test samples of asphalt made with pellets were prepared, by mixing pellets with aggregates into the induction-heating crucible especially designed for this investigation (Figure 3.9).

A concrete cylindrical crucible was manufactured surrounded by an induction coil which will generate an alternating electromagnetic field inside. This varying magnetic field can induce eddy currents in the metallic fibres contained in the pellets previously placed into the crucible. By the Joule effect and due to their electrical resistance, the fibres and embedding bitumen will increase in temperature. The length of the crucible was 20 mm and the inner and external diameter 100 mm and 150 mm respectively. The induction coil was multi-turn helical, connected to a 7.5 kW induction heating generator (EASYHEAT LI 5060) with a working frequency of 272 kHz. The current was set at 300 A, and the power at 1625 W during the experiments. The coil had 6-turns with external diameter of 12 mm, and distance between consecutive turns of 11.6 mm (total length of coil about 130 mm). Inside the crucible, an aluminium (non-conductive) paddle with dimensions about (100*90*0.15) mm3 was placed, connected to an electric mixer drill (ERBAUER ERB 728) that operates with 1600 W of power output, 220-240 V of voltage supply and at a speed of 0-700 rpm.

Pellets and aggregates were introduced in consecutive pairs of layers. Every time a new layer of pellets and a new layer of aggregates was added, 1 min of induction heating and mixing was applied. Hence, the total duration of the mixing was approximately 5 min. Then, the mixture was introduced into a prismatic steel mould with inner dimensions (100*100*100) mm^3. The material was compacted with a vibrating hammer Humboldt H-4115.3 for 1 min until it reached

a thickness of 35 mm. Finally, the specimen was left to cool down at room temperature to simulate road conditions. These test samples were used for tensile and shear strength tests.

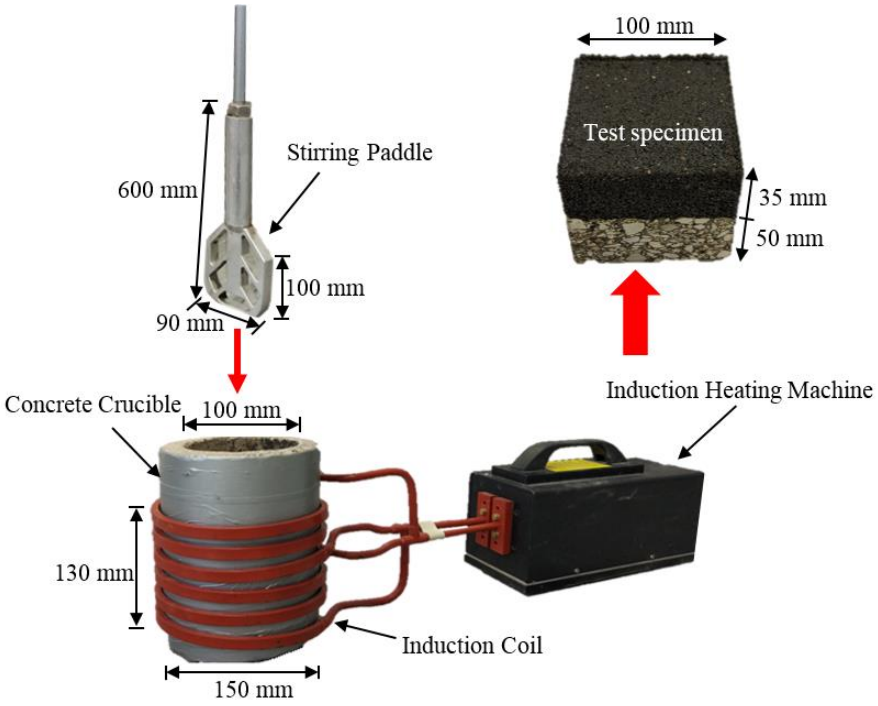


Figure 3.9 Basic equipment used to heat and mix binder pellets with aggregates at ambient temperature

3.7. Slabs preparation of all innovative materials for the Hamburg wheel-tracking test

In order to evaluate the performance of asphalt tile, the latter was tested by its exposing to cyclic loading caused by wheel track tests. With his purpose asphalt slabs with dimensions (305*305*50) mm^3 were prepared. Then, the slabs were used as the base to compact a second slab of (305*305*50) mm^3 on top of them. After this, a pothole was artifically created by drilling the top layer and extracting a core of 150 mm diameter and 50 mm height. The materials used for the slabs were the same as those used for the asphalt tiles. At the same time, cylindrical asphalt tiles of 150 mm diameter and 40 mm height were prepared, using the same material as

before and compacting via gyratory compactor, with 5% target air voids. Right after the cylinders were compacted a circular piece of chicken wire of 74% open area was placed on their hot surface, and covered with 4 circular membranes of 3 mm thickness each, to form a bonding layer of 12 mm thickness. After that, the tiles were inserted in the simulated potholes, exposed to induction heating for 15 seconds and compacted with a vibratory compactor until the surface of the slabs and tile was levelled (Figure 3.10). During this process it could be observed that the bitumen filled the gap between the tile and the slab.

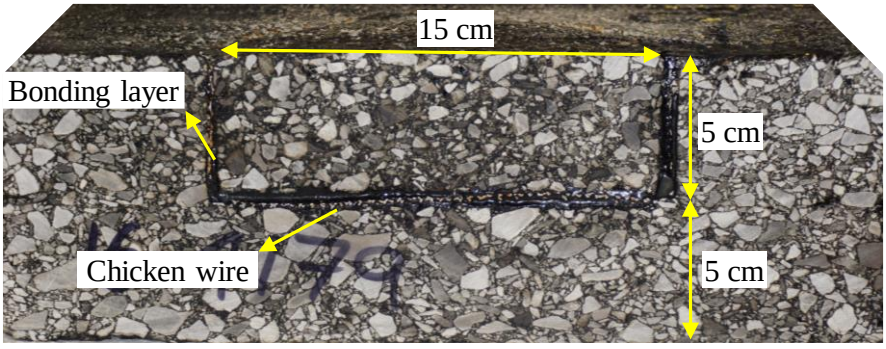


Figure 3.10 Test setup to simulate traffic over a repaired a pothole (section)

Otherwise, the procedure was followed for asphalt pellets, the 300*300*65 mm^3 asphalt slabs were introduced into a concrete prismatic mould with inner dimensions (310*310*100) mm^3. The mould was filled with these pellets at the ambient temperature. The pellets were heated by electromagnetic induction and vibratory-compacted in the same way as described in section 3.6.2. Then, new pellets were added until the height of the slabs was 100 mm. and the surface was levelled.

For binder pellets , the same dimensions of mould and slab were used with manufacturing the slabs with binder pellets, where were filled with mixture of binder pellets with aggregates and follow the same procedure as mentioned in section 3.6.3 in terms of heating and mixing. Then, the mixture was added until the height of the slabs was 100 mm and directly compacted in the same way to get the levelled surface.

3.8. Comparison with conventional pothole repairing materials

3.8.1. Materials used for comparison with conventional pothole repairing materials

Five different mixtures chosen to fill the simulated potholes have been used for comparison purposes. (1) HMA was produced by using binder content of 5% by weight and the limestone aggregates content of 95% by weight with maximum size 10 mm. (2) The commercial cold mix asphalt (CMA) was composed of granite aggregates, with dense gradation and maximum size 6 mm and paving grade bitumen of 5% by weight of total mix. This material was chosen because it is widely used to repair potholes in UK. These materials were used for their comparison with asphalt tile and binder pellets.

In addition, (3) HMA and (4) CMA test samples were carried out to compare the asphalt pellets with these material that used in pothole repairing where were manufactured with the same type of aggregate, gradation and binder and steel contents using to manufacture the pellets. To produce HMA, 47.5 g of 40/60 pen bitumen, 525 g of limestone and 857 g of steel grit were mixed each time. To produce CMA, the binder consisted of 79 g asphalt cationic emulsion, with 60% residual bitumen content and classified according to Standard EN 13808:2013 as C60B3, 525 g of limestone and 857 g of steel grit. This emulsion is named Sprayco K3-60 and is provided by Jobling and Company Limited Trading. This type is characterised by high stability and adhesion between the aggregates particles with relative density at 15 ºC 1.05 g/ml, for this cause that leads to select it as recommended by Garcia (2013). A cationic emulsion was chosen because cold mixtures with the same type of aggregates as the ones used in this research. This type of emulsion showed superior mechanical properties in accordance with BS EN 13808 (2012). The bitumen emulsion properties are presented in Table 3.6. In both materials, the

residual bitumen content was 10% and the steel grit content, 35%. Thus, results can be compared to mix number 4, as shown in Table 3.4.

Table 3.6 Properties of bitumen emulsion

Property	Value	Standard
Appearance	Black to dark brown	
Softening Point (°C)	≥ 46 ºC	EN 1427
Viscosity - Efflux time 2mm - 40°C (sec)	15-70	EN 12846
Bitumen content (%)	60%	EN 1428
Penetration (dmm)	≤ 100	EN 1426
Breaking value	70-155	EN 13075-1
Water effect on binder adhesion	≥ 90	EN 13614

According to the binder pellets, (5) another type of HMA was composed of fine limestone aggregates with maximum size 2 mm and bitumen 40/60. The content of bitumen and aggregates were 8% and 92% of total weight of mix respectively.

3.8.2. Samples preparation for comparison with conventional pothole repairing materials

Test samples of conventional road patching materials were made by replacing the proposed materials layer on top of asphalt blocks or slabs with these materials as the following below.

In case of asphalt tile, test samples as cubes containing (1) HMA layer were produced by heating bitumen and aggregates with maximum 10 mm at 170 ºC for 3 and 1 hour respectively, mixing them for 3 min at 170 ºC. In addition, test specimens as cubes with (2) Commercial CMA layers were produced where were added 955g of it. Then, the materials were placed on top of an asphalt block (100*100) mm^2 and vibratory-compacted for 1 min until reached 35 mm. CMA test samples were cured for 7 and 28 days at room temperature.

However, test slabs were prepared with two different ways where the slabs in both cases were used as the base to compact a second slab of (305*305*50) mm^3 on top of them. The first type

to HMA was made without drilling pothole on the top surface of slab as a simulation of new paved road with dimensions (305*305*50) mm^3. The second type to commercial CMA was produced with drilling pothole (150 mm of diameter and 50 mm of height) on the top layer of slab. This pothole was filled with this material and compacted with a vibratory compactor, to ensure maximum packing and let to cure during two periods of 24 hours and 7 days at 20 ºC before testing with the wheel track.

In case of asphalt pellets, test samples containing (3) HMA layers were produced by heating bitumen and aggregates at 170 ºC for 3 and 1 hour respectively, mixing them with steel grit particles for 3 min at that temperature. Afterwards, the material was poured on top of an asphalt block or slab, at approximately 140 ºC and vibratory-compacted for 1 min, following the same procedure described before for test samples containing pellets. In addition, test samples containing (4) CMA layers were produced by mixing aggregates and steel grit with 2% of pre-wetting water (by volume) for 1 min, at ambient temperature. Then, bitumen emulsion was added, and the materials were mixed for a further 1 min. Afterwards, the material was poured on top of an asphalt block or slab and compacted using the vibratory method for 1 min obtaining samples with the same dimensions as in the previous cases. Finally, test samples containing CMA were cured for 1, 7 and 28 days at room temperature (20 ±2) ºC respectively.

Finally, the case that related to binder pellets where test samples containing (5) HMA layers were produced by heating bitumen and aggregates with maximum size 2 mm at 170 ºC for 3 and 1 h respectively, mixing them for 3 min at 170 ºC. Subsequently, the materials were placed on top of an asphalt block (100*100) mm^2 or slab (300*300) mm^2 and vibratory-compacted for 1 min to reach 35 mm of height.

3.9. Laboratory testing program

3.9.1. Volumetric properties of asphalt pellets and binder pellets

The air voids of the studied materials were evaluated using the methodology based on the calculation of the maximum and bulk densities proposed by BS EN12697-5:2009, BS EN12697-6:2012 respectively. Hence, the air voids content according to BS EN12697-8:2003 was calculated as:

$$V_a = \left(1 - \frac{\rho_b}{\rho_m}\right) * 100 \quad (3.1)$$

where ρ_b is the bulk density in the mixture measured in kg/m^3, ρ_m is the theoretical maximum density of the mixture without voids measured in kg/m^3, and V_a is the air voids content in the pellets mixture measured in %.

3.9.2. Storability test of binder pellets

This test was performed to study the type of cover for the pellets which produces the best storage-stability by reducing the adhesion between them for long storage periods at ambient temperature. Four types of pellet were tested, all of them containing 50% bitumen and 50% steel wool: (1) pellet cores without cover; (2) pellets covered in limestone filler; (3) pellets encapsulated into alginate-calcium chloride polymer shell and (4) pellets encapsulated into alginate-calcium chloride polymer shell and then covered in limestone filler.

For the test, hollow plastic cylinders of 150 mm diameter and 120 mm height were vertically filled with pellets and a steel plate of 7.5 kg was placed on top. This weight represents approximately the weight of a column of 1 m of pellets on top of the tested samples. Then the containers were placed into a cabinet at 20 ºC for 7 days. After this, the steel plate and the

cylinder were removed. The distance between the original height and the height of the sample after removing the cylinder was measured and compared.

3.9.3. Testing of bonds between pavement layers

3.9.3.1. Tensile bond test (TBT)

In this study, tensile bond test (TBT) was used to evaluate the tensile adhesion strength between new proposed materials (asphalt tile, asphalt pellets and binder pellets) and asphalt blocks, according to BS EN 12697-48:2013. TBT's were conducted using an Instron hydraulic machine with computer control. To do the tests a steel plate was glued on the surface of the tiles using epoxy glue (Araldite). After, the test samples were placed in a temperature-controlled cabinet at 20 °C for 24 hours. The tensile load was applied to the samples through the steel plate. The surface layer was pulled off in an axial direction at the rate of 20 mm/min until the test sample failed, at which point the tensile force was measured. Finally, the tensile strength was calculated as the ratio between the tensile load (kN) and the cross sectional area of the test specimens.

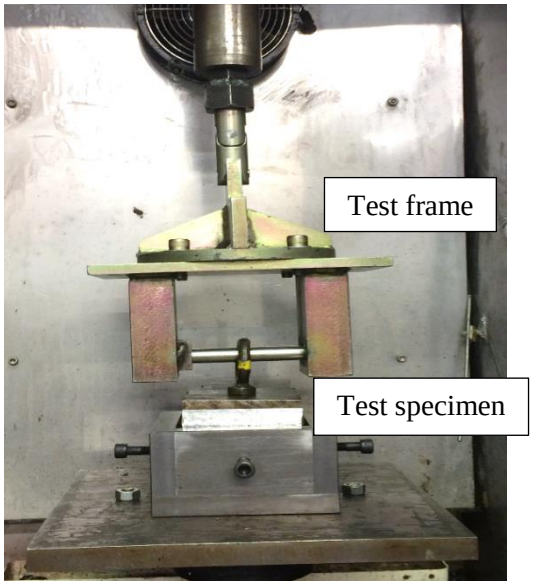


Figure 3.11 Tensile bond test

3.9.3.2. Shear bond test (SBT)

In this study, shear bond test (SBT) was used to measure the interface shear strength of the new proposed materials (asphalt tile, asphalt pellets and binder pellets), according to BS EN 12697-48:2013. SBT's were conducted using an Instron hydraulic machine with computer control, using a shearing rig specifically designed for the dimension of the test samples used in this study. The test samples were first placed in a temperature-controlled cabinet at 20 °C for 24 hours. Then, the shear load was applied at the rate of 20 mm/min until the interface failed. The shear bond strength of the interface was calculated by dividing the maximum shear load by the cross sectional area of the interface.

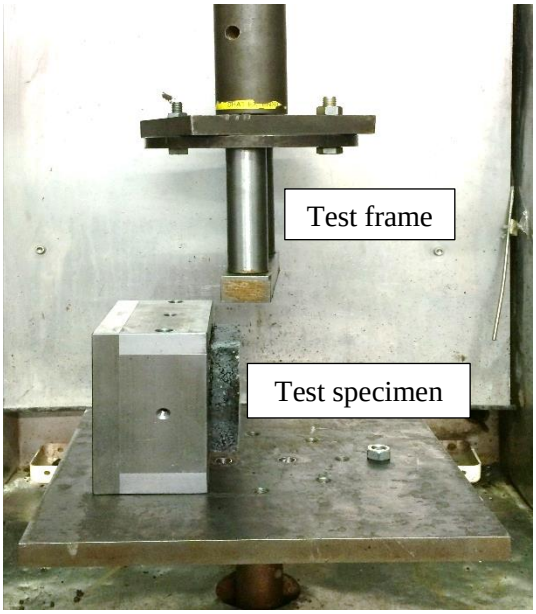


Figure 3.12 Shear bond test

3.9.4. Wheel tracking test (WTT)

The wheel track test (Figure 3.13) is probably the most common type of laboratory equipment used for the determination of rutting susceptibility (Hall et al., 2005). All wheel tracking equipment typically operate on the basis of applying load by a rolling steel wheel along the surface sample of an asphalt concrete slab that is submerged in hot water, thereby creating

conditions conducive for the rut development (Yildirim and Kennedy 2002). In 1970, the Hamburg wheel-track device (HWTD) was developed by Esso A.G. of Hamburg in Germany (Aschenbrener and Far, 1995, Romero and Stuart, 1998).

Traffic was simulated by means of a Hamburg wheel tracking device, according to AASHTO T 324-04 standard, under submerged conditions, at 25 ºC. The width of the wheel was 47 mm and its load, 705 N. The test is finished when a total of wheel passes have reached to 20000 on the sample accumulates 15 mm of rut depth. Every case was repeated on two specimens, obtaining the final results as their average value. The parameters analysed in this research were the accumulated deformation of the centre of the specimens at the end of the test.

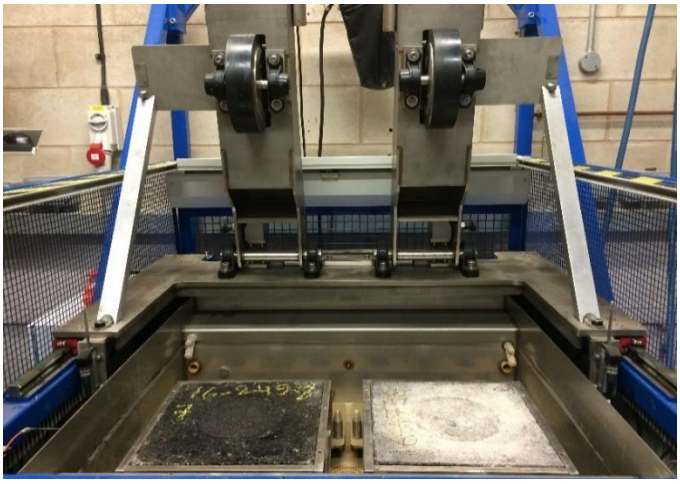


Figure 3.13 Wheel tracking test configuration

3.9.5. Moisture sensitivity test

Moisture sensitivity test is used to assess moisture damage of asphalt concrete mixtures (Santucci, 2002, Ahmad, 2011). Moisture sensitivity relates to the adhesion loss between the binder and aggregate when the materials are exposed to moisture (Airey et al., 2007).

In this study, the procedure prescribed in the British standard (BS EN 12697-12:2008) was followed. In order to compare the behaviour of asphalt materials with and without moisture conditioning, physical tests such as strength (destructive test) or modulus (non-destructive test) were used and a ratio computed by dividing the result from the conditioned specimen by the result from an unconditioned specimen. Where the computed ratio was less than a specified value, the mixture was considered to be moisture susceptible.

Firstly, the destructive test was performed using a shear test for two separate groups of asphalt tile specimens. Similarly, a non-destructive test was carried out the second set of asphalt pellets specimens using the indirect tensile stiffness. The two subsets of specimens were conditioned as follows: Dry group with cubical and cylindrical specimens conditioned in a temperature controlled room at 20 ºC. Wet group with cubical and cylindrical specimens conditioned in water at 40 ºC during 72 hours and then 25 ºC in water during 2 hours prior to starting the test. Before placing the specimens in the water bath the specimens were saturated in a vacuum container for 30 min, using a residual pressure of 6.7 kPa, as defined in the British standard.

3.9.6. Indirect tensile stiffness modulus (ITSM) test

The Nottingham Asphalt Tester (NAT) (Figure 3.14) is equipment that can be used to perform the indirect tensile test on asphalt materials. Test specimens are prepared in laboratory by compacting the materials into suitable cylindrical moulds, or cores are taken from slab (Hassan and Al-Busaltan, 2016). The thicknesses of these samples range from 30-75 mm. They cannot be too small owing to effects of the three-dimensional and cannot be very high because the compaction of sample could differ. According to the British Standard (BS EN 12697-26:2012), displacement of 7 ± 2 μm can be used for a sample with a diameter of 150 mm and a 5 ± 2 μm displacement for a sample with a diameter of 100 mm. The testing parameters used and associated procedures are described in chapter five.

This test was carried out for test sample of pellets asphalt type as followed specific procedure for preparation of samples. Six cylindrical pellets samples of 100 mm diameter and 40 mm of height were prepared, using the same material as before (55% of fine aggregates, 10% of bitumen and 35% of steel grits) by volume. Mixing and preparation of pellets were carried out as described in section 3.6.2. The test samples for stiffness test were manufactured using cylindrical mould (100* 200) mm and filled it with enough pellets at room temperature. The pellets was placed under the induction coil and exposed to induction heating and heating and compacted as described in section 3.6.2. Afterward, the specimens were left in the moulds for 24 hours after which they were demoulded. After, the test samples were placed in a temperature-controlled cabinet at 20 °C for 24 hours.

HMA and CMA mixes were tested for comparison purposes with pellets materials as presented in section 5.7. A gyratory compactor was used to compact the cylindrical specimens with target air voids of 18% and 35% respectively and demould the samples after 24 hours as well. Finally, test samples containing CMA were cured for 7 and 28 days at room temperature (20 ±2) ºC respectively.

Each set were divided into two groups; one for dry (unconditioned) testing and the other for saturated testing. The dry group was tested in Nottingham Asphalt testing Machine (NAT) without moisture conditioning. Three test specimens of each set were vacuum-saturated and submerged in a 40°C water bath for 3 days. After this, the specimens were immersed in a water bath at (20 ± 1) °C for 2 hours according to BS EN 12697-12:2008. The saturated group was tested by the same machine after the moisture conditioning.

Following the test conditions as in Table 3.7 and as prescribed by the BS EN 12697-26:2013, an impulsive load was applied with a rise-time of 124±4 ms, to achieve a target horizontal deformation of 5±2 μm. Ten conditioning pulses were applied to the specimens followed by five test pulses. Automatically, the test data load and horizontal strain were measured and

stored. The test machine directly produces the stiffness modulus and after repeating the test along two diameters, the average stiffness values were calculated.

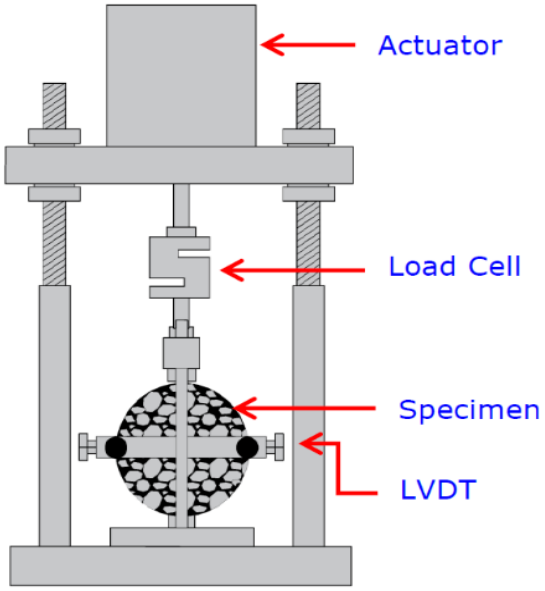


Figure 3.14 General view of the ITSM test (Nassar, 2016)

Table 3.7 ITSM test conditions

Item	Range
Specimen diameter	100±2 mm
Rise time	124±4 ms
Transient peak horizontal deformation	5±2 μm
Loading time	3-300 s
Poisson's ratio	0.35
No. of conditioning plus	10
Test temperature	20 °C
Specimen thickness	40 mm

3.9.7. Indirect tensile strength (ITS) test

Three cylindrical asphalt specimens made of each type of binder pellets were conditioned at 20 ºC before tested. The samples had a diameter of 100 mm and a thickness of 40 mm. The ITS test involved applying diametric compression with a constant deformation rate of 50 ± 2 mm/min to the samples between two loading strips, which creates tensile stresses along the vertical diametric plane causing a splitting failure. The test was conducted using an Instron hydraulic press in accordance with Standard BS EN 12697-23:2017. After testing them, the indirect tensile strength of each sample could be calculated by using the following equation:

$$ITS = \frac{2P}{\pi\, D\, H} \tag{3.2}$$

where *ITS* is the indirect tensile strength (MPa), P is the total applied vertical load at failure in Newton (N), D is the diameter of specimen in millimetres (mm) and H is the height of specimen in millimetres (mm). The tests were repeated on three samples per case, obtaining the final result as the average of them.

3.9.8. X-Ray CT Scanning

To know the internal structure of materials used for potholes repaired using induction energy, X-Ray CT was carried out where an XRadia Versa XRM-500 scanner operated at 80 kV and 120 µA was used. The test sample was mounted on a rotational table at a distance of 11.8 mm from the X-ray source and the distance between the X-ray source and the X-ray detector was 1155 mm. It was ensured that the focal spot size of the X-ray tube was about 2 µm and therefore, a spatial resolution of 4 µm was achieved.

In case of asphalt tile technology, a specimen containing 106 g of loose steel fibres and exposed to 15 s induction heating was observed using it. Reconstructions of the air voids were prepared

by segmenting the materials found in a specific volume, based on thresholding. With this method, aggregates, steel particles, bitumen and air voids could be readily separated. The software tools used for this reconstruction were ImageJ and Meshlab. This test also applied to the asphalt pellets and binder pellets.

Chapter 4

Mechanical assessment of asphalt tile and bonding layer

4.1. Introduction

Asphalt tile an innovative material for repairing potholes that consists of an asphalt mixture tile with a bottom bonding layer made of polymer modified bitumen, and steel fibres. To use this technology, potholes have to be first cleaned, second filled with an asphalt tile and third, exposed to high frequency electromagnetic fields to heat the fibres up and melt the bitumen in the bonding layer.

This chapter discusses and analyses the results of asphalt tile and bonding layer as an innovative materials that was developed to repair the pothole after tested with several tests in terms of mechanical and durability properties. This chapter also assessed the bonding properties of tiles built with bonding layers of five various thicknesses and four amounts and distributions of fibres. Furthemore, the effect of moisture on the bonding properties of asphalt tiles has been examined and the functionality of the tiles observed using wheel track tests.

4.2. Temperature reached by the bonding layer

Figure 4.1 shows the temperature reached by the bonding layer in test samples built with loose fibres after 40 sec exposition to induction heating. As it has been reported in previous studies, for example, Garcia et al. (2013a), it can be observed that in general, the temperature was higher in test samples with higher content of fibres.

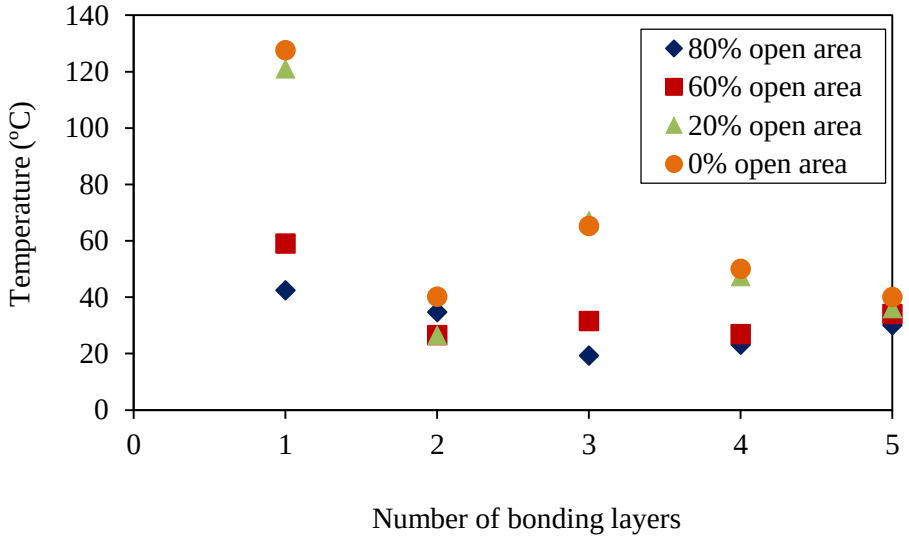


Figure 4.1 Maximum temperature reached by the bonding layer in test samples with loose fibres

Heat during induction is generated by Joule losses due to eddy currents in the surface of the fibres (Garcia et al., 2012) and dielectric hysteresis and contact resistance in the fibres crossover junctions (Kim et al., 2002a). Contact resistance heating is the dominant mechanism for the heat generation. Besides, the amount of contacts increases exponentially with the numbers of fibres in the material (Ekman et al., 2012). As a consequence, the temperature was higher in test samples with higher amount of fibres.

Moreover, the temperature decreased with the number of bonding layers. As the total energy induced depended only on the amount and distribution of fibres in the material (Garcia et al., 2012), one can only conclude that the higher temperature observed in test samples with less bonding layers was due to lower efficiency of thermal transfer and higher thermal losses. This may have happened because the fibres did not completely coated and air bubbles remained between the asphalt tile and block (see also reference (Garcia et al., 2013b), where a similar conclusion was reached). As an example, in Figure 4.1, it can be observed that the temperature remained practically constant in test samples with more than 3 layers, which shows that there was enough bitumen in the samples for effective heat transfer. Moreover, Figure 4.2 shows a

test sample with 4 bonding layers that was CT-Scanned and reconstructed using Image and Meshlab. It can be observed that 8% of the bonding layer volume is composed of air bubbles, which could have had a strong effect on the bonding and heat transfer properties, as it has been also shown in (Hasan et al., 2016).

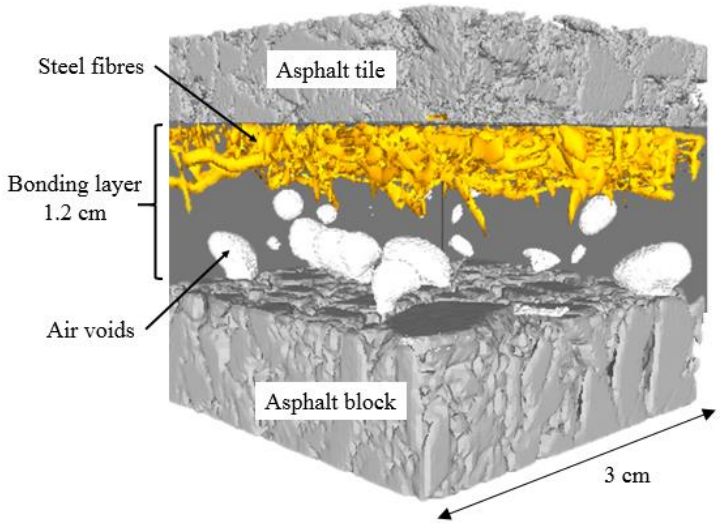


Figure 4.2 Distribution of materials in the bonding layer

In addition, Figure 4.3 shows the maximum temperature reached by test samples with chicken wire and four bonding layers. A remarkable point is that while test samples with four SBS and the highest amount of loose steel fibres reached 50 °C after 40 sec heating, the temperature of test samples with chicken wire (open area 37%) was 220.6 °C after 1 sec heating. It can also be seen that the maximum temperature reached by test samples increased with the mesh density of the chicken wire.

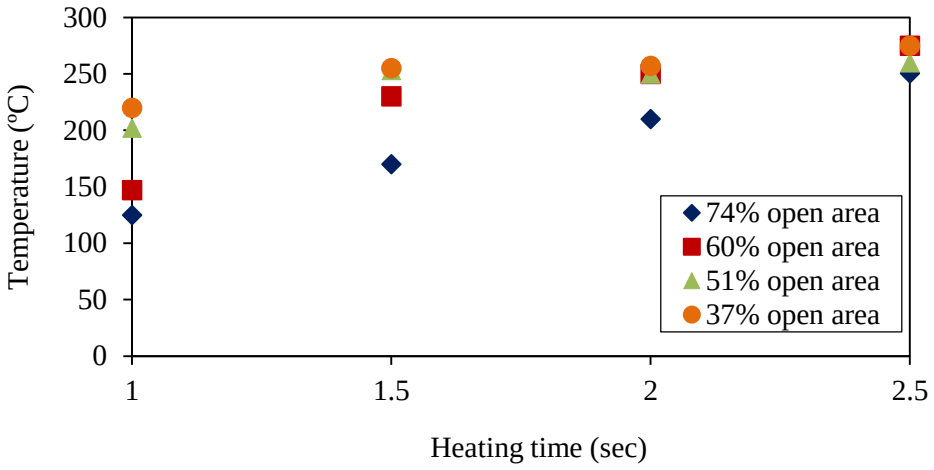


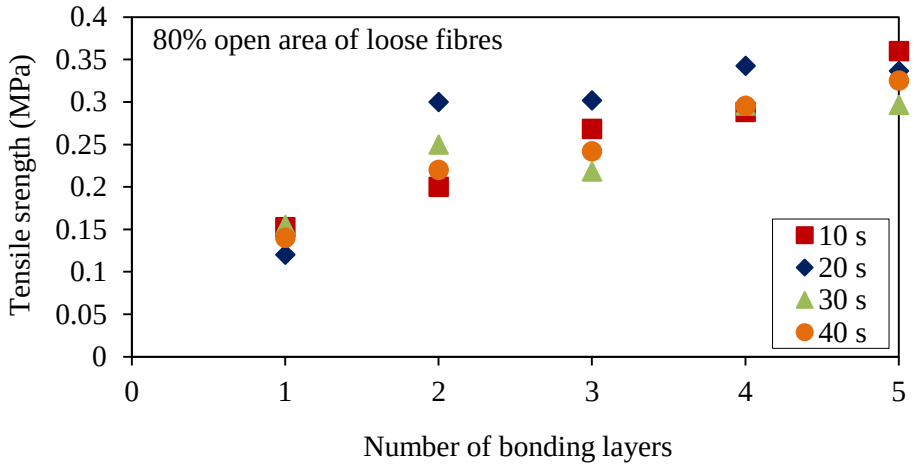
Figure 4.3 Maximum temperature reached by the bonding layer in test samples with chicken wire

The reason why the temperature reached was much higher in test samples with chicken wire is because when loose fibres were used there could be a thin layer of electrically insulating bitumen between two fibres. This did not happen when chicken wire was used. In reference Kim et al. (2002b) it has been explained that the amount of heat generated in the unidirectional fibres is much smaller than the intersections. This effect maximized the heat generated by the chicken wire. Furthermore, this high temperature could not be due to energy losses caused by poor coating of the fibres. The reason for this is that 4 bonding layers were used in every case, which were enough to guarantee an appropriate heat transfer in test samples built with loose fibres.

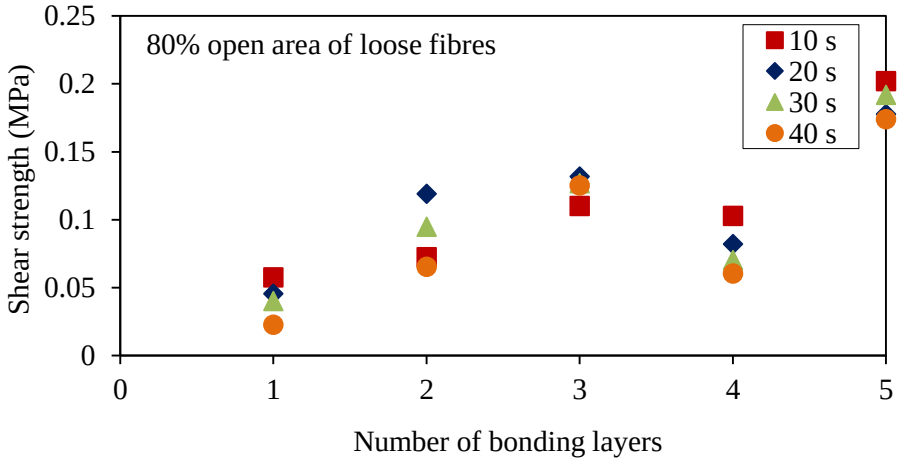
4.3. Tensile bond and shear bond strengths results

Figure 4.4 shows the tensile and shear strength of test samples containing loose fibres after induction heating. The first observation is that there is a linear relationship between shear and tensile strength and that shear strength seems to be 2.54 times smaller in average than tensile strength. Shear and tension are interrelated by formulae that incorporate the Poisson's ratio (Timoshenko and Young, 1968) and obey to the homogeneous nature of the bonding layer that

is mostly constituted of bitumen modified with SBS (see Figure 4.2). A similar linear relationship has been previously reported for isotropic and elastic materials, such as rubber (Gent, 2005). Besides, many of the test specimens broke through the bonding layer.



(a)



(b)

Figure 4.4 (a) TST's and (b) SBT's strengths of test samples containing loose fibres according to the number of bonding layers

Furthermore, the tensile and shear strength grew with the number of bonding layers (see Figure 4.4 (a) and (b)). This phenomenon is very similar to the self-healing phenomenon of cracks in asphalt mixture (Garcia, 2012) and is influenced by the packing density of bitumen between the aggregates and fibres (Qiu, 2012). When the temperature increases bitumen tends to flow

as a consequence of gravity and surface tension towards the bottom parts of the test specimen (Garcia, 2012). For this reason, a thicker bonding layer produced higher strengths.

In addition, it has been found that the range of induction heating times studied in this article was not relevant for the strength reached by test samples. Closing the gap between the asphalt tile and block may depend on the viscosity of bitumen and weight of the asphalt tile (Garcia, 2012). The fact that the strength gain is independent of the induction heating time shows that (1) the viscosity of bitumen does not play an important role on this process, possibly because the time at high temperature is too short to be noted, and (2) the gravity flow of bitumen, influenced by weight of the tile and thickness of the bonding layer, is the main parameter affecting the strength.

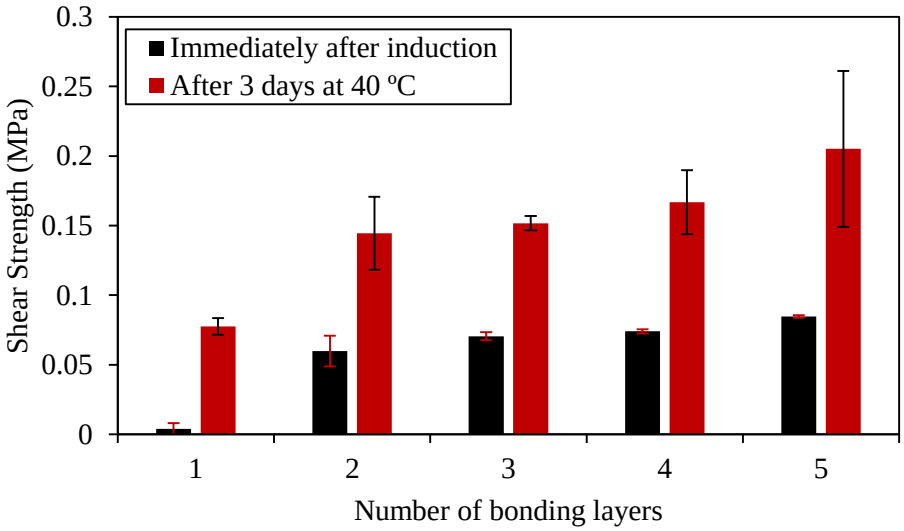
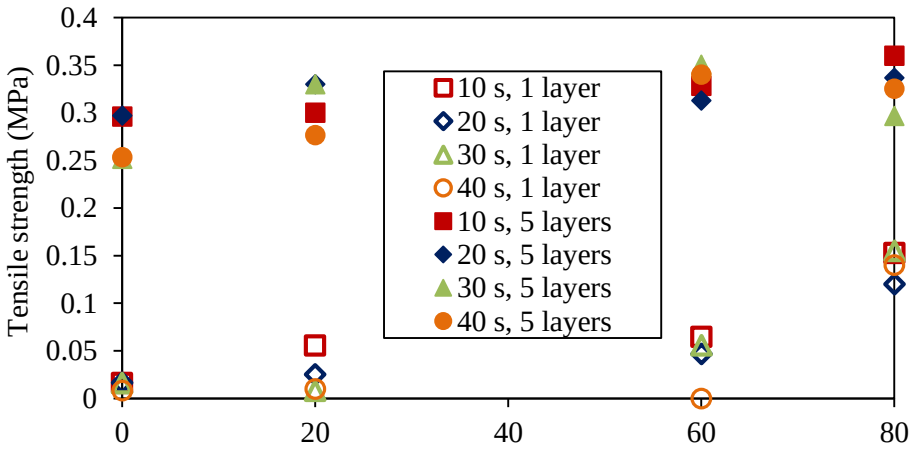


Figure 4.5 Shear strength of test samples after 3 days in water at 40 °C

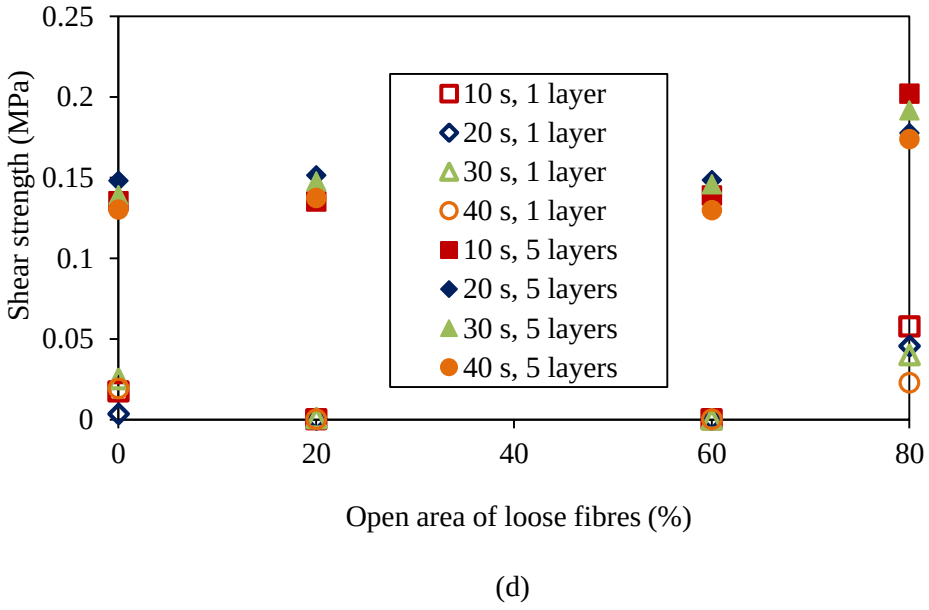
To prove this, the maximum shear bond strength that the test samples could reach was analysed by letting them rest in a water bath at 40 ºC for 3 days, after 20 sec exposure to induction heating. With this purpose, test samples containing 106g of loose steel fibres were used and the results are shown in Figure 4.5. It can be seen that in general, the strength of the test samples cured at 40 °C more than tripled that of test samples cured at 20 °C, which shows that the

strength gain is due to the compaction and drain of bitumen into the gap between the tile and the asphalt block, as it is explained in reference (Garcia, 2012).

In addition, Figure 4.6 (c and d) show that the strength increased with the open area of loose fibres. The reason for this is that steel fibres are simply heating elements that do not provide mechanical strength to the bituminous materials (Garcia et al., 2014). Moreover, as reported in reference (Garcia et al., 2013b), when an excessive amount of fibres was used, these made bundles and absorbed the bitumen in the space left between the fibres and would not allow it to coat the aggregates. The same phenomenon happened when only one bituminous layer and the maximum amount of fibres were used. As a consequence, the tile and the block were not bonded. On the other hand, when an excess of bitumen was provided, or the amount of fibres in the mixture was reduced the strength of the test specimens increased. Besides, it was obtained that the minimum amount of fibres used, 26 g per specimen that left 20% of the area open, was enough to produce the highest bonding strength, enough to cause fracture in the asphalt block instead of the bonding layer. In general, when the tensile strength was higher than approximately 0.33 MPa, the breaking happened through the asphalt block instead of the bonding layer.



(c)



(d)

Figure 4.6 (c) TST's and (d) SBT's strengths of test samples containing loose fibres according to open area of fibres

Figure 4.7 shows the shear and tensile strengths of test samples containing chicken wire. These test samples were made with four bonding layers. It can be observed that in average, the tensile strength was 3.26 times higher than the shear strength.

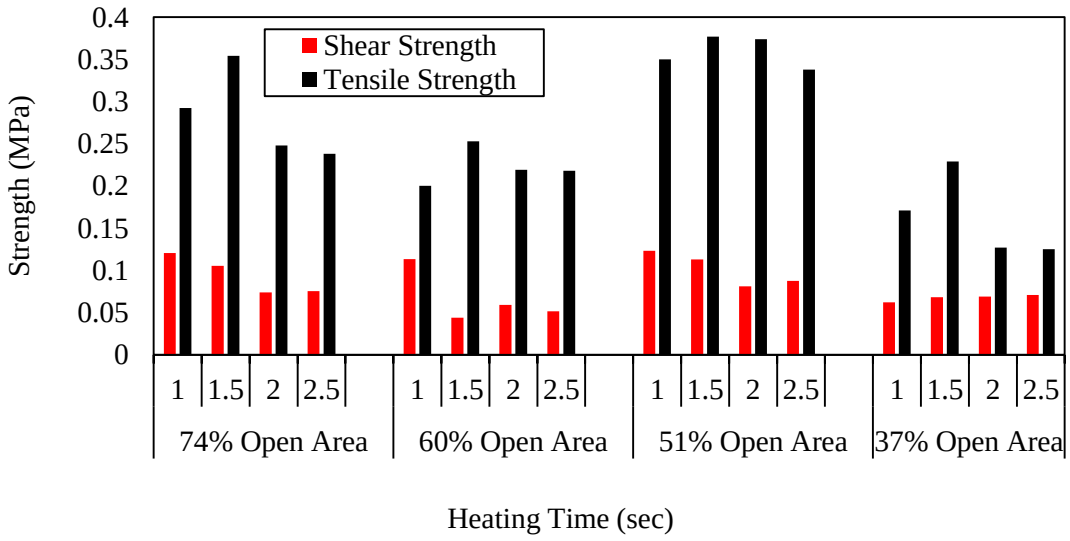


Figure 4.7 TST's and SBT's strength of test samples containing chicken wire according to the induction heating time

In general the shear strength was 54% lower than when loose fibres were used, while the tensile strength was 12% lower. The reason for this is that the loose fibres occupied a larger area and may have acted as a reinforcement. Moreover, as is in the cases where loose fibres were used, the heating time did not influence the total strength reached by the test samples and the strength increased with the open area of the chicken wire.

4.4. Comparison of the strength of asphalt tile technology with current conventional materials

Figure 4.8 shows the results from testing HMA and commercial CMA that were compared with asphalt tile materials with 80% open area and five bonding layers. The strength in this figure was depended on the tensile and shear strengths of asphalt tile that was plotted verse the strength of current materials for repairing the potholes.

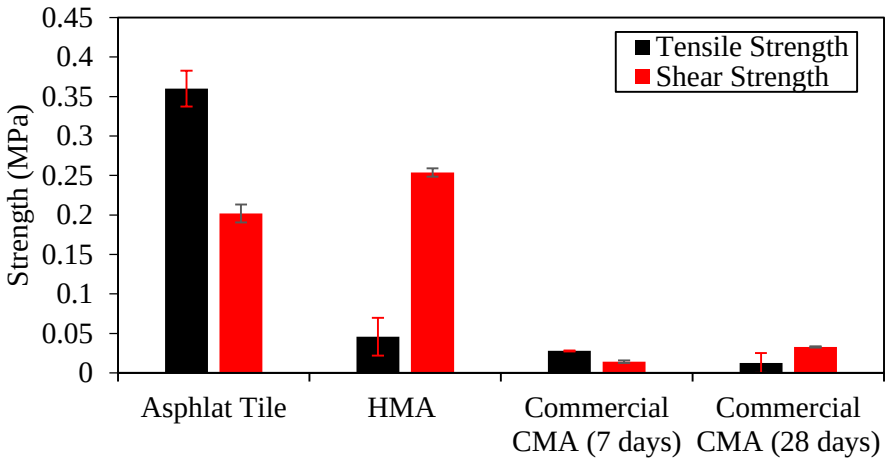


Figure 4.8 Strength of asphalt tiles with different types of conventional mixtures

From this figure, it can be seen that tensile strength of tile had higher strength than the strength of HMA and CMA materials. The performance of asphalt tile was 7.8, 12.9 and 9.5 times stronger than HMA, CMA cured for 7 and 28 days respectively. While the shear strength of HMA was slightly higher than tile was about 25% although the tensile strength of HMA was

much lower than the tile. Although, the strength of CMA was developed with curing periods but the results asphalt tile remain significantly better.

4.5. Wheel track demonstration

Figure 4.10 shows the deformation of the slab materials after testing them with the wheel track for 20000 cycles. It can be observed that test samples with tiles bonded using induction heating (see Figure 4.9) suffered 1.66 times more rutting than the original asphalt (0.73 mm vs 0.44 mm), while the deformation in test samples with cold mix asphalt was approximately 40 times higher than in the original test samples.

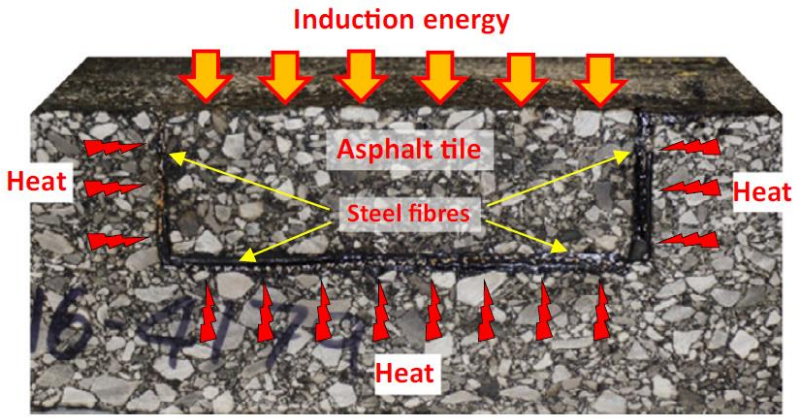


Figure 4.9 A pothole is filled with tile and bonded using induction energy

This high level of deformation was practically independent of the time curing the test samples, 1 day (rutting: 17.35 mm) or 7 days (rutting: 15.03 mm). Results for cold mix asphalt were similar to those reported in reference (Atkins, 2010).

The higher deformation resistance of asphalt mixture can be attributed to (1) the better packing of aggregates during prefabrication and (2) excellent bond between aggregates, binder, the tile and original pavement materials. While the materials in the tiles are very similar to those used in the original road and have been designed to resist traffic loads, cold mix asphalt needs time to harden and the material may have not been designed for heavy loading applications.

When we compare the durability of the potholes repaired filled with cold mix asphalt and with a tile, it can be observed that the last ones produced the most durable road. Consequently, it can be concluded that induction heating is a suitable method to repair potholes on-site. On the other hand, giving the potholes the shape of a tile may seem rather complicated, especially if loose stones or dirt penetrate between the tile and the old road. For that reason, future research must explore ways to create pothole repair materials that can easily adapt their shape and be heated using induction energy.

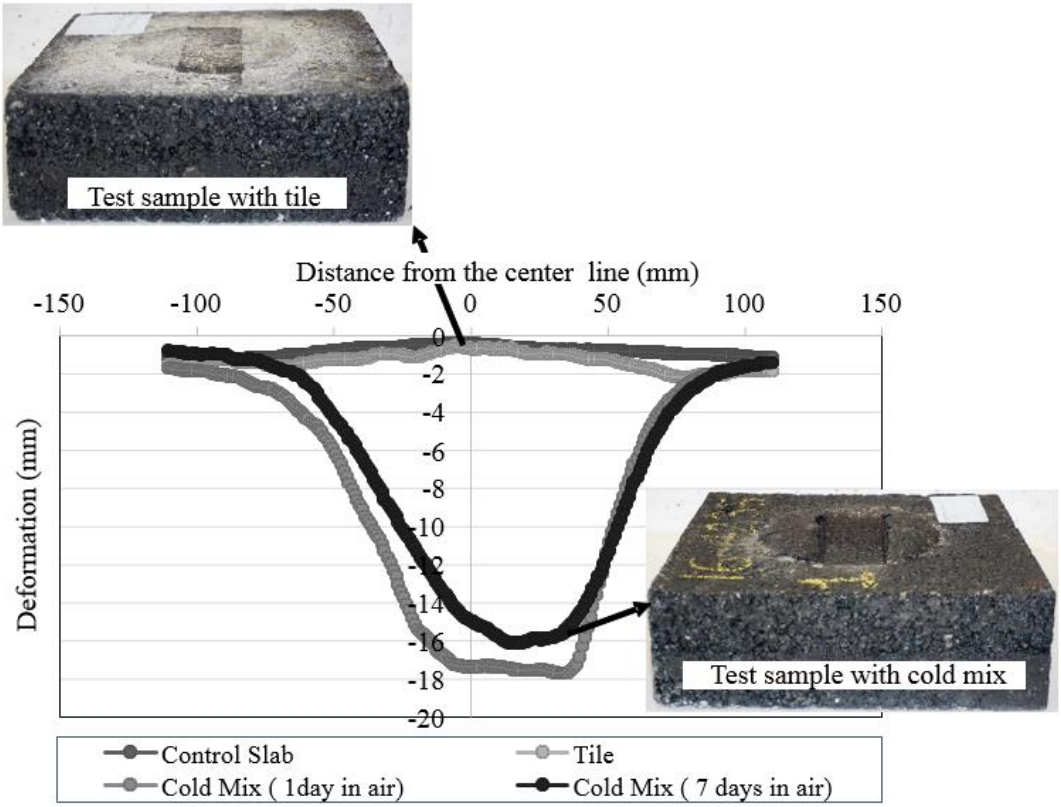


Figure 4.10 Rutting profile of different slabs at 25 °C after 20000 cycles

Chapter 5

Mechanical assessment of asphalt pellets

5.1. Introduction

In the present investigation, asphalt pellets containing bitumen, aggregates and steel grit have been prepared and tested as an energy-efficient and durable alternative to conventional road construction materials, such as hot and cold asphalt mixtures. Among other advantages, this technology is highly energy-efficient and could reduce traffic disruption and improve health and safety conditions for operators. Pellets are simply used in the road by laying, induction-heating and compacting them.

In this chapter, their heating potential under the action of electromagnetic induction, as well as volumetric and mechanical properties of the material resulting after compaction, such as tensile strength, shear strength and resistance to permanent deformation, were obtained to assess the proposed technology and compare it to hot and cold mix asphalt.

5.2. Temperature reached by asphalt pellets during induction heating

Figure 5.1 shows the maximum average surface temperature reached by (100*100*35) mm^3 pellets layers built on top of (100*100*50) mm^3 asphalt blocks (Figure 3.8), after 1, 1.5 and 2 min exposure to induction heating. Samples total mass were between 567 g and 917 g, depending on the steel content (from 5% to 45%). Although samples with different sizes and weights would present different heating rates, the effect of steel content can be assumed analogous. In addition, HMA and CMA were not exposed to induction heating, because the aim is to compare the results of pelletised asphalt to conventional paving materials. As can be

seen in Figure 5.1, the temperature during the first minute of heating increased steadily with the amount of steel grit in asphalt mixture, e.g. from 50°C with 5% steel grit content to 115.2°C with 45% steel grit content, which is comparable to results reported in previous research (Atkins, 2015).

On the other hand, it can be observed that there is a steady-state temperature at approximately 125°C above which the temperature of the test samples does not increase any more, independently of the heating time. The reason for this is that, above this temperature, the energy induced in the steel grit equals the total losses in the material due to energy radiation and conduction to the air and into the pellets (Gomez-Meijide et al., 2016).

It is important to remark that the induction heating process must be calibrated to reach temperatures that are high enough to allow the compaction of pellets, but not so high that the binder will be chemically damaged. In this case, short heating periods (2 and 1 min respectively) were applied and lower temperatures were reached (maximum about 120 ºC). Hence, no significant effect of induction heating on bitumen rheology is expected.

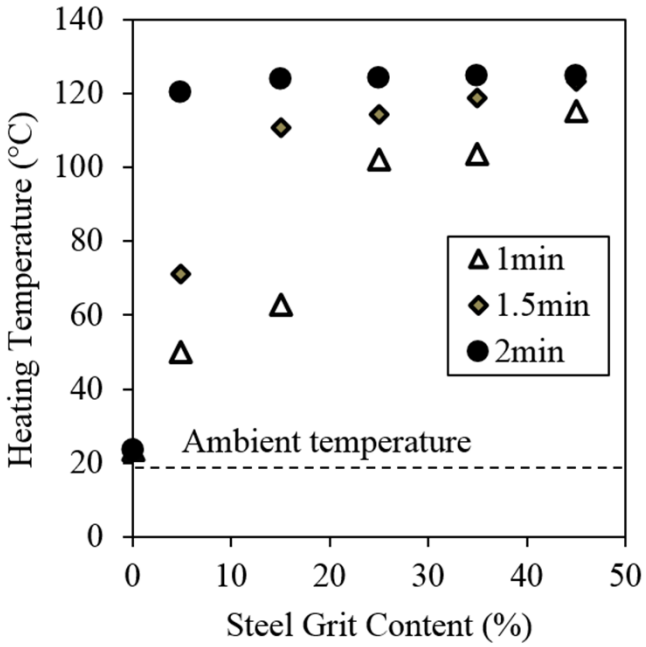
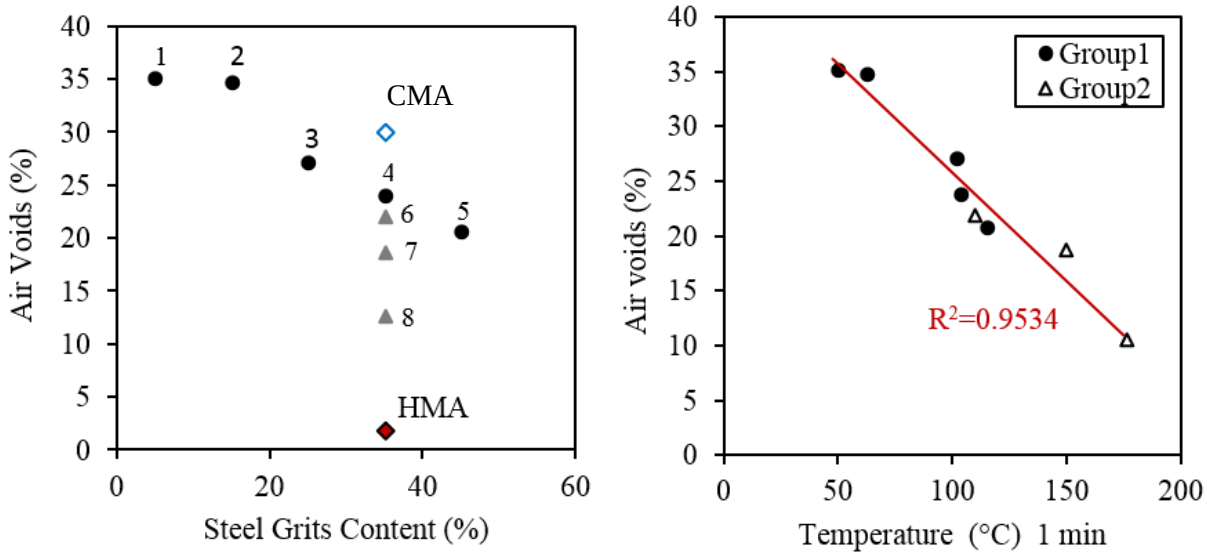


Figure 5.1 Effect of steel content on the heating temperature of asphalt pellets (Group 1)

5.3. Volumetric properties of asphalt pellets samples

Figure 5.2 (a) shows the air void content (AVC) of asphalt blocks whose top layer was built with pellets as a function of the steel grit content. In pellets from Group 1 (materials 1 to 5), the air void content reduced with the amount of steel grit particles in the pellets, e.g. the air void content decreased from 35.1% AVC with 5% of steel grit to 20.7% AVC with 45% of steel grit. The reason for this is that the maximum temperature reached during compaction was higher in mixtures with higher steel grit content: e.g. 50 ºC for mixtures with 5% steel grit and 115.2 ºC for mixtures with 45% steel grit (see Figure 5.2 (b)). Therefore, the viscosity of bitumen decreased and bitumen worked as a lubricator during the compaction process. Because of the reduction of air voids content, the thermal conductivity and specific heat capacity of pelletised asphalt increased, as shown in reference (Hasan et al., 2016). Also it is expected a better mechanical performance and resistance to water damage (Tarefder and Ahmad, 2015).



(a) (b)

Figure 5.2 Effect of steel content on air voids of the layer made of asphalt pellets (a) and air void content versus compaction temperature of different mixtures (b)

Furthermore, the air void content in test samples containing pellets of Group 2 (materials 6 to 8) reduced linearly with the amount of bitumen in the pellets (see Figure 5.2 (a)), e.g. AVC reduced from 20.7% AVC with 10% of bitumen to 12.51% AVC with 25% of bitumen. The same happened with the temperature which increased linearly with the air voids content, e.g. 50 ºC for mixtures with 35.1% AVC vs 176 ºC for mixtures with 12.51% AVC.

In addition, in Figure 5.2 (b) it can be observed that the temperature and air void content were linearly related and independent of the type of amount of steel of grit or bitumen in the mixture. AVC reduced with the increase of the amount of bitumen and steel grit particles, thus the conclusion from this section is that the amount of these two components in the pellets has to be maximised as far as the positive economic benefit of this material allows.

5.4. Tensile strength

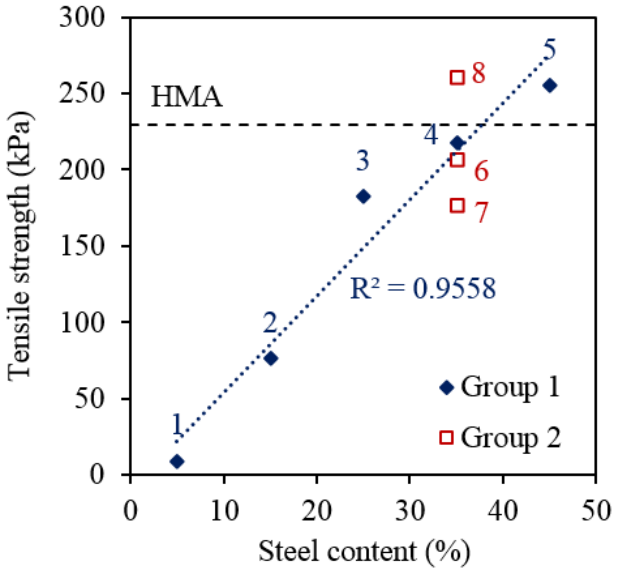


Figure 5.3 Tensile strength of test samples containing asphalt pellets

Tensile strength results are shown in Figure 5.3. As can be seen, there is a direct correlation between strength and steel content, being 22 times higher for samples with 45% (255 kPa) than

for samples with 5% (9 kPa) steel content. These results are clearly affected by the improved compaction level obtained by increasing the metal content and the consequent manufacturing temperature (see Figure 5.1 and Figure 5.2).

Changes in bitumen content in test specimens of Group 2, did not influence the tensile strength as much as the steel grit content as, in all the tests conducted, tensile strength values were within the range of 170 to 260 kPa. For example, in Group 2, the strength obtained for test samples with 25% bitumen content (260 kPa) was 19% higher than for test samples with 20% bitumen content (218 kPa).

In order to assess the significance of the correlation between tensile strength results and both steel and bitumen contents a two-factor analysis of variance (ANOVA) was carried out. This type of statistical test estimates and compares the amount of variance between, and within, samples through F-tests. Hence, it is widely used in the analysis of comparative experiments, when only the difference in outcomes is of interest. The analysis assumes the independence, normality and homogeneity of the variances of the residuals. Steel and bitumen contents are independent but, in order to check normality and homogeneity of variances, a statistical Shapiro-Wilk test (sample size $N<50$) and a Levene test were carried out respectively. The p-values obtained were $p_{normality} = 0.138$ and $p_{homogeneity} = 0.080$. As both values are higher than 0.05, the null hypothesis H_0 of normality and homogeneity could not be rejected and the ANOVA could be undertaken. From the ANOVA test, the statistics obtained were $t_{steel} = 4.264$ and $t_{bitumen} = 0.423$, with associated p-values $p_{steel} = 0.029$ and $p_{bitumen} = 0.740$. As $p_{steel}<0.05$, it can be concluded that the steel content affects, at a significance level of 95%, the tensile strength results, while the bitumen content does not.

The average results of tensile strength obtained for mix number 4 were compared to those of HMA and CMA after 1, 7 and 28 curing days, as can be seen in Figure 5.4, as they all had the same steel and bitumen contents. The performance of asphalt pellets with only 10% of bitumen

and 35% of steel was 37 times stronger than CMA cured for 1 day, 36 times stronger after 7 days and 5 times stronger after 28 days. Thus, even for long curing periods, when practically all the strength of CMA is developed, pelletised asphalt gave significantly better results.

On the contrary, in Figure 5.4, it can be seen that the performance of pelletised asphalt is 5% lower than HMA. As explained before, the lower compaction level, resulting from a lower compaction temperature, is probably behind such behaviour.

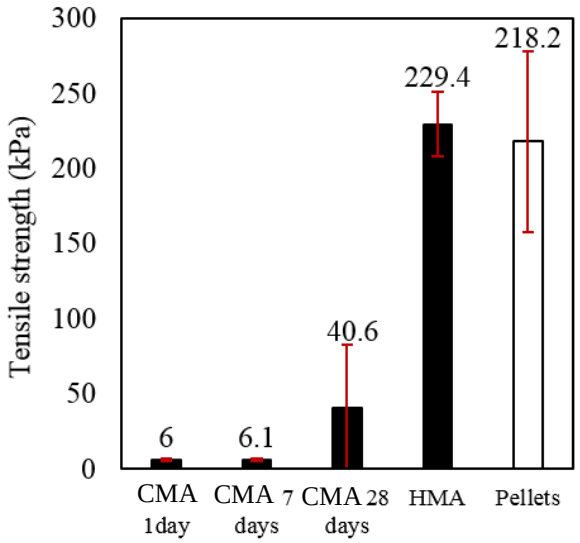


Figure 5.4 Tensile strength of test samples with different types of mixtures

Taking the reference tensile strength of 229.4 kPa obtained for HMA, it can be observed from Figure 5.4 that the tensile strength of pellets samples manufactured with the highest bitumen and steel grit contents exceeded such value. As a result, pelletised asphalt samples failed through the bottom HMA block, instead of through the interface between layers or through the pellets layer (Figure 5.5). In other words, in a hypothetical repaired pothole, not only the strength of the filling material but also the adhesion between this and the pothole surface, would be stronger than the original asphalt in the road.

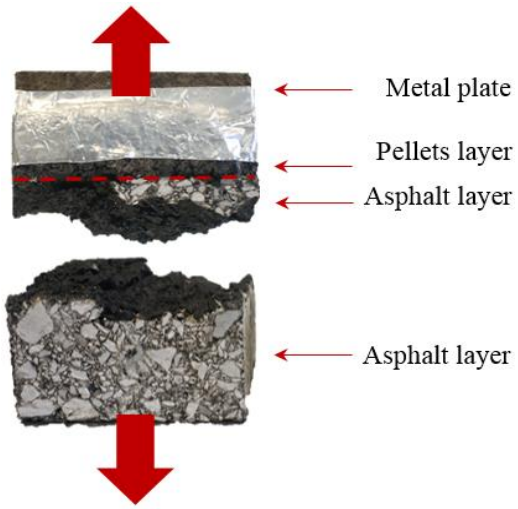


Figure 5.5 Sample failed through the bottom asphalt block instead of through the interface between layers during the tensile strength test

5.5. Shear strength

Variations of shear strength in asphalt pellets samples built with different steel and bitumen contents can be seen in Figure 5.6. The shear strength tends to strongly increase with the steel content, as the temperature reached during induction heating will be higher. For example, the strength of pelletised asphalt with 45% steel grit content is 7 times higher than that of asphalt with 5% steel grit content. In addition, a higher bitumen content increases the asphalt mixture strength, as can be observed in the shear strength values of mixes 7 and 8 that are far from the general trend produced by mixes 1 to 5.

It must be highlighted again, that all the specimens made with 25% bitumen content and approximately half of the samples made with 20% bitumen content failed through the bottom block, instead of through the interface or pellets layer. This suggests that the strength of the pellets layer and the adhesion between asphalt layers may be stronger than the original asphalt used to build the road.

As in the tensile strength section, statistical Shapiro-Wilk and a Levene tests were carried out on shear strength results obtaining $p_{normality} = 0.300$ and $p_{variable} = 0.226$. As both values are

higher than 0.05, it can be assumed that results follow the Normal distribution and have homogeneity of variances. The statistics obtained by the 2-way ANOVA were t_{steel} = 9.958 and $t_{bitumen}$ = 2.864, with associated p-values p_{steel} = 0.002 and $p_{bitumen}$ = 0.090. Again, only p_{steel} is lower than 0.05, showing that only steel content can be considered to affect shear strength results at a significance level of 95%. Nevertheless, in this case, the effect produced by the bitumen content can still be considered at a significance level of 90%.

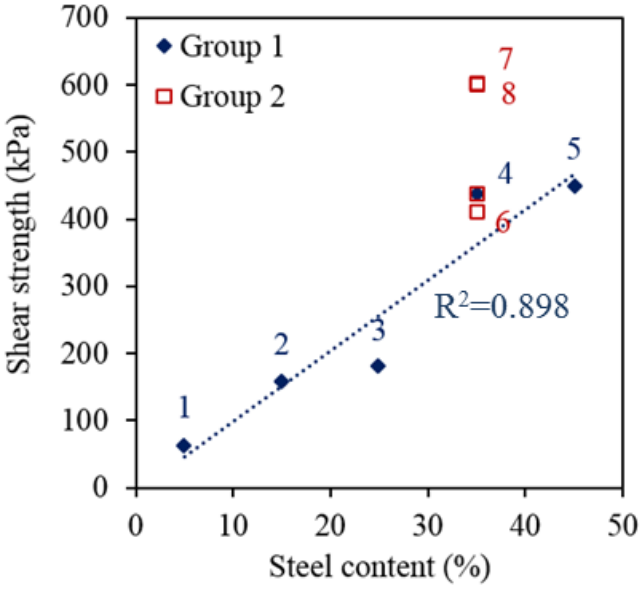


Figure 5.6 Shear strength of test samples containing asphalt pellets

Compared to pellets samples (Figure 5.7), it can be seen that the strength of CMA is 70% lower after 1 curing day, 40% lower after 7 days and still 16% lower after 28 days. However, the shear strength of asphalt pellets was 30% lower than HMA. Thus, asphalt pellets behave better than CMA but, due to their less-effective compaction, results are poorer than HMA.

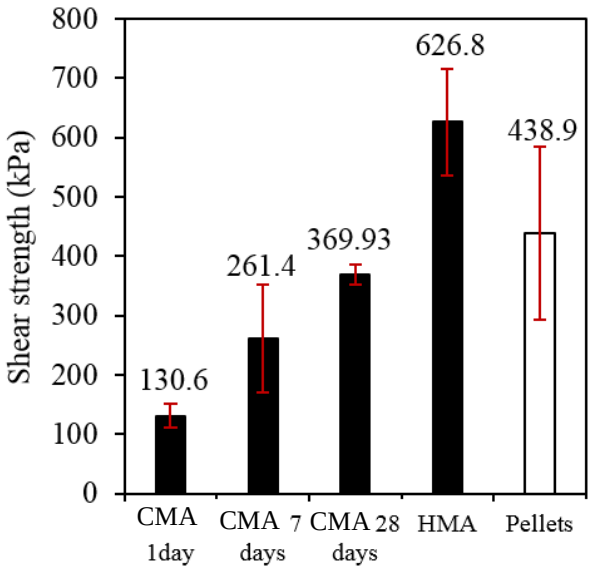


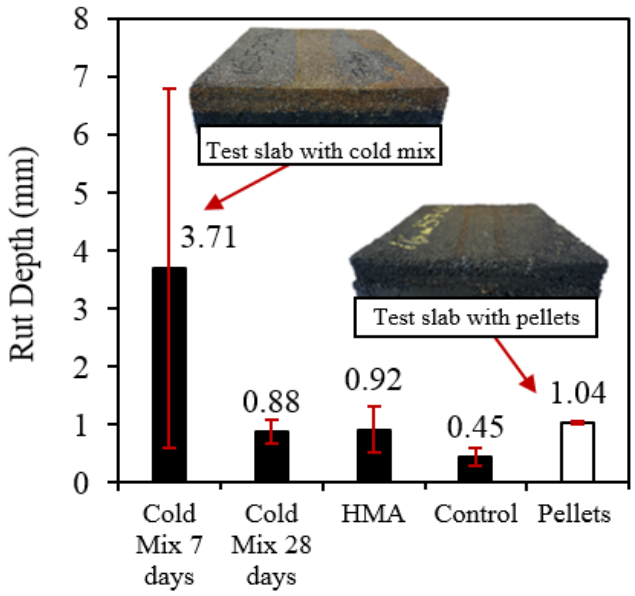
Figure 5.7 Shear strength of test samples with different types of mixtures

5.6. Wheel track demonstration

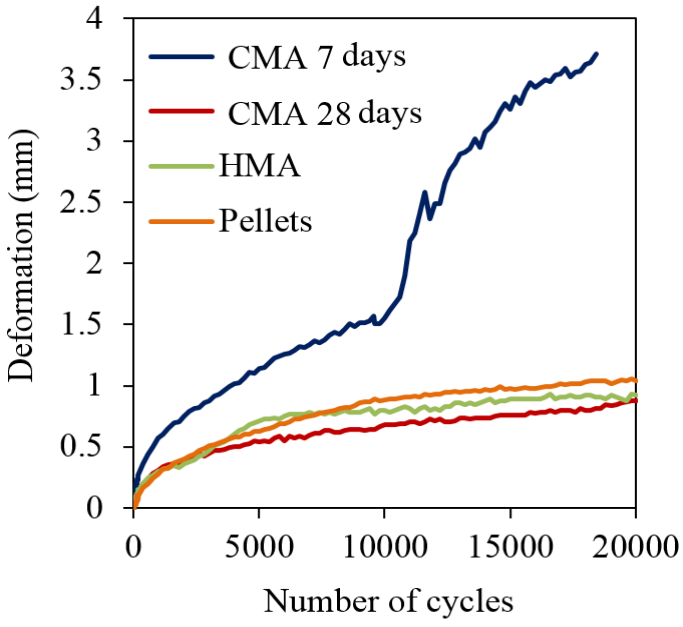
Rutting behaviour under simulated traffic conditions was examined through wheel-tracking tests for test samples composed of a bottom layer of conventional HMA and a top layer of different repairing materials, including HMA. The purpose of this research was to simulate the combination of old asphalt at the bottom of a pothole and the filling material. In addition, to simulate the performance of a completely repaved road, control samples made of one single HMA layer were tested.

In Figure 5.8 (a), the maximum deformations at the end of the rutting test are shown. As can be seen, pellet samples (1.04 mm) performed similarly to common repairing materials, such as HMA (final deformation 0.92 mm) and CMA after 28 curing days (0.88 mm), with differences between them in the range of 0.2 mm at the end of the test (20,000 cycles). In addition, CMA needed long curing times in order to obtain those values as, after 7 days, the permanent deformation (3.71 mm) was more than 4 times higher than that after 28 days. Results of CMA were similar to those published in reference (Atkin 2015). On the contrary, asphalt pellets

produced very similar resistance to HMA within the time needed to cool down the material at ambient temperature.



(a)



(b)

Figure 5.8 Deformation at the end of wheel track test observed at the midpoint of the samples (a) and evolution of deformations over the load cycles (b) for the studied materials

In Figure 5.8 (b) the curves of accumulated deformation over the number of loading cycles are shown. CMA cured for 7 days collapsed after around 10,000 cycles, registering a sharp increase in permanent deformation. On the other hand, CMA cured for 28 days, HMA and pellets samples all performed very similarly, with an initial densification behaviour (curve with decreasing slope) followed by a linear stage with constant increasing rate. The slope of the tangent line during this linear stage gives an idea of the speed at which the damage is accumulated in the material. For the present study, this was evaluated by dividing the increment of deformation between cycles 10,000 and 15,000 by the elapsed number of cycles (5,000 cycles). The results obtained for CMA (28 days), HMA and pellets were respectively 16.4 μm/1000 cycles, 18.1 μm/1000cycles and 19.5 μm/1000 cycles. All of them within the range of 3.1 μm every 1000 cycles. This means that the evolution of rutting performance over the loading cycles is very similar among these materials. As a consequence, it is not expected that the properties of pellets layers decrease with time faster than those produced by any other material commonly used in road maintenance.

Based on these and the other results commented on in previous sections, it can be deduced that the reasons for the high deformation resistance of pellets layers involve: (1) excellent bond between aggregates (mastic cohesion); (2) good adhesion between pothole surface and pellets layer; (3) high packing level of solid particles with reduced amount of interstitial air voids; and (4) satisfactory performance of steel grit as aggregate particles within the mix. The performance of pelletised asphalt is similar to competitor materials without the need for waiting long curing times or heating aggregates and bitumen at high temperatures before placing the material into the pothole.

Finally, it can also be seen that the deformation registered for pelletised asphalt after 20,000 cycles (1.04 mm) was still higher than that obtained for the control mix (0.45 mm). As commented in previous sections, these results could be improved by increasing the bitumen

content and compaction temperature, which can be obtained through higher steel grit content or longer heating times. However, both solutions could increase implementation costs.

For all the reasons mentioned above, the authors believe that asphalt pellets are strong competitors among current repairing techniques for isolated and punctual potholes but need further optimisation before they are offered as a material for major road maintenance operations, such as road milling and re-paving.

5.7. Indirect tensile stiffness modulus

Table 5.1 shows the stiffness of the different asphalt mixtures starting from dry condition at room temperature and exposure to water at 40 ºC for durations about 3 days. Each value represents the average of three replicate specimens. Generally, the effect of moisture conditioning has led to significant reduction in mixture stiffness. For example, the stiffness of the pellets mixtures changed from 3762.8 MPa to 2806.6 MPa after 3 days of moisture conditioning, a reduction of about 24%. Although pellets mixtures have the highest values in stiffness compared with mixtures with HMA and CMA. For examples, the stiffness of HMA and CMA after 7 days were lower than the stiffness of the pellets material about 63% and 79% respectively in the moisture condition.

The ITSM values of HMA in moisture condition are higher than CMA after 7 and 28 days whereas the ITSM value of HMA in dry condition are less than CMA after 28 days. That may be related to cold mixes develop cohesion and strength depending on mixture components and curing condition (Swaroopa et al., 2015).

Table 5.1 ITSM of asphalt mixtures in different conditions

Type of mixture	ITSM in dry condition 20 ºC (MPa)	ITSM in moisture condition (MPa)
Pellets	3762.80	2806.60
HMA	2754.63	1031.13
CMA (7 days)	2447.00	599.67
CMA (28 days)	3782.38	972.13

From Figure 5.9 shows ITSM percentages with various asphalt mixtures. As can be seen that the behaviour of pellets samples compared to other mixtures where the stiffness modulus percentages of pellets were about 74.6% that was the highest value compared to HMA and CMA after 7 and 28 days that were 37.4%, 25.7% and 24.5% respectively. This indicates that asphalt pellets have acceptable resistance to moisture damage. This material is better asphalt material for road maintenance in adverse climate condition.

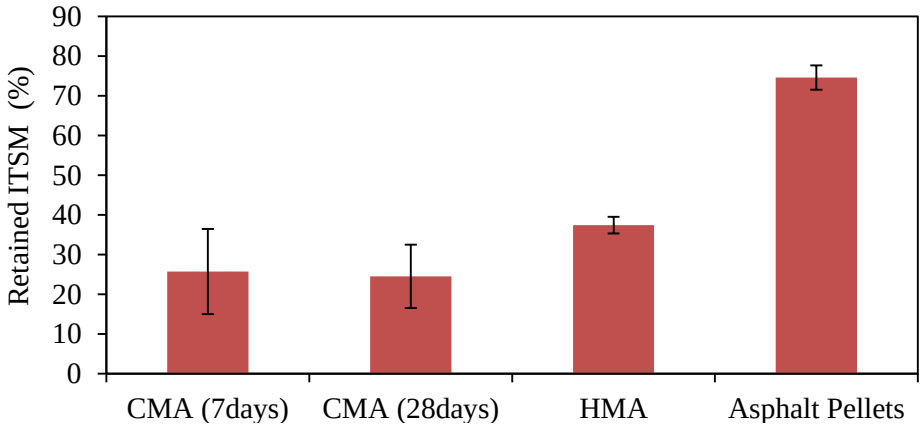


Figure 5.9 ITSM ratios of test samples with different types of mixtures

Chapter 6

Mechanical assessment of binder pellets

6.1. Introduction

In the present research, an innovative patching material to repair potholes is developed, evaluated and compared to current patching materials. Binder pellets are composed of bitumen, steel wool and a protective shell to avoid them sticking to each other. Such pellets can be packed, stored, and transported like a simple aggregate. Once on-site, the required amount of pellets is heated and mixed with cold aggregates in a portable mixer with an electromagnetic induction generator.

In this chapter the heating, volumetric and mechanical properties (indirect tensile, tensile and shear strength, as well as resistance to permanent deformation) of the resulting material were assessed and compared to conventional patching materials.

6.2. Type of shell

Figure 6.1 (a) shows the indirect tensile strength of cylindrical samples of asphalt made of pellets (50% bitumen / 50% steel wool) without shell and with the different covers as explained in section 3.4.1. From the results of this figure, it can be observed that the type of shell does not affect significantly the mechanical properties of the compacted material. Hence, although the maximum strength (1.615 MPa) was reached by pellets covered with alginate-calcium chloride polymer and filler, the truth is that the strength of pellets without any cover was 1.582 MPa, only 2% lower. On the other hand, Figure 6.1 (b) shows that the use of alginate-calcium

chloride shells increases the air voids content, from values of 3.35% and 3.32% to 6.26% and 5.87%, which is a significant difference. The evaporation of water from the alginate-calcium chloride shell, leaving empty voids, might be the main reason behind this behaviour.

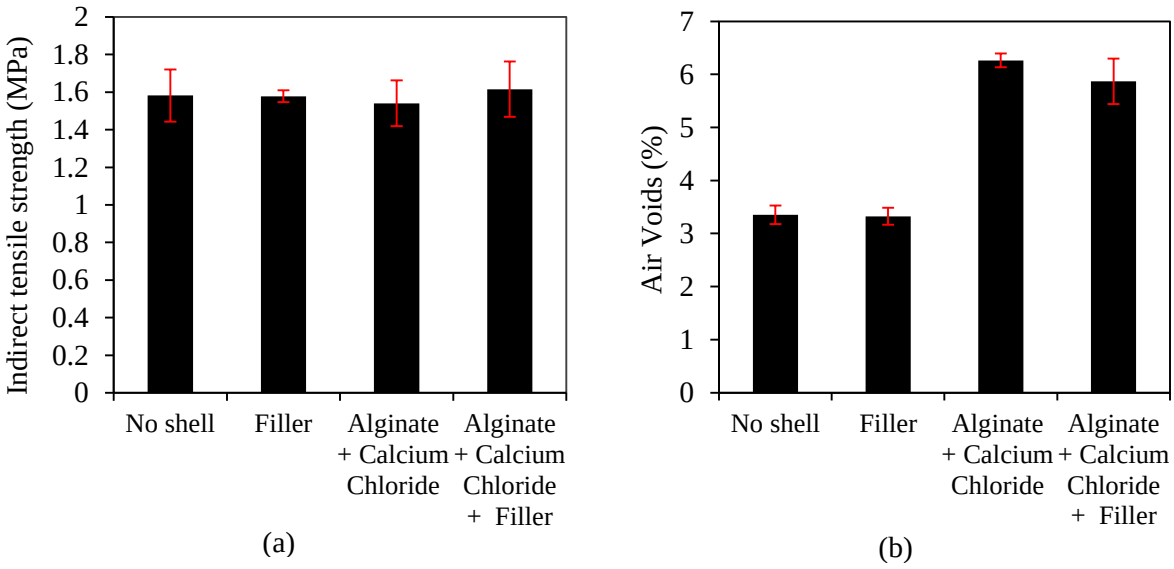


Figure 6.1 The relation of different shells for pelletised asphalt with (a) indirect tensile strength and (b) air voids

Although as seen before, the type of shell does not affect significantly the strength of the resulting material, in Figure 6.2 it can be seen that it is a key factor directly related to the storability of the pellets. Pellets without any protection and pellets just covered in limestone filler formed a consolidated block during the 7 days of the test at 20ºC inside the cylinder. Hence, when this was removed, the shape of the set remained practically unaltered. On the contrary, when an alginate-calcium chloride protective shell was added, a significant amount of pellets crawled down, leaving the top surface about 30 mm lower than before removing the cylinder (25% of total height). Finally, when both alginate-calcium chloride shell and filler were used, the collapse of the sample was practically complete, with a height loss of 100 mm. This indicates that this is the most suitable method by far to ensure the store-stability of the

material at ambient temperature, although as seen above, it will tend to increase the air voids content and likely the costs.

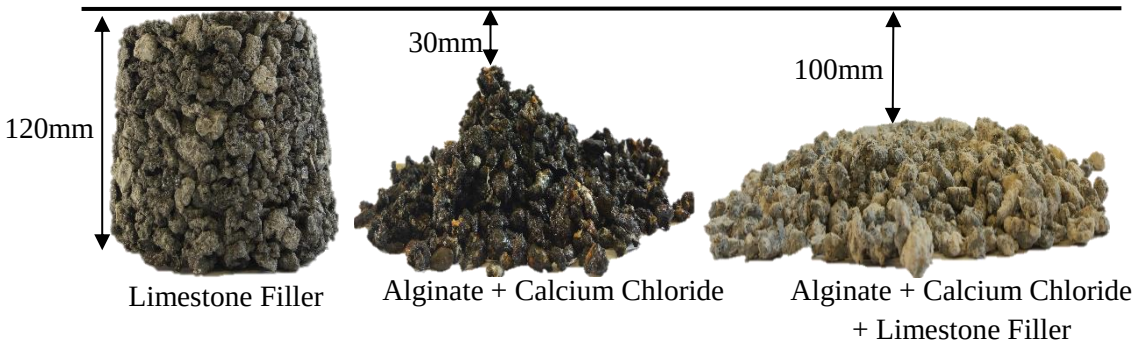


Figure 6.2 Results of storage-stability test obtained by pellets with different protective shells

6.3. Heating potential of binder pellets

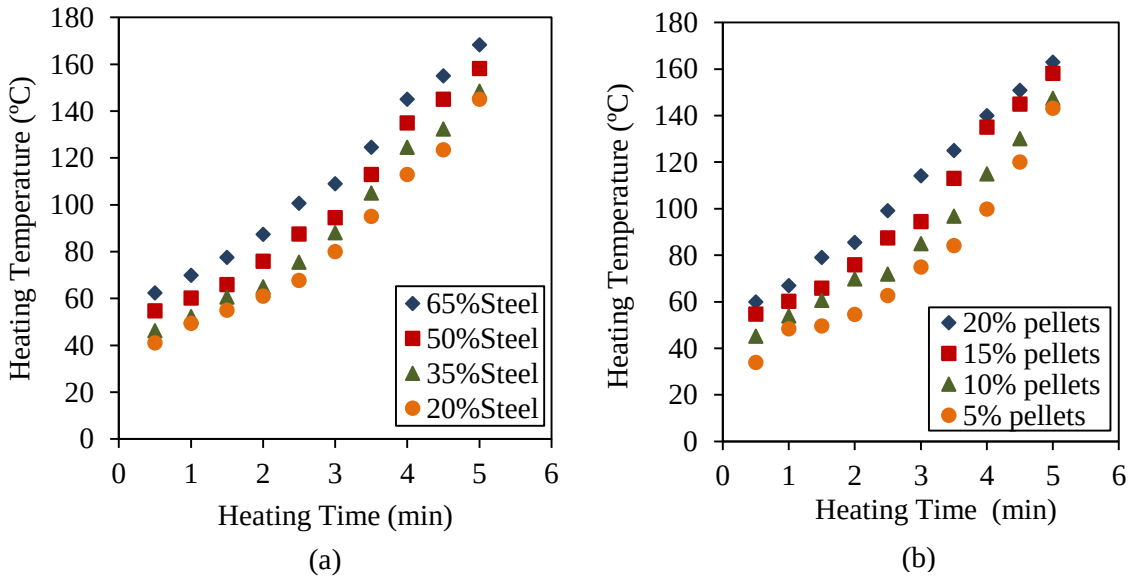


Figure 6.3 Maximum temperatures of pelletized asphalt depending on (a) the content of steel wool and (b) the content of pellets

Figure 6.3 shows the heating temperature reached by the mix of pellets and aggregates during the blending process in the crucible and under the action of the electromagnetic induction. As

explained in section 3.4.1, the test was carried out on mixes: (1) containing a fixed amount of pellets but these containing different amounts of steel (Figure 6.3 (a)), and (2) mixes containing the same type of pellets but in different amounts (Figure 6.3 (b)).

In both cases, it can be seen that the correlation between heating time and temperature is quasi-exponential where the curvature reduces when the steel or pellets contents increase. Thus, the curvature is more noticeable in the samples, whose heating capacity is lower (mixes with a low amount of pellets or containing pellets with a low steel content). For the mixes with the greatest heating potential, the resulting curves were practically linear.

In addition, it can be also seen that, for any given time, the temperature of the mix clearly increases with the metal content. Hence, samples made with pellets containing 20% steel, reached 41ºC and 145ºC after 1 min and 5 min respectively. On the other hand, mixes made with pellets containing 65% steel, reached, for the same times, temperatures of 62ºC and 168ºC. In average terms, the fact of increasing the steel content, from 20% to 35%, 50% and 65% produced increases of the temperature of 8.1%, 19.2% and 32.4%.

In an analogous analysis, it can be seen how the fact of increasing the amount of pellets from 5% to 10%, 15% and 20%, produced increases in the average temperature of the mix of 13.5%, 28.3% and 40.4%.

Both experiments show that in order to increase the heating potential of the mix, it is fundamental to increase the steel content. This can be obtained through any of the previous methods; that is, either increasing the steel content within the pellets to be used, or by adding more pellets to the mix.

6.4. Volumetric properties of binder pellets samples

Figure 6.4 (a) shows the air void content of asphalt samples depending on their pellets content. In general, the air void content reduced with increasing amounts of the pellets, from 26.8 % with 5% of pellets content to 3.4% with 20% of pellets. This is due to: (1) an increase in the bitumen content which can fill the pores, and (2) a higher mixing and compacting temperature (explained in Figure 6.3 (b)), which reduces the viscosity of the binder allowing it to flow better and reach higher compaction levels.

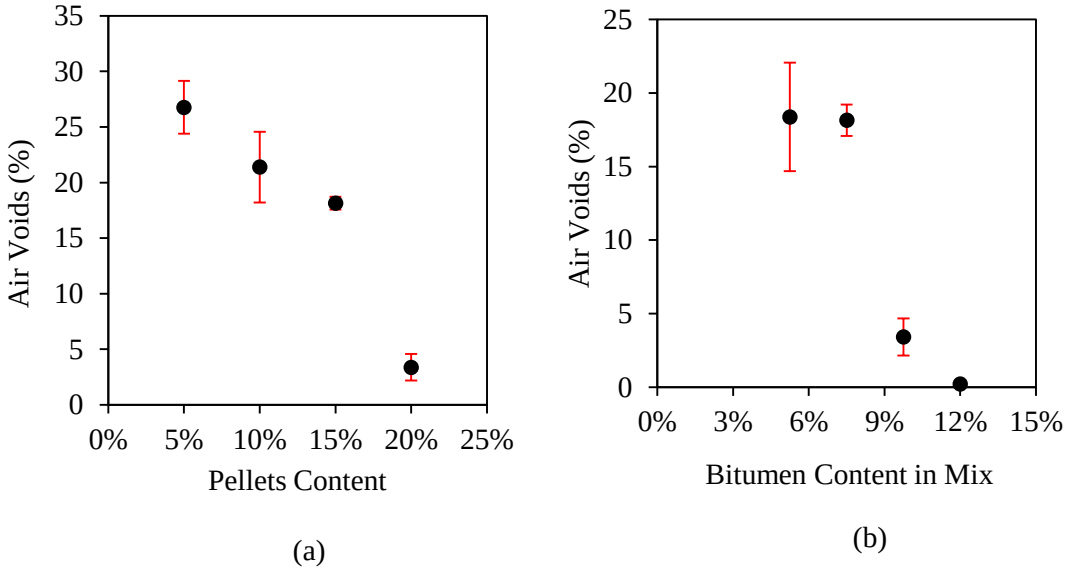


Figure 6.4 Illustration of air void contents of different (a) pellets content and (b) different bitumen content in binder pellets mixtures

In addition, Figure 6.4 (b) shows the results of samples, all containing the same amount of pellets, but changing the bitumen content of these. It can be seen that by using pellets richer in bitumen, the air voids content also decreases very sharply despite, in this case, lower steel contents being used and, as a consequence, also lower mixing temperatures. Hence, mixes made with 12% of bitumen and 3% of steel by total weight of mix, produced very dense mixes with 0.22% air voids content. On the other hand, mixes containing 5.25% bitumen and 9.75% steel produced porous mixes with 18.37% air voids.

For these reasons, it can be concluded that air voids content can be decreased by increasing the amount of pellets and, as a consequence, the mixing and compaction temperature. However, more important than that, is to increase the amount of bitumen in the mix, which can be produced by either increasing the amount of pellets or by increasing the bitumen content in these.

6.5. Tensile strength

Figure 6.5 (a) shows the results of the tensile test obtained by samples containing different amounts of pellets. For this test, all the pellets used were composed of 50% bitumen and 50% steel wool. It can be observed that the tensile strength increased sharply when the amount of pellets was higher than 15%, which can be translated into 7.5% of bitumen and 7.5% of steel in total mix. With lower contents, the material did not have the consistency necessary to actually produce significant values. However, after these critical contents, the strength reached values around 0.35-0.40 MPa.

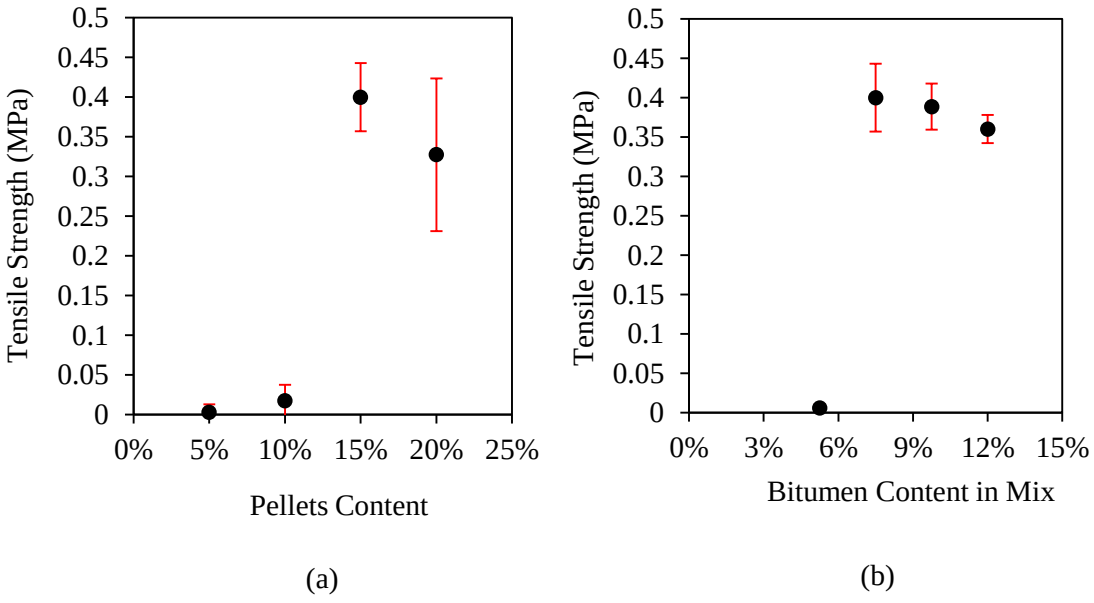
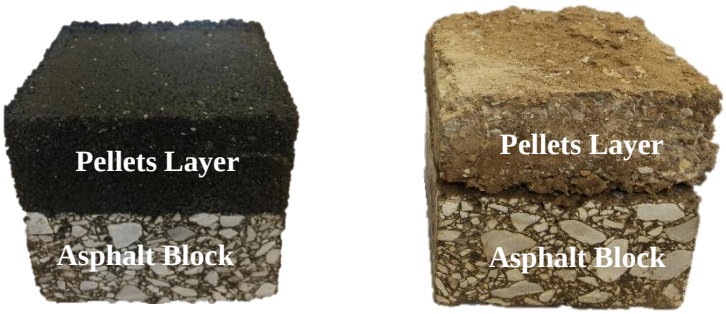


Figure 6.5 Tensile strength of samples with (a) different pellets content, and (b) with pellets containing different bitumen contents

Figure 6.5 (b) shows the results of samples, in which the content of pellets was fixed to 15% of the total mix but pellets with different bitumen/steel contents were used. Again, it can be seen that very similar tensile strength values, around 0.35-0.40 MPa, were obtained once the critical value of 7.55% bitumen content was reached. Figure 6.6 shows the picture of two samples made with pellets 50% bitumen–50% steel, and 35% bitumen–65% steel. In the first case, (a), the total bitumen content in the mix was 7.5%, while in the second, (b), the bitumen content was 5.25%. As can be seen, the cohesion of the second sample, whose bitumen content is lower than the critical value of 7.5%, is clearly poor, the low test results (0.006 MPa against 0.39 MPa) not being surprising.



7.5% Steel Wool /7.5% Bitumen (a)

9.75% Steel Wool /5.25% Bitumen (b)

Figure 6.6 Pictures of samples were made with different pellets

Taking previous considerations into account, it can be concluded that in order to optimise the asphalt mix from a mechanical and economic point of view, the content of binder pellets, as well as the bitumen content of these, must be the minimum possible, as long as the critical bitumen content, which ensures the cohesion of the material, is exceeded (in this case 7.5% bitumen content).

6.6. Shear strength

Analogously to the previous case, Figure 6.7 (a) shows the results of shear strength of asphalt samples, which were manufactured either with a fixed type of pellet (50% bitumen / 50% steel) but different amounts of pellets, or with the same amount of pellets (15% of total mix) but containing these different amounts of bitumen.

As can be seen, the results are completely in line with those extracted from tensile test. Hence, the maximum strength (1.16 MPa) was obtained again for a pellets content in the mix of 15%, which corresponds to a bitumen content of 7.5% and a steel wool content of 7.5% by weight of total mix.

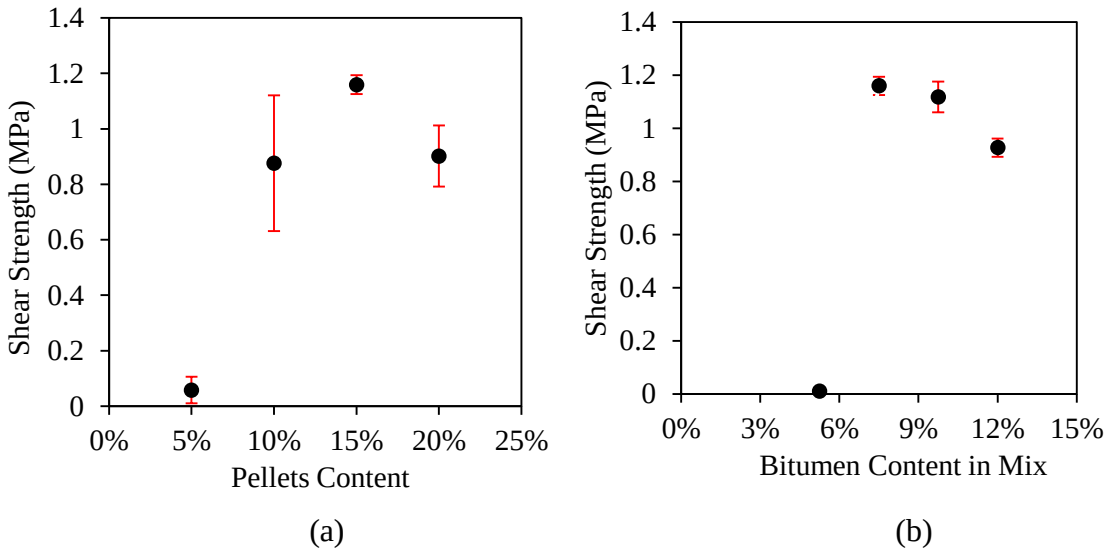


Figure 6.7 Shear strength of (a) different pelletized asphalt content and (b) different bitumen content in binder pellets mixtures

In Figure 6.7 (b), it is confirmed again that mixes with bitumen content lower than 7.5% did not have the cohesion necessary to produce any significant results. In addition, after this point, increases in bitumen content and, consequently, reductions in steel content and mixing temperature, produced reductions in strength.

For these reasons, the asphalt mix can be optimised by minimising the amount of pellets and bitumen in the mix, as long as a minimum value, which ensures the cohesion of the material is exceeded (in this case 7.5% bitumen content).

6.7. Comparison between the mechanical performance of pelletised asphalt mixes and current patching materials

Figure 6.8 shows a comparative analysis between the mechanical performance of asphalt made with pellets and the control mixes of HMA2 (8% binder content, 2 mm aggregates maximum size), HMA10 (5% binder content, 10 mm aggregate maximum size), and a commercial CMA (5% residual bitumen content and 6 mm aggregate maximum size) after 7, and after 28, curing days. In the figure, the results of tensile and shear stress obtained by these mixes were divided into the results obtained by pellets samples. Hence, if the result is higher than one, it means that the material is stronger than asphalt made of pellets, while if it is lower than one, then the performance of the material is worse.

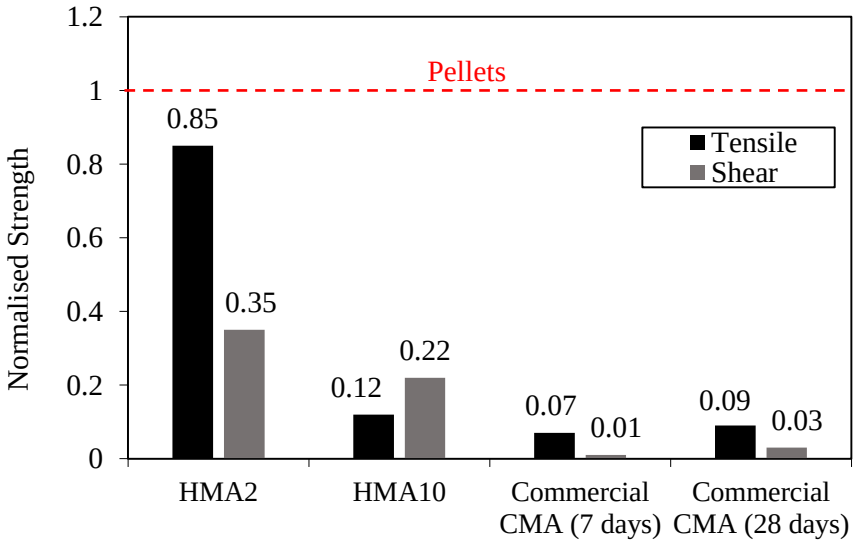


Figure 6.8 Normalised strength ratio of the samples made of different materials

In general, it can be seen from this figure that all control mixes had lower strength (tensile and shear) than the strength of binder pellets materials. The tensile and shear strengths of HMA2 were 7 and 1.6 times stronger than HMA10, and 9.4 and 11.6 times stronger than CMA even cured for 28 days. This was expected, as HMA2 had the lowest air voids content (6.1% against 19.46% of HMA10). Although the strength of CMA increased over the curing time, results were never comparable to those obtained by binder pellets.

Finally, the wheel tracking test was carried out on slabs composed of a bottom layer of conventional HMA and a top layer of the previous repairing materials. The objective of this experiment was simulating the performance of a repaired pothole, which was filled by different materials under the action of traffic loads. For the case of HMA10, results could be also understood as the performance of a new road, right after its construction. Figure 6.9 shows the rutting behaviour registered at the midpoint of the slabs after 20,000 loading cycles. Again, in order to facilitate the comparison, the results were divided by the results obtained by pellets. Unlike the previous case, now when the values are higher than 1, it means that the rutting was higher and, as a consequence, the mechanical behaviour was poorer.

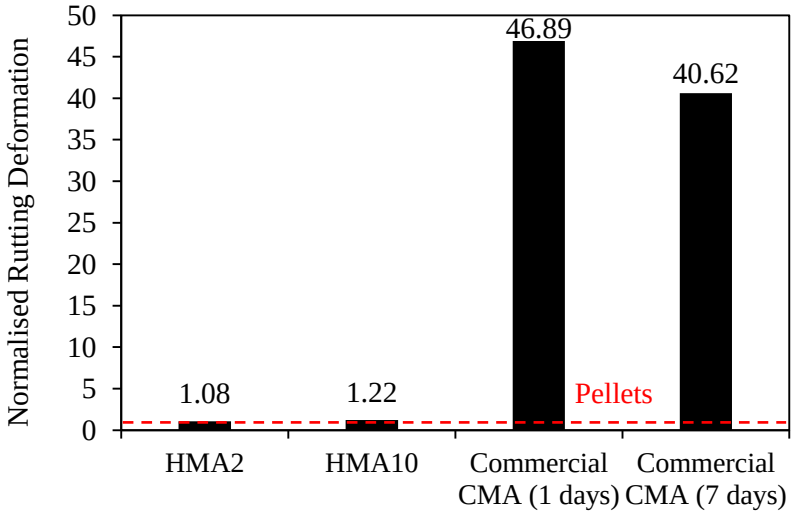


Figure 6.9 Normalise rutting ratio of the samples made of different materials

The final deformation obtained by asphalt samples made of pellets was 0.37 mm. As can be seen in Figure 6.9, the deformation obtained by CMA after 7 curing days (17.35 mm) and even after 28 curing days (15.03 mm) was significantly higher. In addition, the results obtained by HMA2 and HMA10 were practically the same, or even slightly higher, which means that pelletised asphalt mixes can provide as good, or even better, rutting resistance, not only than other conventional repairing materials but also than a recently repaved road.

Chapter 7

Economic and environmental assessment of the innovative materials

7.1. Introduction

Pothole repair is a common pavement maintenance practice that is performed by many highway agencies. This type of maintenance includes different combinations of patching materials and repair procedures. Much research have evaluated patching performance but these studies have failed to evaluate the pothole patching materials in terms of economic and environmental aspects. The objective of this study was to assess the three innovative patching materials of pothole repair developed in this thesis (asphalt tile, asphalt pellets and binder pellets), in relation to the aforementioned aspects and to compare the outcomes with conventional patching materials, such as HMA and CMA. These patching materials were implemented by using different raw materials and procedures. The results of the wheel track test were used to determine the service life of each innovative patching material. The analysis was performed to quantify the energy, material inputs, and emission during production of raw materials, prefabrication of each product until they were installed. The data was taken from different sources based on the literature review.

7.2. Overview of the study

7.2.1. Description of the studied cases

In the present study, the impact of the three innovative patching materials proposed to repair potholes by electromagnetic induction were assessed from three different points of view:

economic, energy consumption and CO_2 emissions. In order to define the inputs of the model, the steps needed to implement these patching materials are described below and a summary of the materials necessary in each case is included in Table 7.1.

Table 7.1 Composition of each innovative patching material

Innovative patching material	Component of materials		Content in each product by weight
Asphalt tile and bonding layer	Asphalt tile	Limestone Aggregates	
		10 mm	19%
		6 mm	28.5%
		Dust (4 mm)	47.5%
		Bitumen 40/60 in tile mix	5%
	Bonding layer	Bitumen 40/60	96%
		Styrene-butadiene-styrene (SBS)	4%
	Steel fibre		80% open area
Asphalt pellets	Limestone Aggregates (2 mm)		63.96%
	Bitumen 40/60		3.23%
	Steel grit		32.80%
Binder pellets	Limestone Aggregates (2 mm)		85%
	Binder Pellets	Bitumen 40/60	7%
		Steel wool	7%
		Sodium alginate used for protective pellets shell	0.5%
		Calcium chloride used for protective pellets shell	0.5%

1. **Asphalt tile and bonding layer:** This involves two phases: prefabrication and on-site implementation as shown in Figure 7.1. The first phase is performed in an asphalt plant, where an asphalt tile with standardised dimensions is wrapped into a bonding skin of elastic polymer modified (SBS) bitumen containing electrically conductive particles (Steel fibre). The latter were characterised with low cost and more environmental. During the on-site stage, the pothole to be repaired is cut by a hole saw and water and impurities are

removed. Then the tile is placed into it and the bonding bitumen layer is heated by applying an external alternating electromagnetic field, which induces electric currents through the embedded metal particles. The heating process lasts 1 min, after which the tile is compacted by vibratory compactor for another 1 min. When the bonding layer cools down both the asphalt tile and old material present at the inner surface of the pothole remain glued and the pothole is considered repaired.

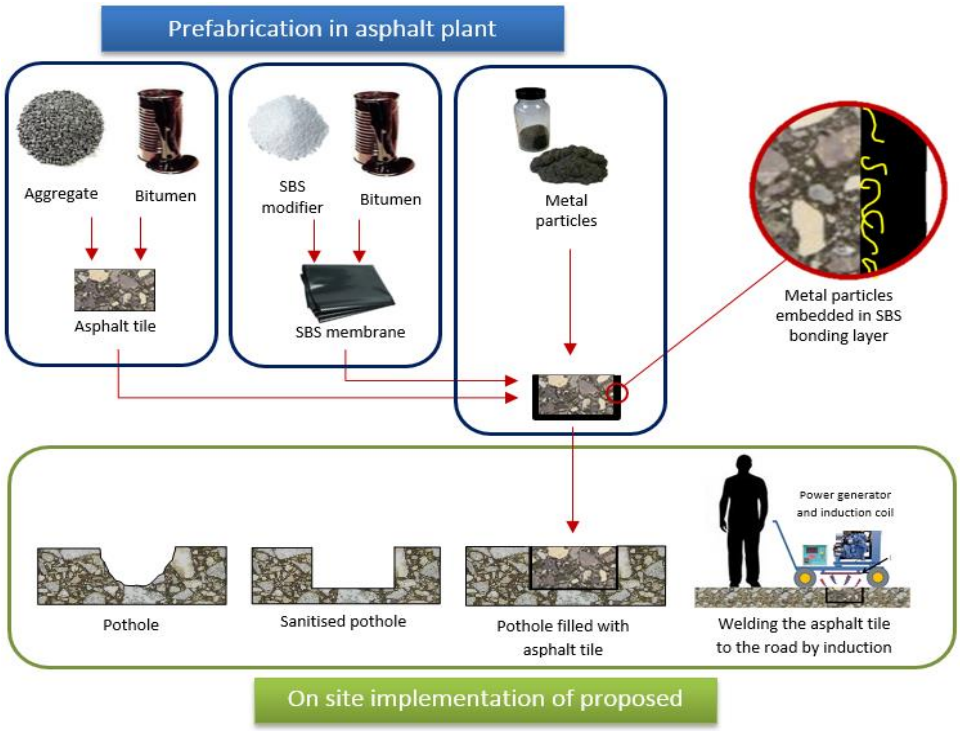


Figure 7.1 Schematic implementation of the proposed technology for potholes repairing

2. **Asphalt pellets:** In this case, asphalt pellets, containing aggregates, bitumen and electrically conductive particles (Steel grit) are first pre-fabricated in an asphalt plant. The choice of steel grit is very fine fibres which behave as fine aggregates. These pellets can be packed and stored at the ambient temperature. When a pothole needs to be repaired, the pellets at the ambient temperature can be introduced into the pothole and melted by applying electromagnetic induction for 3 min. After such time, the material can be easily compacted by a vibratory compactor for 2 min, producing a road material that can resist

traffic loads, as shown in Figure 7.2. In this case, the pothole does not need to be sanitised or cut into standard shapes or dimensions. However, for better results, it must be clean of loose particles and water inside.

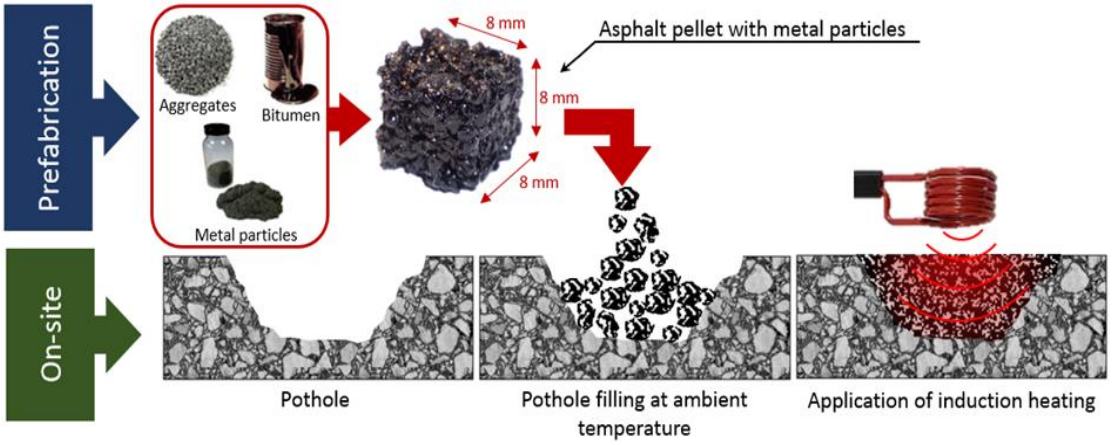


Figure 7.2 Schematic pothole repairing process by induction-heating asphalt pellets

3. **Binder pellets:** this type of pellets contains bitumen and electrically conductive particles (Steel wool) are prefabricated; although in this case, no aggregates are included. Steel wool is chosen due to its fine particle size and which allows bitumen to pass through during mixing. As the pellets tend to stick to each other over storage periods, they become encapsulated into a protective shell made of alginate-calcium and filler. These pellets can be melted and mixed with aggregates on-site using portable asphalt mixer-heater system by an electromagnetic induction generator. A stirring paddle made of non-conductive material spins into crucible during this operation to mix the materials, which lasts 5 min. After that, the material can be easily poured and compacted into the pothole by vibratory compactor for 1 min, as shown in Figure 7.3. In this case, the pothole does not also need to be sanitised or cut into standard shapes or dimensions.

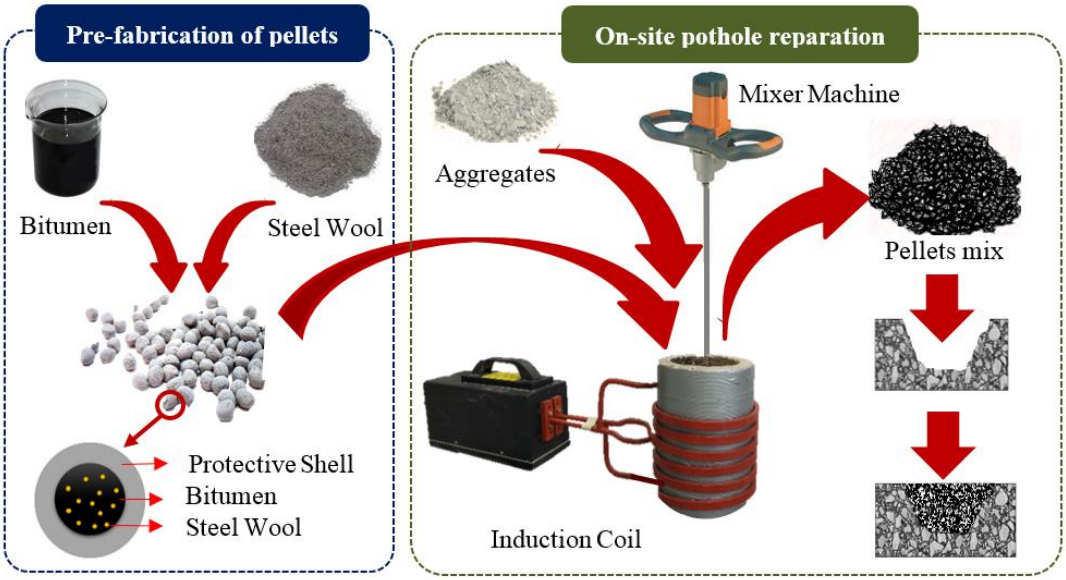


Figure 7.3 Schematic pothole repairing process by induction-heating binder pellets

Table 7.2 presents the duration of the on-site activities involved in each patching material. In addition, a transportation time of 10 min necessary to move equipment, materials and personnel from asphalt plant to worksite, was assumed for all patching materials. Hence, the total time to repair a pothole was determined to be longer than 30 min.

Table 7.2 Estimation of duration of on-site activities involved in each patching material

Patching material	Cleaning	Cutting	Laying	Heating	Compacting	Finishing	Total time
Asphalt tile	2 min	3 min	2 min	1 min	1 min	2 min	11 min
Asphalt pellets	2 min	-	2 min	3 min	2 min	2 min	11 min
Binder pellets	2 min	-	2 min	5 min	1 min	2 min	12 min
HMA	2 min	3 min	2 min	-	2 min	2 min	11 min
CMA	2 min	3 min	2 min	-	2 min	2 min	11 min

The theoretical pothole to be repaired was taken as a 1 m^2 road area with a depth of 35 mm. The number of times such a pothole would need to be repaired over the service life of a road depends on the service life of the repairing material, as well as the time until the pavement will demolished and rebuilt.

In the literature it was found that the service life of a pothole repaired by HMA and CMA is 4 and 2 years respectively (Hartmann, 2013). As the innovative patching materials have not yet been implemented in real roads, the service life of these patching materials was estimated by comparing the laboratory results of their rutting resistance to that of HMA and CMA (obtained before), assuming a linear correlation, as follows:

$$\frac{Yr_{HMA} - Yr_{CMA}}{Rd_{HMA} - Rd_{CMA}} = \frac{\boldsymbol{Yr_{Product}} - Yr_{CMA}}{\boldsymbol{Rd_{Product}} - Rd_{CMA}} \quad (7.1)$$

Where Y_r is the number of years to repair a pothole and R_d is rut depth measured in the laboratory (in mm).

In addition, the service life of the road depends on factors, such as the raw material they are made of and the quality of the construction process. For this reason, the present study will consider 10 and 20 year periods for the calculations. The results of patching survival were obtained as shown in Table 7.3.

Table 7.3 Calculation of number of pothole repairs needed over the road service life

Patching material	Rut Depth (mm)	Patching Survival (years)	No. repairs in 10 years	No. repairs in 20 years
Asphalt tile	0.74	3.96	2.53	5.05
Asphalt pellets	1.04	3.92	2.55	5.10
Binder pellets	0.37	4.01	2.49	4.99
HMA	0.46	4	2.5	5
CMA	15	2	5	10

Finally, as the innovative patching materials containing metal particles can be reheated over the service life of the repaired pothole, two maintenance hypothesis were considered. The first hypothesis consists on repairing the pothole with the innovative material (year 0) and after 10 and 20 years a simple reheating and compacting treatment by induction is applied. Hence, equipment and labour costs are needed but the manufacturing and use of new material is not. The second hypothesis, more conservative, assumes that the patching material is not suitable

after 10 years, so after 10 and 20 years, the old material is removed, the pothole is refilled with new induction heatable material and compacted.

7.2.2. Data Source

The data inventory source relating to cost, energy consumption and CO_2 emission for raw materials, transport, fuel, etc., was taken from different sources based on the literature review as shown in Table 7.4, 7.5 and 7.6. The type of data collection focussed on variables such as asphalt pavement material, recipes of mix design, manufacturing of each product and installation practices. Other sources of data were used to obtain energy consumption values of constituent materials used during production, fuel, transport, laying and compaction and compared their conventional alternatives. These were acquired from Hartmann (2013) and Wayman et al. (2014) that provided an insight into the effect of durability and environmental impact.

Table 7.4 Inventory data collection of costs

Material	Cost (£/t)	Data source
Virgin aggregates 0.075 – 20 mm	14.94	(Wayman et al., 2014)
Filler <0.075 mm as aggregate	14.94	(Wayman et al., 2014)
Bitumen (40/60) pen	579.60	(Rodrquze, 2015)
Polymer modified bitumen	651.71	(Wayman et al., 2014)
SBS	753.48	(King, 2016)
Emulsion (60%)	860.59	(Quarry price list, 2013)
Recycled steel fibres	30-80	(Pilakoutas et al., 2004)
Steel grit	1000	Scangrit Company
Steel wool	1411.80	Global sources company
Sodium alginate	87000	Fisher scientific company
Calcium chloride	49650	Fisher scientific company
Transport - Rigid>17 t,20 ton payload	0.92	(Wayman et al., 2014)
Fuel	0.66	(Wayman et al., 2014)

Table 7.5 Inventory data collection of energy

Product	Energy (MJ/t)	Data Source
Bitumen	4900	(Eurobitumen, 2011)
Emulsion 60%	3490	(Eurobitumen, 2011)
PMB as bonding layer	5940	(Wang and Gangaram, 2014)
Aggregates	41.85	Aggregate Industries Ltd. AI, UK
Steel fibres, steel grits and steel wool	9500	(Purnell, 2011)
Cement	4976	(Bilal and Chappat, 2003)
Sodium alginate	560	(Paxman et al., 2008)
Calcium chloride	108000	(Cardarelli, 2013)
Production of HMA	275	(Bilal and Chappat, 2003)
Production of CMA	14	(Bilal and Chappat, 2003)
Laying of HMA	9	(Bilal and Chappat, 2003)
Laying of CMA	6	(Bilal and Chappat, 2003)
Remixing of HMA (MJ/m^2)	1.5	(Huang, 2007)
Lorry Transport (km/t): transport to work site HMA	79	(Bilal and Chappat, 2003)
Lorry Transport (km/t): transport to work site CMA	86	(Bilal and Chappat, 2003)
Lorry Transport (km/t)	29	(Wang and Gangaram, 2014)
Total energy of fossil and electricity of steel fibre	12.24	(Bilal and Chappat, 2003)
Fuel	35	(Bilal and Chappat, 2003)

Table 7.6 Inventory data collection of CO_2 emission

Product	CO_2 (kg/t)	Data Source
Bitumen	190	Eurobitumen 2011
Emulsion 60%	221	Eurobitumen 2011
PMB as bonding layer	370	(Wayman et al., 2014)
Aggregates	9.4	(Bilal and Chappat, 2003)
Steel fibres, steel grits and steel wool	430	(Purnell, 2011)
Cement	1003.55	(Cagiao et al., 2011)
Sodium alginate	180	(Sodium alginate Database,1997)
Calcium chloride	890	Emission factors in kg CO_2-equivalent per unit (Appendix7)
Production of HMA	22.4	(Bilal and Chappat, 2003)
Production of CMA	1	(Bilal and Chappat, 2003)
laying of HMA	0.6	(Bilal and Chappat, 2003)
laying of CMA	0.4	(Bilal and Chappat, 2003)
Remixing of HMA (CO_2 (kg/m^2)	0.0959	(Wang and Gangaram, 2014)
Lorry Transport (km/t): transport to work site HMA	5.3	(Bilal and Chappat, 2003)
Lorry Transport (km/t): transport to work site CMA	5.7	(Bilal and Chappat, 2003)
Lorry Transport (km/t)	0.0617	(Wang and Gangaram, 2014)
Fuel	4	(Bilal and Chappat, 2003)

System boundaries were defined for energy usage and emissions associated with the production of raw materials, plant operations, and placement (including heating and compaction, transport to the site, and site worker and equipment), see Figure 7.4. According to BRE Global (2013), general or specific data for use in the calculations must be updated within 5 years for manufacturer-specific data and within the last 10 years for generic data.

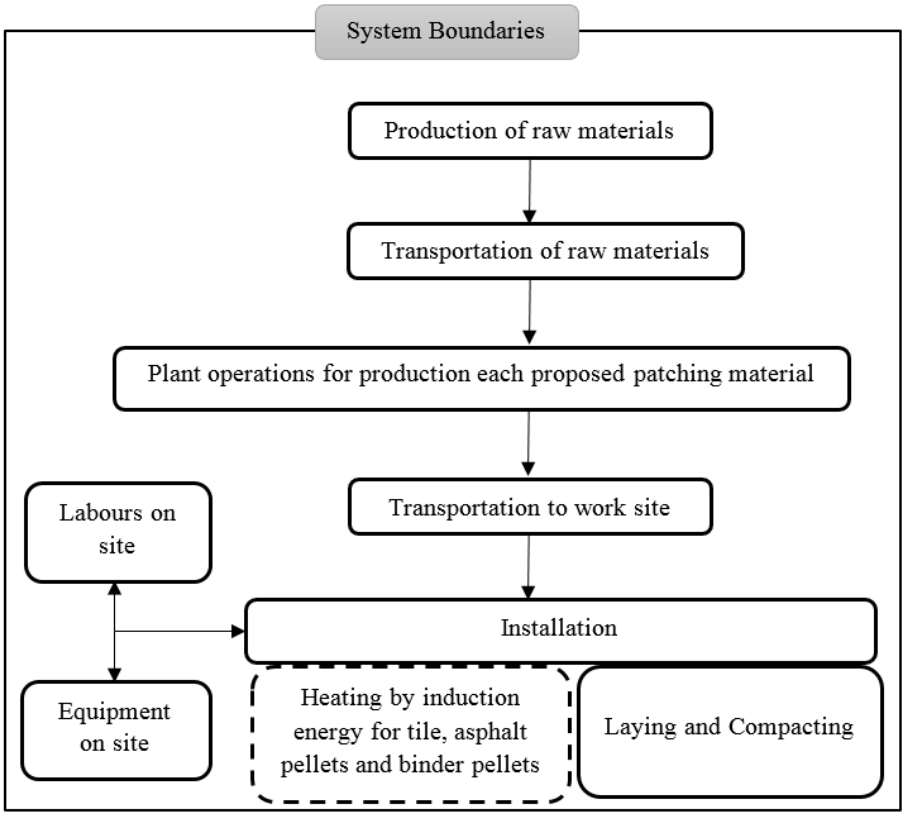


Figure 7.4 System boundaries of pothole repair procedure

7.2.3. Patching Cost

The total cost of the pothole repairing materials described earlier in section 7.2.1 were obtained based on estimated costs of raw materials, labours, equipment and energy that are typically associated with manufacture and installation each product.

Labour costs depend on the number of workers that implement the patching operation and the average daily wage per worker. The latter in turn depends on the workers' skills because the

price of workers differ if the workers skilled or unskilled (Langdon, 2017). It is necessary for inspectors to be trained on how to determine and evaluate potholes. Similarly workers should be appropriately trained to in the best use of new materials and technologies and correct installation (Wilson and Romine, 2001). In this study, three operators were considered necessary. One to drive the truck and two as general operative and supervisor. The labour costs were taken from Spon's Civil Engineering and Highway Works Price Book (Langdon, 2017).

Equipment costs differ from agency to agency. These can be identified with any equipment used to prepare the pothole before and after placing the patching material. In this study, the amount entered should be in pounds per 30 min. The equipment included in this study are: air compressor, saw, roller (compactor), drilling equipment and induction heating generator. All information regarding the equipment cost were taken from Spon's Civil Engineering and Highway Works Price Book (Langdon, 2017).

For transport to site, the haulage distance from asphalt plant to a site was assumed as 1 km and the journey time was also assumed approximately 10 min one-way. The type of truck for transporting the materials to the site was assumed to have a 20 ton payload (>14 t) that returned the same distance to plant empty. Haulage costs were assumed to be £0.92 per vehicle-km travelled. The return journey is assumed to cost the same amount as the original journey, despite carrying no payload. Diesel oil is used as fuel as reported in (Wang and Gangaram, 2014).

Tables 7.7, 7.8 and 7.9 show the calculated cost of repairing a pothole (1 m^2 * 0.35 m) by asphalt tile, asphalt pellets and binder pellets. The calculated cost of manufacturing the needed amount of HMA to repair the pothole is £1.226, while the total costs of implementing the reparation is £53.29. For CMA, these costs resulted respectively £0.088 and £53.10.

Table 7.7 Approximate estimating of patching cost for asphalt tile and bonding layer

Asphalt Tile and Bonding Layer						
NO.	Item	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
1	Raw materials				Volume=(1*1*0.035) m^3	
1.1	Limestone Aggregates	10 mm	kg	0.15	15.41	2.30
		6 mm	kg	0.15	23.11	3.47
		Dust (4 mm)	kg	0.15	38.53	5.78
1.2	Bitumen 40/60	Bitumen in tile mix	kg	0.58	4.34	2.51
1.3	PMB as a bonding layer	Bitumen in bonding layer	kg	0.58	7.22	4.19
		SBS polymers	kg	0.75	0.30	0.23
1.4	Steel fibres		kg	0.08	0.30	0.02
				Total cost of materials with steel mesh		18.50
2	Rental of equipment	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
2.1	Air Compressor	portable	min	0.141	30	4.24
2.2	Saw	12" Petrol Disc Cutter (petrol two-stroke)	min	0.028	30	0.84
2.3	Roller (compactor)	28" Ped Roller (diesel) electric start	min	0.052	30	1.56
2.4	Drilling equipment	Combination Hammer Drills ATC – medium (110v)	min	0.033	30	1
2.5	Generator	10 kVA water cooled	min	0.025	30	0.74
2.6	Induction heating	induction heating energy is 6 kW Total cost/ hr =£1.714	min	0.029	30	0.857
					Total cost of equipment	9.237
3	Labours	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
3.1	supervision	1 supervision	min	0.32	30	9.54
3.2	Driver (truck)	1 Driver (truck)	min	0.42	30	12.67
3.3	General assistants	1 General assistants	min	0.25	30	7.5
					Total cost of labours	29.71
4	Transport	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
		Transport - Rigid>14 t,20 ton payload	min	0.0307	30	0.92
					Final cost	58.36

Table 7.8 Approximate estimating of patching cost for asphalt pellets

Asphalt Pellets						
NO.	Item	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
1	Raw materials				Volume=(1*1*0.035) m^3	
1.1	Limestone Aggregates	Dust (4 mm)	kg	0.15	71.66	10.75
1.2	Bitumen 40/60	bitumen in tile mix	kg	0.58	3.62	2.10
1.3	Steel grit		kg	1.00	36.75	36.75
				Total cost of materials with steel grit		49.60
2	Rental of equipment	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
2.1	Air Compressor	portable	min	0.141	30	4.24
2.2	Roller (compactor)	28" Ped Roller (diesel) electric start	min	0.052	30	1.56
2.3	Generator	10 kVA water cooled	min	0.025	30	0.74
2.4	Induction heating	induction heating energy is 6 kW Total cost/ hr =£1.714	min	0.029	30	0.857
					Total cost of equipment	7.397
3	Labours	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
3.1	supervision		min	0.32	30	9.54
3.2	Driver (truck)		min	0.42	30	12.67
3.3	General assistants		min	0.25	30	7.5
					Total cost of labours	29.705
4	Transport	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
		Transport - Rigid>14 t,20 ton payload	min	0.0307	30	0.92
					Final cost	87.62

Table 7.9 Approximate estimating of patching cost for binder pellets

Binder pellets						
NO.	Item	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
1	Raw materials				Volume=(1*1*0.035) m^3	
1.1	Limestone Aggregates	Dust (4 mm)	kg	0.15	81.2	12.18
1.2	Bitumen 40/60	bitumen in tile mix	kg	0.58	7.15	4.14
1.3	Steel wool		kg	1.41	7.15	10.09
1.4	Sodium alginate		kg	87.00	1.5	130.50
1.5	Calcium chloride		kg	49.65	1.5	74.48
				Total cost of materials with steel wool		231.40
2	Rental of equipment	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
2.1	Air Compressor	portable	min	0.141	30	4.24
2.2	Roller (compactor)	28" Ped Roller (diesel) electric start	min	0.052	30	1.56
2.3	Generator	10 kVA water cooled	min	0.025	30	0.74
2.4	Induction heating	induction heating energy is 7.5 kW Total cost/ hr =£2.284	min	0.038	30	1.142
2.5	Mixer machine + paddle manufacturing		min	0.0052	30	0.156
2.6	Concrete Pot		min	0.00525	30	0.1575
					Total cost of equipment	7.996
3	Labours	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
3.1	supervision		min	0.32	30	9.535
3.2	Driver (truck)		min	0.42	30	12.67
3.3	General assistants		min	0.25	30	7.5
					Total cost of labours	29.705
4	Transport	Description	Unit	Cost (£)/unit	Quantity	Total Cost (£)
		Transport - Rigid>14 t,20 ton payload	min	0.0307	30	0.92
					Final cost	270.01

Furthermore, the calculation of cost of energy demand for the prefabrication phases of the different methods are presented in Table 7.10. The main data of all fuel costs used in this study were taken from Spon's Civil Engineering and Highway Works Price Book (Langdon, 2017). These costs were added to the final cost of each approach to ensure that the cost of each variable costs was accounted in the calculations.

Table 7.10 Approximated cost estimation of energy usage for pothole reparation by asphalt tile and asphalt pellets and binder pellets (in £ per pothole)

Energy cost (£ per pothole)	Natural gas	Oil	Electricity	Total
Production of bonding layer	0.587	0.776	-	1.152
Production of tile		1.053	0.099	1.363
Production of asphalt pellets	-	1.323	0.124	1.447
Production of binder pellets	-	1.253	0.419	1.672

Finally, authors, such as (Wilson and Romine, 2001) recommend to consider also the user costs in this type of analysis. However, these costs composed of vehicle operation costs, delay costs and crash costs were assumed the same for all the patching materials. Hence, it was not necessary to include them in the present study, as they do not affect the comparison among the innovative patching materials.

7.2.4. Energy consumption and CO_2 emission

In order to identify energy consumption and emissions resulting from pothole repairs, the first stage is to quantify the components of the raw materials, processes of manufacturing and installation operations (laying and compacting) for each patching material.

Prefabrication of each patching material was carried out with different processes to be ready to transfer them to the site. The transport of HMA and CMA requires special requirements such as heat equipment for HMA and providing water for CMA. However, asphalt tiles and two types of pellets can be transported in small quantities and without special requirements, similarly to transport the aggregates. Laying and compacting depends on types of patching materials and equipment especially with three innovative patching materials of repair that were used induction heating to melt them as a heating method. Table 7.11 shows the energy consumption and CO_2 emission for asphalt tiles, asphalt pellets, binder pellets, HMA and CMA used as pothole treatments in this study.

In this study, all data relating to the activities of repair were mainly collected from published reports from previous research as mentioned before. The total value of energy consumption and CO_2 emissions were obtained by summing up all data from production until the implementation of each patching material, as shown in Figure 7.5.

Table 7.11 Energy consumption and CO_2 emission

	Consumption energy (MJ per pothole)					**CO_2 emission (kg per pothole)**				
	Tile	Asphalt pellets	Binder pellets	HMA	CMA	Tile	Asphalt pellets	Binder pellets	HMA	CMA
Total amount of materials (kg)	89.21	112.03	98.50	87.23	86.85	89.21	112.03	98.50	87.23	86.85
Processes										
Manufacture	29.95	30.81	29.24	23.98	1.22	2.44	2.51	2.38	1.95	0.087
Transport	2.59	3.24	2.86	9.94	7.47	0.0055	0.0069	0.0061	0.81	0.49
Laying and compacting	10.88	11.09	6.73	2.29	0.52	0.054	0.067	0.059	0.056	0.034
Raw materials										
Bitumen 40/60	21.24	17.74	35.04	23.27	-	0.82	0.68	1.36	0.902	-
Bitumen emulsion	-	-	-	-	8.73	-	-	-	-	0.55
Aggregates	3.22	2.99	3.39	3.45	3.45	0.72	0.67	0.76	0.77	0.77
PMB	44.68	-	-	-	-	2.78	-	-	-	-
Steel particles	2.85	349.12	67.92	-	-	0.129	15.80	3.7	-	-
Sodium alginate	-	-	0.84	-	-	-	-	0.27	-	-
$CaCl_2$	-	-	162	-	-	-	-	1.34	-	-
Cement	-	-	-	-	9.33	-	-	-	-	1.88

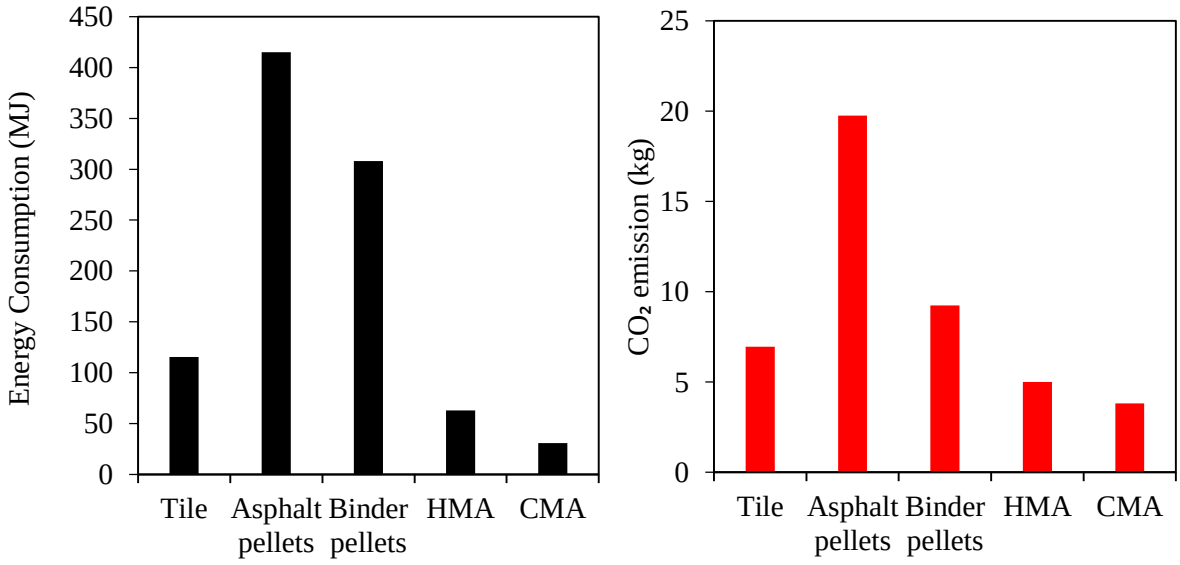


Figure 7.5 Total values of energy consumption and CO_2emission

7.3. Results

7.3.1. Economic impact

The cost analysis performed to evaluate involved respectively aggregating the cost of materials, labour and equipment necessary to repair an identical pothole using three innovative patching materials and under two different hypothesis of maintenance strategies as mentioned in section 7.2.3.

Figure 7.6 (a) shows the costs of repairing potholes under the first hypothesis of maintenance strategy. It can be seen that the total initial cost of repairing the pothole immediately after its occurrence is £53.19, £54.52, £60.88, £89.07 and £271.68 for CMA, HMA, asphalt tiles, asphalt pellets and binder pellets respectively. It can also be seen that binder pellets cost more than other patching materials due to the expensive raw materials needed to manufacture them (especially the protective shell). Furthermore, the total cost when asphalt pellets are used is high due to the use of high content of steel grit (about 33.80% by mass of total mix). Additionally, the initial cost of repairing the pothole by asphalt tiles is slightly higher than current conventional patching materials such as HMA and CMA, due to the need of prefabrication works.

When CMA is used, it is necessary to repair the pothole every two years, while with HMA pothole repair is required every four years. The durability of the new proposed materials is very close to that of HMA but their cumulative maintenance costs after 9 years are slightly lower for asphalt tile and asphalt pellets than HMA. This happened because repair carried out with conventional patching materials is repetitive; requiring materials preparation, manufacturing, necessary labour and equipment each time. However, when asphalt tiles and two types of pellets are used, only induction and compaction treatments are necessary. Binder pellets are more expensive than HMA, even after 20 years. However, they are more cost-effective than

CMA after 12 to 13 years. Therefore, compared to CMA, after 20 years, the cost reductions achieved by using tiles, asphalts pellets and binder pellets were 55.18%, 51.61% and 20.64% respectively. For these reasons, it can be said that these methods contribute to reduce the level of effort and cost of patching operations.

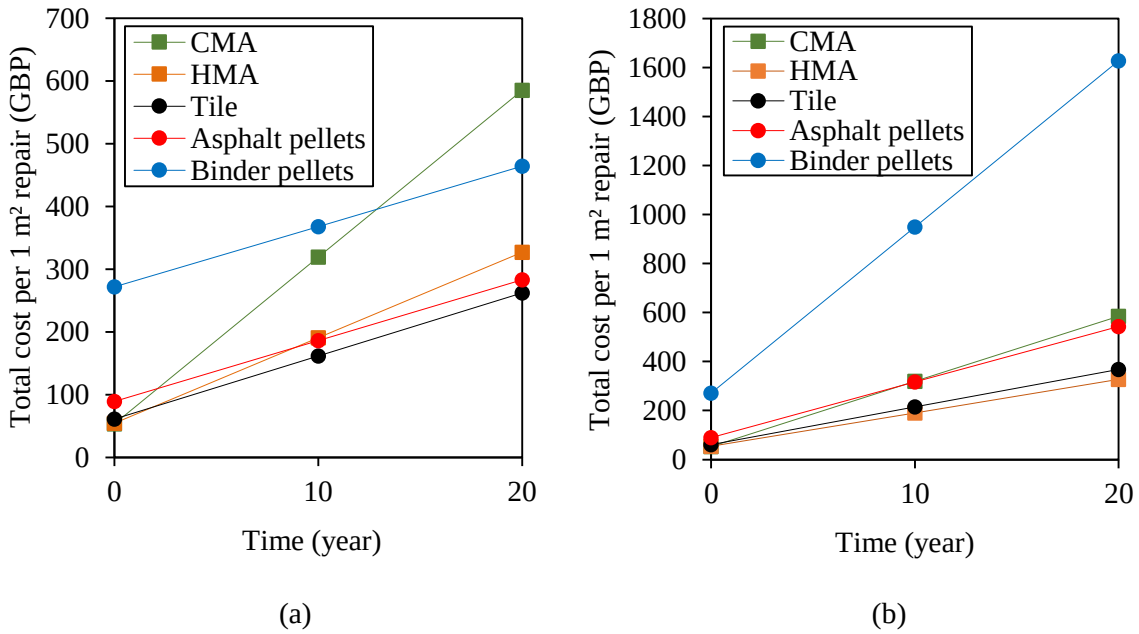


Figure 7.6 Total cost of pothole repair over time (a) hypothesis 1 and (b) hypothesis 2

Figure 7.6 (b) shows the results obtained under the second hypothesis of maintenance strategy. Here, the maintenance cost of HMA and CMA are the same than under first hypothesis. However, in this instance, the cost resulting from the use of binder pellets is shown to be much higher than when asphalt tiles or asphalt pellets are used (about 4.41 and 2.99 times respectively). This is because of the prefabrication stage, which requires expensive materials, such as $CaCl_2$ (£74.48 for the studied pothole size) and alginate (£130.5). According to the second hypothesis, the use of these materials would be necessary every 4 years. The use of CMA also increased the maintenance cost over time, due to its poor quality and shorter service life. On the other hand, the maintenance cost when using tile and asphalt pellets are very similar to HMA.

7.3.2. Energy consumption impact

Figure 7.7 (a) compares the energy consumption of conventional patching materials (CMA and HMA) with the energy consumption of the innovative patching materials. It can be observed that the energy consumption of asphalt pellets and binder pellets is significantly higher than that of other patching materials. This is because the energy used during the production of steel particles was high. In comparison, the amount of steel grit content in the case of asphalt pellets is significantly higher due to consumption energy of it that was about 349.12 MJ to repair $1m^2$.

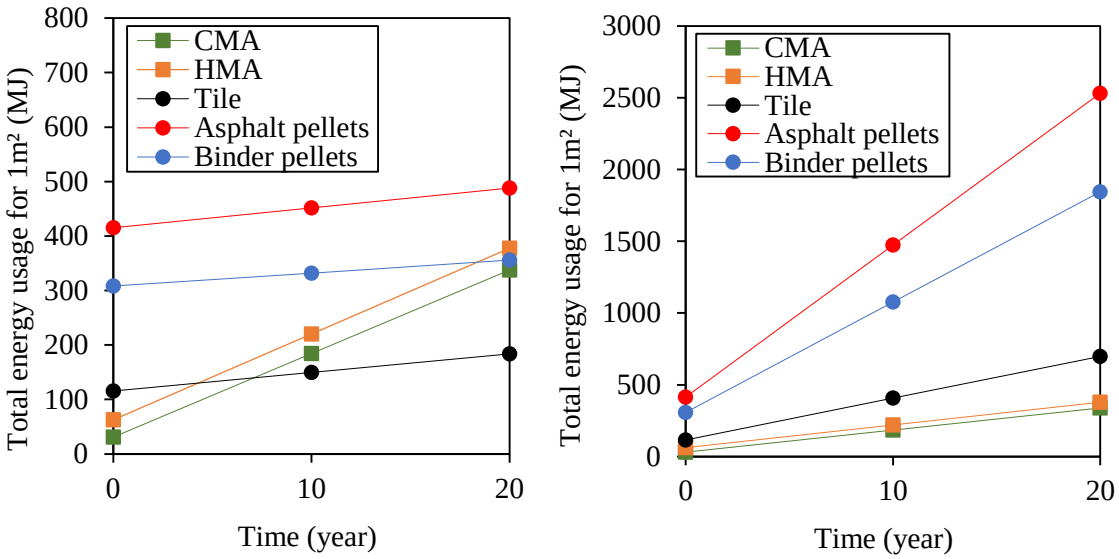


Figure 7.7 Total energy consumption of pothole repair over time (a) hypothesis 1 and (b) hypothesis 2

Figure 7.7 (a) also shows the asphalt tile option becomes more energy-efficient than HMA and CMA after about 4 and 7 years respectively. Therefore, after 10 years, by using asphalt tiles instead of HMA and CMA, reductions in energy consumption of 16.40% and 30.06% respectively may be achievable. On the other hand, asphalt and binder pellets are less energy-efficient, although binder pellets obtained better results than CMA after 18 years. Similarly, significant differences were also observed after 20 years. Energy consumption of HMA was predicted to be 2.06 and 1.06 times of energy consumption of asphalt tile and binder pellets

respectively. But energy consumption of asphalt pellets was higher, about 1.29 times the energy consumption of HMA.

Figure 7.7 (b) (second hypothesis) shows that the total energy consumption of asphalt pellets and binder pellets is significantly higher than asphalt tiles and conventional patching materials. However, after 20 years, the use of asphalt pellets and binder pellets results in a cumulative energy consumption 3.63 and 2.64 times higher than when using asphalt tiles. Based on these results, it can be surmised that the raw materials used for pellets production contribute significantly to increases in the energy consumption of these patching materials.

7.3.3. CO_2 emission impact

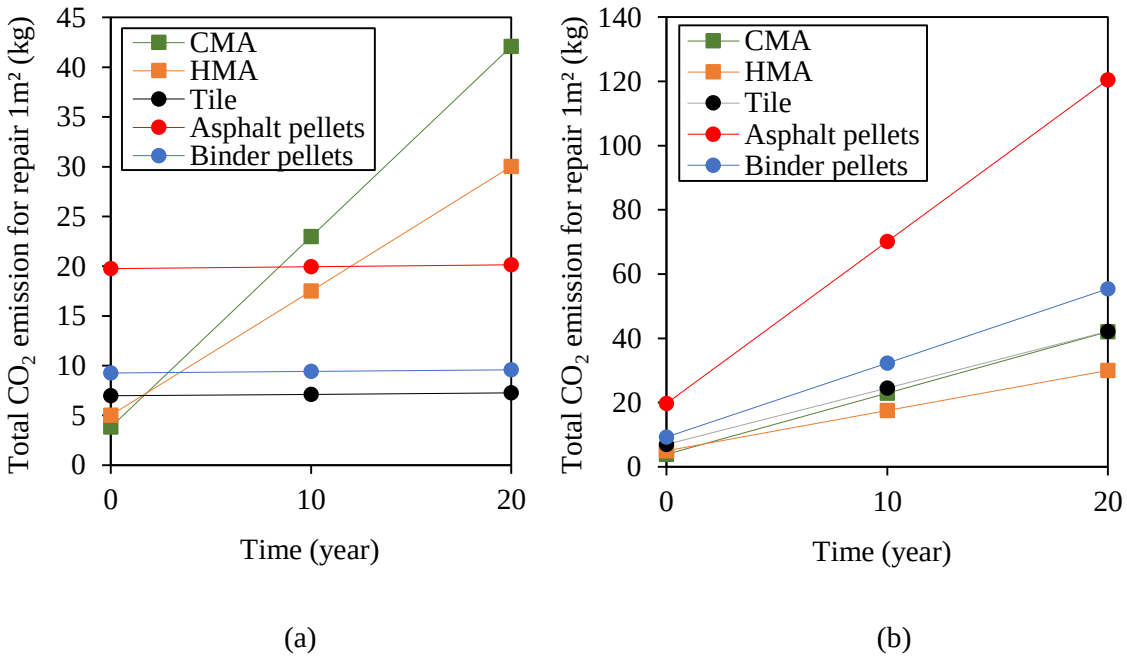


Figure 7.8 Total CO_2 emission of pothole repair over time (a) hypothesis 1 and (b) hypothesis 2

Figure 7.8 (a) shows the total CO_2 emissions produced by the patching methods considered in this study under the first hypothesis of maintenance strategy. The innovative patching materials produced higher initial emissions than traditional patching materials; especially the asphalt

pellets (19.73 kg CO_2). This was caused by the steel grit in its composition. However, emissions during subsequent years are significantly lower. Thus, asphalt tiles started being more sustainable than HMA and CMA after 1-2 years, binder pellets after 3-4 years and asphalt pellets after 8-12 years. After 20 years, the cumulative emissions produced by CMA were 5.59, 2.09 and 4.39 times higher than the asphalt tile, asphalt pellets and binder pellets respectively. This again indicated that the used of innovative patching materials for repairing potholes can be more sustainable.

Figure 7.8 (b) presents the results obtained under the second hypothesis of maintenance technique. It shows that the emissions produced by the innovative patching materials increased significantly, especially for the case of asphalt pellets due to the steel grit used in their production. In addition, after 20 years, the CO_2 emissions produced by the asphalt tiles (4.46 CO_2 kg) remain lower than asphalt pellets and binder pellets (17.16 and 6.80 CO_2 kg respectively). Finally, the emissions that result from using CMA remained high due to the poor quality of patching material and short service life, which leads to greater number of required repairs.

Chapter 8
Conclusions and Recommendations

8.1. Introduction

In this thesis, the induction heating approach has proved successful for the repair of pothole when implemented in conjunction with three novel pothole patching materials. These materials were asphalt tile and bonding layer, asphalt pellets and binder pellets. Laboratory tests were carried out to examine the critical properties of the aforementioned materials required for achieving durable pothole repair.

This chapter summarises the main conclusions that can be extracted from the analysis carried out in previous chapters. Furthermore, some recommendations and future work will be given.

8.2. Main conclusions regarding asphalt tile and bonding layer

In the present experimental investigation a method to repair potholes via induction energy has been tested and demonstrated. The system consists in an asphalt tile which base is composed of a bonding layer made of polymer modified bitumen and steel fibres that can be heated using induction energy. When a pothole appears, it can be cleaned up and filled with a tile that is bonded to the old pavement by means of induction energy. With this purpose, different amounts/distributions of steel fibres, so as different thicknesses have been tried in the bonding layer. Moreover, an ideal pothole has been repaired using the tiles and its durability tested by means of wheel track tests. From this study, the following conclusions could be extracted:

- The temperature increase rate was higher in test samples with higher amount of loose steel fibres or chicken wire with lower amount of open area.

- For a fixed amount of electrically conductive particles in the mixture, increasing the thickness of the bonding layer reduced the maximum temperature observed in the bonding element. This means that the energy was more efficiently distributed and less losses applied.
- Shear and tensile strength were strongly correlated and showed positive relationship. This correlation was strongly dependent of the distribution of electrically conductive particles. Shear strength was higher when the loose particles were used, which may be due to the higher contact area between bitumen and fibres.
- The bonding strength did not depend on the induction heating time, but on the thickness of the bonding layer, the bigger the stronger. If the bonding layer was too thin, fibres were not completely coated, which resulted in heating losses and reduced temperature.
- The physical principle behind the strength gain of tiles is the drain of bitumen towards the gap between the asphalt tile and block. This was powered by the (1) total pressure exerted over the bonding layer, e.g. by the weight of the tile, (2) viscosity of bitumen and (3) total amount of bitumen available.
- Based on this last conclusion, to reach a high bond using induction heating it is more important to apply a high pressure in the tile after heating that heat for a longer time or use an excessive amount of bitumen.
- The rutting deformation of asphalt tiles under simulated traffic conditions was very similar to that of original asphalt mixture and approximately 40 times smaller than commercial CMA for the same loading time and energy.

Based on previous conclusions, it can be summarised asphalt tiles are a suitable patching material to repair potholes, and the durability of the repaired surface is comparable to that of a newly built road.

8.3. Main conclusions regarding asphalt pellets

In the present investigation, the use of asphalt pellets, that can be heated using induction energy, to repair potholes was assessed through mechanical tests and compared to commonly used conventional materials, such as HMA and CMA. The method was designed with the aim of reducing energy consumption, as heating is only concentrated on the binder, and improving work conditions for operators, as no fumes are produced, and the material is only heated once it has been introduced into the pothole. Finally, prefabrication of the pellets would lead to a high product quality and shorter traffic disruptions. Besides these considerations, the main conclusions obtained from the present research can be listed as follows:

- The final temperature that the pellets used in this research can reach after 120 s exposed to induction heating is around 125 ºC practically independent of the steel grit content. However, the heating rate increases with the grit content, reaching such temperature in a shorter time. As a result, the total amount of energy supplied to the material is significantly higher when more steel grit is included in the pellets.
- Pellets with higher steel grit contents produced asphalt with higher density and lower air voids content. This was caused by the higher energy transmitted to the material, which reduced binder viscosity. Hence, pellets with 45% steel grit content produced 61.6% higher density and 70% lower air voids content than pellets with 5% steel grit content.
- Increases in bitumen content also produced a higher density and lower air voids content, as it filled the free interstitial spaces between aggregate particles. Hence, pellets with 25% bitumen content produced 4.3 % higher density and 45.2 % lower air voids content than pellets with 15% bitumen content.
- Compared to CMA after 28 curing days, mixes with pellets obtained approximately 5 times higher tensile strength, 19% higher shear strength and 18% higher resistance to

permeant deformation. When compared to HMA, the performance of pelletised asphalt was similar.

- The strength of the asphalt pellets layer and the adhesion between this and the pothole surface, can be stronger than the original asphalt in the road.
- Although the resistance to permanent deformation of pelletised asphalt was satisfactory (1.04 mm after 20000 cycles) that was around 1 mm, it is still poorer than that measured for the case of simply repaving the road using HMA (0.45 mm after 20000 cycles).
- Samples with a minimum steel content of 25% produced a very fast heating (temperature higher than 100 ºC in 1 min), which consequently reduced the air voids content in the mix after compaction. Hence, the mechanical properties obtained for these mixes, even at low bitumen contents (e.g. 10%), were better than CMA after 28 curing days. Increasing steel and/or bitumen content produced very significant reductions in air voids content and improved the mechanical performance. Thus, mixes with 35% steel and 20% bitumen content obtained even better results than HMA, being the material filling the pothole stronger than the own material of the road. As a conclusion, a wide range of volumetric and mechanical properties can be obtained by modifying steel and bitumen content, being particularly advisable to keep them within the range of 25%-35% for steel and10%-20% for bitumen.
- The ITSM values of pellets mixture in wet conditions are higher than HMA and CMA after 7 and 28 days in dry and wet conditions.

In summary, asphalt pellets have potential to be strong competitors of current repairing techniques for isolated and punctual pothole repairs but still cannot be used as a substitute for major maintenance operations, such as road milling and re-paving. Finally, the mechanical performance of pelletised asphalt could be improved by increasing bitumen and steel contents.

8.4. Main conclusions regarding binder pellets

In the present experimental investigation, a pelletised bitumen containing steel wool particles that can be stored and transported at ambient temperature as a granular material, and heated and mixed on-site by electromagnetic induction, was proposed as a new technology for repairing potholes in asphalt roads. The mechanical performance of this material was studied through different tests and compared to conventional materials commonly used in pothole reparation. From this study, the following conclusions could be extracted:

- Pellets encapsulated within an alginate-calcium chloride polymer shell and covered in limestone filler were the best option to prevent their agglomeration and, consequently, increase their storability at ambient temperature, without reducing their mechanical performance. However, they also tended to produce higher air voids and costs.
- The heating potential of the material being mixed in the crucible (pellets and aggregates) is directly correlated with the amount of added steel. Hence, in order to increase it, it is necessary either to increase the steel content within the pellets or increase the added pellets to the mix.
- The air voids content of asphalt can be reduced by either increasing the bitumen content of the pellets or by increasing the amount of pellets in the mix. In the second case, not only the amount of bitumen is increased, but also the amount of steel, which produces higher mixing temperatures and, consequently, lower binder viscosity and higher compaction levels. By changing these parameters, asphalt samples with air voids content from 0.22% to 26.8% were obtained.
- The tensile and shear strength of the binder pellets increased sharply, from values close to zero to values around 0.35-0.40 MPa, when a critical bitumen content (7.5%) was exceeded. For higher contents, the fact of using pellets with higher bitumen content

tends to reduce the strength, as less steel is added to the mix. Consequently, also the mixing temperature is reduced.

- Samples manufactured with 15% of pellets content (pellets containing 50% bitumen and 50% steel wool) produced a good mixing temperature (higher than 135 ºC after 4 min), and low air voids content in the mix after compaction (18%). In addition, this mixture produced better mechanical performance, not only than other conventional repairing materials (HMA and CMA) but also than a road, which was recently repaved.
- These samples also performed practically at the same level as samples made with the same bitumen and aggregates but heated and mixed by conventional methods (conventional HMA). Hence, the induction heating approach proposed in this investigation does not produce any detriment on the performance of the resulting material, compared to traditional methods.

Based on previous conclusions, it can be summarised that the innovative materials showed excellent durability and performance; higher than a road repaired by cold mix asphalt technologies and even similar to the performance of a road recently repaved.

8.5. Main conclusions regarding the economic and environmental impacts on the innovative materials for pothole repair

This study analysed the performance and efficiency of three innovative patching materials and procedures for potholes repairs (asphalt tiles, asphalt pellets and binder pellets) and compared them to conventional patching materials, such as HMA and CMA. The research outcomes were presented in terms of the economic, energy consumption and CO_2 emission of the patching materials and techniques explored. The following conclusions were derived:

- The service life and number of repairs of the innovative materials was very close to that of HMA, unlike the CMA which needs more frequent repair that leads to increase cumulated cost, energy consumption and CO_2 emissions.

- Under the first and most "optimistic" hypothesis, in which the repair material does not need to be substituted over the service life, but only heated by induction, asphalt tiles are more cost-effective than HMA and CMA practically from the beginning. Asphalt pellets become more cost-effective than CMA and HMA after about 2 and 9 years respectively. The initial costs of binder pellets is around 3 times higher than the rest of the patching materials. Nevertheless, they become more cost-effective than CMA after around 13 years.
- Under the first maintenance hypothesis, the innovative materials consume more energy during the first repair; especially asphalt pellets and binder pellets. Only asphalt tiles need lower and become more energy-efficient than CMA and HMA, although this only happens 4 and 7 years after the initial reparation.
- Regarding CO_2 emissions, all innovative patching materials produced higher results; especially binder pellets, whose emissions are around 3 times higher than HMA and CMA. However, asphalt tiles become more sustainable than HMA and CMA after 1-2 years, binder pellets after 3-4 years and asphalt pellets after 8-12 years.
- Under the second and most "pessimistic" hypothesis, in which all the material needs to be replaced each time the pothole needs maintenance (induction treatment is not enough) the innovative patching materials are less competitive than HMA; especially the binder pellets. Nevertheless, asphalt tiles are more cost-effective than CMA practically from the beginning and very similar to HMA. In addition, asphalt pellets become more cost-effective than CMA after about 10 years.

- Under the second hypothesis, the energy consumption of the innovative patching materials is always higher than HMA and CMA. CO_2 emissions produced by asphalt tiles are slightly higher than HMA and very similar to CMA. However, the emissions produced by binder pellets and especially asphalt pellets are significantly higher.

Taking previous points into account, it can be concluded that if there is no need to add new material every time the pothole needs to be repaired over the service life of the road, binder pellets and especially asphalt tiles are the most advisable options. Their initial repair costs, energy consumption and CO_2 emissions are slightly higher than HMA and CMA due to prefabrications activities and contained metal. However, after a short time, they are more cost-effective and sustainable than traditional materials.

On the contrary, if the material does not resist the traffic conditions and the whole material needed to be replaced during each maintenance operation (worst case scenario), all new options become worse options than the current techniques. Nevertheless, asphalt tiles are still slightly more cost-effective than CMA (similar to HMA) and producing CO_2 emissions simply similar to CMA.

8.6. Recommendations for further research

This section presents a list of recommendations and suggestions for work that was not included in the current research due to the lack of time and resources.

- The type of polymer modified bitumen used in this research was SBS which is used to produce the bonding layer that leads to improving its properties. Since the price of SBS increases the cost of asphalt by about 30%, it is recommended to use another type of polymer modified cheaper than SBS but with similar properties. It is expected that this

may reduce the cost of processing polymers and lead the innovative materials to be more accepted within the road maintenance market.

- The manual manufacturing of asphalt pellets can be problematic due to long production times. For instance, the production of 15 kg of pellets required between 5 and 7 days of laboratory time. Therefore, it is strongly recommended to manufacture or develop equipment for the production of asphalt pellets to reduce the time and effort used in the process.
- The binder pellets were mixed with fine aggregates (maximum size 2 mm) to for the purpose of comparison with the performance of asphalt pellets. It can be suggested that the use of coarse aggregates for a range of maximum sizes: 6, 8 or 10 mm is to check how aggregate size can affect the mixing process and mechanical properties.
    - It is difficult to use the same elements that performed in the laboratory to heat and mix the binder pellets with aggregates. Therefore, it is recommended to open the specialist company to develop portable asphalt mixer-heater system of binder pellets for field implementation.
    - All manufacturing and testing processes were performed in a controlled laboratory environment. Therefore, it is suggested to implement the proposed technologies for a range of environmental conditions which reflect seasonal variations that would be encountered in practice. In addition, it is also recommended to conduct a broad field study to monitor the service life of potholes repaired by the proposed innovative materials.
- As no real field results were available at the time of the investigation or were feasible to acquire, the economic and environmental assessment was based on laboratory results. Therefore, in order to accurately evaluate the economic and environmental impacts of the innovative patching materials, their implementation in real asphalt plants, as well as the

use of life cycle assessment (LCA) and life cycle cost assessment (LCCA) is recommended.

- A statistical field study would be useful to classify potholes in terms of depth, width, shape and content of water, solid or loose particles inside. This may support a decision-making system and the optimization of innovative technologies during the prefabrication stages.

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