Mechanical and sustainability assessment of induction heatable asphalt tiles and asphalt pellets in road maintenance

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Abstract. In this paper, two new methods for pothole repairing are proposed, assessed and compared. The first method is a combination of a prefabricated asphalt tile and a bonding layer that can be placed into a sanitized pothole and bonded by applying electromagnetic induction heating. The second approach consists of the prefabrication of asphalt pellets that can directly fill a given pothole and be heated by induction. By combining prefabrication and on-site induction heating, both methods offer high-quality mechanical performance while reducing the production of debris and noxious fumes. They can also improve work conditions for operators and the cost/time efficiency of road maintenance. In this research, both technologies were experimentally assessed through mechanical properties, such as tensile and shear strength and demonstrated by repairing potholes previously created on testing slabs and subjected to wheel tracking tests. Furthermore, the innovative patching materials have been evaluated from energy consumption. Both methods obtained very satisfactory results, showing excellent durability much more similar to a new road than to a road repaired with current techniques frequently used.

1. Introduction
Within the framework of pavement engineering, the term of durability was defined by [1] as the ability of the material comprising the mixture to resist effects of water, aging and temperature variation, in the context of a given amount of traffic loading, without significant deterioration for an extended period. This property of the materials constituting different road layers, is often deficient for the purpose they were designed. According to [2] asphalt surfacing, such as the Thin Surface Course Systems (TSCS) conventionally used in UK, have a service life of 7-15 years, considerably lower than the expected 10-20. Most reductions in roads service level and the most aggravating pavement distress for traffic safety [3] are caused by chemical degradation of bitumen that becomes brittle due to environmental conditionings [4], loss of binder-aggregate adhesion due to moisture penetration [5], thermal efforts [6] and traffic loads over aged asphalt pavements [7]. When these deterioration agents persist over time, cracks propagate throughout the material producing aggregate losses and the eventual formation of bowl-shaped potholes [8].

Besides temporary methods (e.g. throw and roll) only appropriate when weather conditions are too poor for semi-permanent patching or when the road is due to be rehabilitated soon, contemporary maintenance techniques, such as inlay/overlay or hot on hot paving processes are often expensive, involve high consumption of energy and significant health risks for operators due to high work temperatures and hazardous fumes and conditions [4]. The main costs associated with these techniques are labour, materials, equipment and traffic delays [9]. Just traffic disruptions due to damaged roads or maintenance works can involve great costs when they are produced in delicate
areas. For instance, according to [10], the congestion costs of road works in London could be around £2,000 per road work hour at the busiest places on the TRLN.

The most commonly used materials for repairing potholes are: hot mix asphalt, a mix of asphalt bitumen and aggregates with limited applicability due to requirements, such as minimum mixing batches and high application temperature; cold mix asphalt, a mix of asphalt emulsion, water and aggregates [11] that can be applied at ambient temperature but generally resulting in lower-quality solutions, due to their lower stiffness and required curing time [12, 13]; and a series of polymeric materials and resins that can produce high-quality repairs (e.g. dicyclopentadiene [14] or rapid setting urethane resins [15]) but at high cost.

In order to overcome these issues, the concept of induction heating was introduced in road maintenance engineering through two main different approaches: (a) induction-healing and (b) Rollpave. The first one consists in embedding electrically conductive particles in asphalt mixture and heating them by induction heating. The heat is transmitted by steel fibres to bitumen where the temperature can be increased by inducting heating to decrease the viscosity of bitumen and drain it into the cracks [16]. The second approach is a prefabricated asphalt mixture layer that can be extended over an old road surface and fixed by means of a bituminous membrane containing a steel mesh that can be heated and melted using induction energy [17, 18].

The present paper proposes and compares two new methods to repair potholes through the combination of prefabrication and on-site induction heating. The methods (1) are 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 no needs of heating elements and noxious fumes are necessary, (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 [19]).

2. Description of the proposed technology

Two different methods have been proposed to repair potholes by electromagnetic induction:
1. Asphalt tiles (Figure 1): The technology consists on prefabricating a portion of asphalt upper layer (similar to an asphalt tile) wrapped in a bonding skin of elastic polymer modified (SBS) bitumen containing electrically conductive particles. The bonding layer is very similar to bituminous membranes, which are thin layers of bitumen, of 2-4 mm thickness, modified with polymers. Once a pothole has been cut to dimensions of the tile [20], the tile can be gently placed into the pothole. By applying an external varying electromagnetic field, electric currents are induced through the metal particles embedded into the bonding layer increasing its temperature by Joules effect above 100°C in less than 1 min. When it cools down, and after applying some compaction, both layers remain stuck to each other. That lead to rise the modified binder when is hot to the top to fill the vertical sides and finally, the pothole is permanently repaired. Although each tile can be manufactured a-la-carte, the cost-efficiency of the process can be maximised and logistic issues reduced, by prefabricating the tiles in standardised sizes and compositions. Hence, the on-site work would be reduced to simply cut the pothole to the next tile size, fill it with a tile and apply some seconds of induction energy to bond both parts.

Figure 1. Schematic pothole repairing process by asphalt tile approach
2. Pelletized asphalt (Figure 2): In this case asphalt pellets are first prefabricated in asphalt plant, containing aggregates, bitumen and electrically conductive particles. These pellets can be packed and stored at ambient temperature. When a given pothole needs to be repaired, the pellets can be introduced into the pothole at ambient temperature and melted by applying electromagnetic induction. When the material reaches enough temperature, it can be easily compacted, leaving it ready for use as it cools down again. 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.

Both processes can be divided into two independent sub-processes: (1) prefabrication of asphalt tiles or asphalt pellets in asphalt plant and (2) on-site filling of pothole by asphalt tile or asphalt pellets and fixation of both elements by electromagnetic induction. Pre-fabrication allows the achievement of a high-quality materials, with aggregate gradation, bitumen type/content, air voids content, etc. that can be selected a-la-carte depending on the characteristics of the road where the intervention is going to be undertaken. On the other side, the on-site operations require significantly lesser time and do not require the emission of noxious fumes or the handling of materials at very high temperature.

![Figure 2. Schematic pothole repairing process by pelletized asphalt approach](image)

3. Materials and Methods

3.1 Samples Manufacturing

For the first approach (Figure 3(b)), the tiles were manufactured with hot mix asphalt, dense gradation, limestone aggregates, 5% binder content (by mass of total mix) and 5% target content of air voids (Table 1), according to Standard BSI 13108-1:2006. The bonding layer placed between tile and pothole was obtained by mixing 96% (by mass) of bitumen 40/60 pen and 4% of styrene-butadiene-styrene (SBS) during 2 h at 170°C, using a high shear mixer.

| 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%                                    |

The bonding layer was manufactured by heating the modified bitumen at 170°C and pouring it into a flat tray of 360 x 470 mm² until a thickness of 3 mm was reached. Then the membrane was cooled down at 5°C and cut into 100 x 100 mm² sections. Asphalt tiles with dimensions of 100x100x20 mm
were obtained by cutting 305 x 305 x 20 mm$^3$ asphalt slabs compacted at 140ºC by roller compactor with target air void content of 5%. While asphalt was still hot, loose steel fibres obtained from recycled tyres, with average diameter 0.34 mm and length distribution showed in Figure 4, were sprinkled on the upper surface of slabs and the bonding membrane was added on top. Taking advantage of the high temperature of asphalt layer, manual compaction was gently undertaken fixing all the components together. For the present research, four different amounts of steel particles were used according to the percentage of surface they cover (0%, 20%, 60% and 80%). In addition, the influence of bitumen content in the bonding layer was determined by fixing the steel content and adding 1, 2, 3, 4 or 5 layers of modified bitumen.

On the other hand, asphalt pellets (Figure 3(a)) were manufactured by mixing limestone aggregate (maximum size 2 mm) with bitumen 40/60 pen (four different contents: 10%, 15%, 20% and 25%) and steel grit with uniform size 1-2 mm (five contents: 5%, 15%, 25%, 35% and 45%). The blending was carried out at 170ºC for 2 min because of high bitumen viscosity. Then the mixed material was introduced into non-stick silicone cubic moulds with interior dimensions 8x8x8 mm, compacted manually and cooled down at 5ºC. 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. At this temperature, the pellets could be easily demoulded without producing any damage. Finally, they were stored in plastic containers at ambient temperature.

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Figure 3. Samples of bottom asphalt layer (simulating pothole surface) bonded to a top layer of pelletized asphalt (a) or to an asphalt tile with bonding membrane (b)

Figure 4. Steel fibres size distribution

3.2 Tensile Bond Test (TBT)

The adhesion between asphalt tiles or pellets layers and the bottom asphalt layer was measured according to Standard BS EN 12697-48:2013 by using an Instron hydraulic press (Figure 5). The top
and bottom surfaces of the specimens were bonded with epoxy glue (Araldite) to steel plates and the set was introduced into a temperature-controlled cabinet for 24h at 20ºC. During the pull-off test, a tensile load was applied from the plates at a deformation rate of 20 mm/min until the bonding between both layers failed. The tensile strength was calculated as the ultimate tensile load resisted by the sample (kN) divided by its cross-sectional area.

Figure 5. Tensile bond test

3.3 Shear Bond Test (SBT)

The interface shear strength was measured with the same Instron hydraulic press (Figure 6) and a shearing rig specially designed for the dimension of the test samples used in the present research. The samples were also pre-conditioned at 20ºC for 24 h. During the test, a shear load was applied by relatively moving the tile/pellets layer and the asphalt layer in opposite directions at a constant rate of 20 mm/min until the sample fails. The shear strength was calculated as the ratio between the maximum load (kN) and the cross-sectional area of the interface.

Figure 6. Shear bond test

3.4 Simulation of Traffic over a Repaired Pothole

The proposed concepts were demonstrated by creating artificial cylindrical potholes in asphalt slabs and repairing them by using asphalt tiles or pelletized asphalt (Figure 7). The slabs were manufactured
as two asphalt layers compacted one on top of another, producing a block of 330.5 x 330.5 x 100 mm³. Later, a cylindrical pothole of 150 mm diameter and 50 mm height was created by drilling and extracting a core from the top layer. Asphalt material was the same used to manufacture the tiles. The potholes were repaired by introducing a tile with same dimensions or by filling them with pelletized asphalt, as described above, and bonded to the bottom block by applying 15 s of electromagnetic induction. Finally, manual compaction by vibratory compactor was applied until both surfaces (slab and repairing material) were levelled. Traffic was simulated by using a Hamburg wheel tracking device, according to Standard AASHTO T 324-04, with the samples immersed in water at 25°C as a normal condition. The dynamic load was applied by passing 20,000 cycles of a 47 mm width wheel with vertical load of 705 N.

In order to compare the performance of the proposed technologies with the current applications, the tests were repeated with commercial cold asphalt mix (CAM) commonly used in UK, with dense gradation (maximum size 6 mm), granite aggregates and polymer modified bitumen emulsion. The compaction in this case was also carried out by vibratory compactor.

Figure 7. Section of sample used to simulate traffic over repaired pothole (tile setup)

3.5. Energy Consumption and CO₂ 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 requires special requirements such as heat equipment for HMA. 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 2 shows the energy consumption and CO₂ emission for asphalt tiles, asphalt pellets and HMA used as pothole treatments in this study [21]. The total value of energy consumption and CO₂ emissions were obtained by summing up all data from production until the implementation of each patching material, as shown in Figure 8.
Table 2. Energy consumption and CO₂ emission

| Consumption energy (MJ per pothole) | CO₂ emission (kg per pothole) |
|-----------------------------------|------------------------------|
|                                   | Asphalt | Asphalt | HMA  | Asphalt | Asphalt | HMA  |
| Total amount of materials (kg)    | Asphalt | Asphalt | HMA  | Asphalt | Asphalt | HMA  |
| 89.21                             | 112.03  | 87.23   |      | 89.21   | 112.03  | 87.23 |
| Processes                         |         |         |      |         |         |      |
| Manufacture                       | 29.95   | 30.81   | 23.98| 2.44    | 2.51    | 1.95  |
| Transport                         | 2.59    | 3.24    | 9.94 | 0.005   | 0.0069  | 0.81  |
| Laying and compacting             | 10.88   | 11.09   | 2.29 | 0.054   | 0.067   | 0.056 |
| Raw materials                     |         |         |      |         |         |      |
| Bitumen 40/60                     | 21.24   | 17.74   | 23.27| 0.82    | 0.68    | 0.902 |
| Aggregates                        | 3.22    | 2.99    | 3.45 | 0.72    | 0.67    | 0.77  |
| PMB                               | 44.68   | -       | -    | 2.78    | -       | -     |
| Steel particles                   | 2.85    | 349.12  | -    | 0.129   | 15.80   | -     |

Figure 8. Total values of energy consumption and CO₂ emission

3.5.1. Overview of the studied cases

In the present study, the impact of the two innovative patching materials proposed to repair potholes by electromagnetic induction were assessed from two different points of view: energy consumption and CO₂ emissions. In order to define the inputs of the model, the steps needed to implement these patching materials are described in section 2.

Table 3 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 3. 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     |
| HMA               | 2 min    | 3 min   | 2 min  | -       | 2 min      | 2 min     | 11 min     |

The theoretical pothole to be repaired was taken as a 1 m² 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 be demolished and rebuilt.

In the literature it was found that the service life of a pothole repaired by HMA is 4 years [22]. 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 (obtained before).

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 4.

Table 4. 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                   |
| HMA               | 0.46           | 4                         | 2.5                     | 5                      |

Finally, as the innovative patching materials containing metal particles can be reheated over the service life of the repaired pothole, two maintenance hypotheses 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.

3.5.2. Data Source

The data inventory source relating to energy consumption and CO₂ emission for raw materials, transport, fuel, etc., was taken from different sources founded on the literature review as shown in Table 2 and 3. The 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 [22] and [23] that provided an insight into the effect of durability and environmental impact. In this study, all data relating to the activities of repair were mainly collected from published reports from previous research as mentioned in Table 5 and 6.
Table 5. Inventory data collection of Energy consumption

| Product                          | Energy (MJ/t) | Data Source |
|----------------------------------|---------------|-------------|
| Bitumen                          | 4900          | [24]        |
| PMB as bonding layer             | 5940          | [25]        |
| Aggregates                       | 41.85         | [26]        |
| Steel fibres, steel grits        | 9500          | [27]        |
| Production of HMA                | 275           | [28]        |
| Laying of HMA                    | 9             | [28]        |
| Remixing of HMA (MJ/m²)          | 1.5           | [29]        |
| Lorry Transport (km/t): transport to work site HMA | 79 | [28] |
| Lorry Transport (km/t)           | 29            | [25]        |
| Total energy of fossil and electricity of steel fibre | 12.24 | [28] |
| Fuel                             | 35            |             |

Table 6. Inventory data collection of CO₂ emission

| Product                          | CO₂ (Kg/t) | Data Source |
|----------------------------------|------------|-------------|
| Bitumen                          | 190        | [24]        |
| PMB as bonding layer             | 370        | [25]        |
| Aggregates                       | 9.4        | [28]        |
| Steel fibres, steel grits        | 430        | [27]        |
| Production of HMA                | 22.4       | [28]        |
| laying of HMA                    | 0.6        | [28]        |
| Remixing of HMA (CO2 (kg/m²))    | 0.0959     | [25]        |
| Lorry Transport (km/t): transport to work site HMA | 5.3 | [28] |
| Lorry Transport (km/t)           | 0.0617     | [25]        |
| Fuel                             | 4          | [28]        |

4. Results

4.1 Tensile and Shear Bond Tests

Figures 9 show the tensile and shear strength of tile samples (a) and pellet samples (b) with different amounts of conductive particles. It is very noticeable that higher amounts of steel improve the results of pellets samples (above 0.4 MPa) but reduce the tensile strength of the bonding layer between tiles and asphalt (values between 0.1 and 0.3 depending on number of bonding layers). It was checked that in both cases, higher fibre contents can be translated into higher heating potential, which is consistent with other publications [16], as it helps asphalt pellets to reduce their viscosity and fill the pothole in a more effective way (increasing results in Figure 9-right). However, metal fibres do not significantly provide mechanical strength to the bonding layer between tile and bottom block [30] and excessive amounts can lead to bundles formation and bitumen absorption in the space left between the fibres [31]. Because of the high surface area of fibres, aggregates could not be fully coated that led to weakening of the bonding layer (Figure 9(a)).

Figure 10 shows the effect of bitumen content for both approaches for a given amount of fibres. In Figure 10(a) for asphalt tiles, when increasing the number of the bonding layer (i.e. increasing bitumen...
content), both tensile and shear strength increase practically linearly. This phenomenon is similar to the self-healing of cracks in asphalt mixture, which is influenced by the packing density of bitumen between aggregates and fibres. When the binder is heated, its viscosity reduces and flows by gravity and surface tension filling the gaps and increasing the bonding between tile and pothole [16]. For the case of pellets (Figure 10(b)), this trend was not so evident, indicating that bitumen content does not affect the results as much as the steel content. Nevertheless, it must be highlighted that in all the samples manufactured with 25% of bitumen content and half of the samples manufactured with 20%, the failure occurred through the bottom asphalt layer instead of through the pellets layer or interface between both. For the case of tiles, also 60% of samples made with 5 bonding layers and 40% of samples with 4 bonding layers broke through the bottom layer (Figure 11). These results give an idea of the high potential of these materials to resist tensile and shear loads being even able to reach higher strength than the original asphalt.

![Figure 9](image9.png) **Figure 9.** Tensile and shear strengths of asphalt tiles (a) and asphalt pellets (b) depending on the content of steel

![Figure 10](image10.png) **Figure 10.** Tensile and shear strengths of asphalt tiles (a) and asphalt pellets (b) depending on the content of bitumen

![Figure 11](image11.png)
Figure 11. Pictures of samples were the failure happened through the bottom layer instead through the top layer or interface a) shear test b) tensile test

When comparing both methods, the tensile strength of pellets is 40.3% lower than the tensile strength of asphalt tiles. However, they also resisted 1.84 times higher shear stress. On the one hand, the strength of pellets resulted quite stable when varying the bitumen content but both tensile and shear strength reduced considerably for low steel contents. On the other hand, with the tile approach, it happens the opposite, significantly reducing the strength when reducing the amount of bitumen in the bonding layer. As an example, tensile strength of the tiles is 29.1% lower than for pellets when only one membrane is used for the bonding layer, but also 67.1% higher when 5 membranes are used.

4.2 Resistance to Traffic Loads
Figure 12 shows the deformation registered at the midpoint of the specimens after 20,000 cycles of wheel tracking test. The results obtained for pellets and asphalt tiles are shown together with the results obtained by a commercial cold asphalt mix (CAM) and the control slabs, where no pothole was produced (case of a road newly paved). As can be seen, pellets (1 mm) and tiles (0.7 mm) kept deformations within the range of 0 – 1 mm, obtaining values very similar to control slabs (0.4 mm). In addition, the results obtained for CAM were similar to those reported in [32] and significantly higher than those previously mentioned (17.4 mm one day after manufacturing and 15.0 after 7 curing days at ambient temperature). This means that the proposed methods perform better than commercial solutions currently used in maintenance.

Figure 12. Deformation at the end of wheel track test observed at the midpoint of the slabs made of different materials
From the proposed methods, the tiles obtained lower deformation due to (1) high-quality asphalt mixing and compaction of the tile during prefabrication, (2) strong bond between tile and bottom asphalt and (3) excellent performance of bonding layer under dynamic loads. When using pellets, the compaction cannot be undertaken under so-well controlled conditions. During the test, further densification of the material is produced, resulting in slightly higher deformation. Nevertheless, both approaches behave very similarly to a hot mix asphalt, producing excellent results without the need of any curing time, the possibility of opening the road when the temperature of the material decreases back to ambient temperature. On the contrary, the presence of water in CAM requires that the road is closed for long periods of time with no traffic loads acting.

4.3. Energy Consumption Impact

Figure 13 (a) compares the energy consumption of conventional patching materials (HMA) with the energy consumption of the innovative patching materials. It can be observed that the energy consumption of asphalt 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 1m².

Figure 13 (a) also shows the asphalt tile option becomes more energy efficient than HMA. Therefore, after 10 years, by using asphalt tiles instead of HMA, reductions in energy consumption of 16.40% and may be achievable. On the other hand, significant differences were also observed after 20 years. Energy consumption of HMA was predicted to be 2.06 times of energy consumption of asphalt tile. But energy consumption of asphalt pellets was higher, about 1.29 times the energy consumption of HMA.

Figure 13 (b) (second hypothesis) shows that the total energy consumption of asphalt pellets is significantly higher than asphalt tiles and conventional patching materials. However, after 20 years, the use of asphalt pellets results in a cumulative energy consumption 3.63 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.
4.4. CO₂ Emission Impact

Figure 14 (a) shows the total CO₂ 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 CO₂). 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 asphalt pellets after 8-12 years. This again indicated that the used of innovative patching materials for repairing potholes can be more sustainable.

Figure 14 (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 CO₂ emissions produced by the asphalt tiles (4.46 CO₂ kg) remain lower than asphalt pellets and binder pellets (17.16 CO₂ kg).

Figure 14. Total CO₂ emission of pothole repair over time (a) hypothesis 1 and (b) hypothesis 2

5. Conclusions

The present research assessed and compared two proposed methods for pothole repairing by using electromagnetic induction. Based on the obtained results and comparing them with commercial CAM frequently used in road maintenance, the following conclusions could be extracted:

- Both methods offer high-quality mechanical performance (in some cases even better than the original asphalt) and efficiency through the combination of in-plant prefabrication and on-site implementation by electromagnetic induction. The proposed methods also reduce the amount of debris and improve the conditions of health and safety for operators.
- The performance of asphalt tiles is slightly better than asphalt pellets in terms of shear strength and resistance to permanent deformations but worse when it comes to tensile strength.
- While asphalt pellets perform better with high steel contents (at least 35% by mass), the results of asphalt tiles improved especially when increasing bitumen content in the bonding layer (3-5 SBS membranes). However, high steel contents are counterproductive when using asphalt tiles, as it reduces the bonding capability of the interface layer.
- When the bitumen content is high enough (at least 4 bonding layers for tiles and 20% for pellets) the mechanical properties of the repaired material can be even better than the original asphalt, what gives an idea about the great potential of the proposed technologies.
- The resistance to permanent deformations of both methods resulted more than 15 times better than the commercial CAM, even after 7 curing days. In fact, the performance was much more similar to a road newly paved. Results of asphalt tiles were slightly better, although the pellets are easier to use and implement, as no sanitation of the pothole is needed before reparation.
- Under the first maintenance hypothesis, the innovative materials consume more energy during the first repaire: especially asphalt pellets. Only asphalt tiles need lower and become more energy-efficient than HMA, although this only happens 4 and 7 years after the initial repARATION.

- Regarding CO₂ emissions, all innovative patching materials produced higher results, whose emissions are around 3 times higher than HMA. However, asphalt tiles become more sustainable than HMA after 1-2 years and asphalt pellets after 8-12 years.

- Under the second hypothesis, the energy consumption of the innovative patching materials is always higher than HMA. CO₂ emissions produced by asphalt tiles are slightly higher than HMA. However, the emissions produced by binder pellets and especially asphalt pellets are significantly higher.

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