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Is this the end of the road for bio-inspired road construction materials?

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Abstract

The global road network spans 64.3million km and is of huge significance for the social and economic development. The level of investment in road construction and maintenance is high, e.g. EU €44billion/year (2019), China €614.7billion/year (2019) and US €94billion/year (2019). Despite the level of investment, there has been minimal investment in the development of new asphalt technologies, particularly when compared with R&D investment in other industries, such as the automotive industry.

Despite the limited investment, there have been some innovations in asphalt technology. For the past 20 years, researchers have developed bio-inspired asphalt technology, self-healing and bio-binders and have applied them to asphalt pavements. This research has emerged as a response to global warming and the need to reduce both carbon emissions and reliance on oil in asphalt technology.

This paper charts the development of two bio-inspired technologies and considers their significance in relation to the need to reduce carbon emissions and oil dependence (in line with the UN strategic goals, specifically: SDG 9, 11 and 12). This paper considers the potential benefits of bio-inspired technologies and outlines the current barriers to their further development. This paper aims to begin a conversation with stakeholders on how to speed up the acceptance of bio-inspired asphalt technologies and their adoption in road design, construction and maintenance. Or is it the case that we have reached the end of the road for bio-inspired road construction materials?

Keywords: Bitumen; Asphalt; Bio-innovation; Self-healing asphalt; Biomass; Bio-bitumen/rejuvenator

1 Introduction

The global road network spans 64.3million km [1], of which 6.25million km is in the EU(27), 6.8million km in the US, 5.2million km in China. Road networks are a major national asset, fulfilling l key economic and social goals by facilitating the movement of goods and people [2]. National governments invest heavily in their road networks, e.g. in 2019, €44 billion was invested in the development and maintenance of the EU road network [3], in the same year China invested €614.7 billion and the US invested €94 billion into their national road networks.

The world produces 1.6 trillion tonnes of asphalt annually [4], of which 218 million tonnes is produced in the EU [5]. The current cost of asphalt in the EU is €200 per tonne [6]. Road construction and maintenance are a significant cost to tax payers globally. These costs will increase as the sources of bitumen (a product of crude oil) diminish [7, 8]. Improved road design and alternative road materials offer the road industry:

i. an opportunity to develop alternatives to crude oil,
ii. the potential to improve efficiency and generate financial savings,
iii. the opportunity to develop road materials and road construction methods which can reduce the environmental and the economic costs of road construction.

Unlike other construction materials, road materials have barely evolved in 100 years [9], despite a focus (since the 1970s) on developing more sustainable materials for road construction, e.g. recycled asphalt pavements [10]. Recycling asphalt involves removing the old asphalt; and mixing it with new (fresh) aggregates, binder and/or rejuvenator [10, 11]. The primary purpose of the recycling process is to restore the original rheological properties of the aged bitumen in order to extend the life of the asphalt pavement (road). The road lifespan is extended by adjusting the properties of the asphalt mix, i.e. reducing its stiffness [12]. Traditionally petroleum based oils are used as aged asphalt bitumen rejuvenators. However, recent studies [13-17] have demonstrated that food by-products (i.e. vegetable oil) can also be used as an asphalt rejuvenator. Though, diverting plants from potential food resources to asphalt production is unacceptable given the increased pressure on food resources globally. Biomass is a promising alternative material source [14]. It is a renewable bio-material source which can be linked to the circular economy whereby industrial by-products and secondary

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materials, can be used in an alternative bio-binder/rejuvenator production [14, 18].

There are two drivers of change; one is the need to develop alternatives to bitumen (a crude oil biproduct) but also the growing pressure on construction industry more generally (including the road industry) to reduce its environmental impact [19]. However researchers have shown [19] significant resistance from the road industry to any change to its traditional practices. Using the innovation to bring about change will enable the asphalt industry to develop more environmentally friendly materials, construction and maintenance processes.

This paper describes two bio-inspired technologies (self-healing asphalt and bio-binders/rejuvenators), outlining the benefits of each. The paper discusses some of the reasons for the slow industry uptake of these two innovative and disrupting technologies. The purpose is to initiate a discussion within the asphalt industry/asphalt research community on how obstacles to innovation take-up might be overcome to ensure more rapid translation of innovative, environmentally friendly technology into road design, construction and maintenance.

2 Bio-inspired Solutions

Bio-innovations are inspired by the world around us. All of the inventions are inspired by nature and have inspired innovative, eco-solutions with a minimal environmental costs [20]. Scientists and engineers worldwide are beginning to consider bio-inspired solutions to some of our greatest challenges. Two bio-inspired asphalt technologies are: (1) Self-healing asphalt Technology which mimics healing within nature and (2) bio-oil utilisation which mimics a circular (closed loop) system used by forests where biomass from forest floor is used as source of nutrients for plants and animals.

2.1 Bio-mimicking: Self-Healing Asphalt Technology

Self-healing technology seeks to enable material systems to heal after damage and to extend or to renew the functionality and life-time of the damaged part, system or device[21]. Fisher [21] defines the self-healing and self-repair of a material or system as: "*the ability to substantially return to an initial, proper operating state or condition prior exposure to a dynamic environment by making the necessary adjustments to restore to normality and/or the ability to resist the formation of irregularities and/or defects*". The repair should be an automatic response to damage or failure. Fisher [21] classifies repair into two categories:

Attributive repair – restoring the attributes of the system to their original state, i.e. to full capacity.

Functional repair – restoring the function of the system. If full functionality cannot be restored, this strategy will use remaining resources maximise the available functionality.

Attributive repair is the optimal solution. Living organisms possess intrinsic self-healing properties, enabling them to recover from damage or injuries sustained. This repair or healing occurs with no external intervention. Some natural self-healing composite systems - such as bones - go beyond simple healing to continuous remodelling and strengthening [22]. In relation to self-healing asphalt, RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures) Technical Committee TC 278-CHA (Crack-Healing of Asphalt Pavement Materials) has classified the asphalt self-healing technology into two categories [23]:

i. Intrinsic (Self-)healing: asphalt self-healing behaviour that is inherent to the material used and
ii. Extrinsic (Self-)healing: asphalt self-healing behaviour that can be attributed to additives, such as: conductive particles (iron fibres or powder) and capsules and fibres encapsulating bitumen rejuvenator, added to the asphalt to improve self-healing capabilities, trigger crack-healing or prevent crack propagation.

To date, researchers have tested four extrinsic self-healing methods for asphalt pavements [24]:

i. *Induction heating*; involves adding electrically conductive fillers (steel fibres and steel wool) into the asphalt mix and initiates healing by sending an alternating current through the coil. When the conductive asphalt specimen is placed beneath the coil for 3-5 minutes, the electromagnetic field induces currents flowing along the conductive loops within the asphalt formed by steel fibres [25]. The current causes the conductive particles - steel fibres or iron powder - within the asphalt to heat, the heat softens the bitumen allowing it to flow, thereby sealing the cracks and repairing the damaged asphalt [24, 26-28].
ii. *Microwave heating*; creates high-energy wavelengths which react with the conductive particles in the asphalt. As with induction heating, microwave heating causes the conductive particles (steel fibres) embedded in the bitumen mix, to heat up. The heat causes the aged bitumen to soften, allowing it to flow and repair the micro crack damage. Laboratory studies have shown that this method can repair test specimen damage within 3 minutes [29-31] of heating. The microwave method requires fewer conductive fibres to achieve the temperature required for healing to occur.

    Researchers have demonstrated that the induction and microwave heating methods are efficient methods for healing asphalt damage, (3 to 5 minutes) in comparison to rejuvenation [32, 33]. However, a challenge with both methods is that the heating process (both induction and microwave) ages the bitumen, causing binder brittleness and the premature failure of the asphalt.
iii. *The rejuvenation* method was developed to address the challenge of bitumen ageing caused by induction and microwave heating. Rejuvenation involves adding an encapsulated healing agent (rejuvenator) into the

asphalt mix to restore the original bitumen properties[34]. When micro-cracks form within the pavement, they encounter a capsule. The fracture energy at the tip of the propagating crack opens the capsule, releasing the healing agent which then diffuses within the bitumen to seal the crack [35-37]. The rejuvenator encapsulation approach represents a more favourable method of asphalt self-healing as it enables the aged bitumen to return to its original chemical, physical and mechanical properties. However, there are limitations with this method of self-healing because the healing rate is slow and healing efficiency low [33, 38].

iv. *Hybrid self-healing systems*, provides a solution to the challenges associated with induction, microwave and encapsulated rejuvenation. The hybrid self-healing technology combines induction heating and encapsulated rejuvenation [33]. In this process, induction heating is used to repair the asphalt damage (and the cracks) while rejuvenation is used to replenish the aged asphalt binder (bitumen). For the asphalt pavement with an hybrid self-healing system when pavement damage occurs, induction heating is used to close the cracks. After several cycles of healing, the asphalt binder (bitumen) will oxidise and become brittle, rendering further induction heating ineffective. At this point rejuvenator is released from the capsule core passively, via crack propagation which will open the capsule and release the rejuvenator into the asphalt or thermally by applying the induction heat > 80^{o}C which will cause alginate in the capsule to disintegrate and release the rejuvenator. Xu *et al.* [35] demonstrated that a hybrid healing system improves the healing efficiency allowing for rapid damage repair and a simultaneous rejuvenation of the aged asphalt. However, a challenge with this approach is that the bituminous mix must be adjusted to accommodate both capsules and steel fibres. A solution to this challenge lies in combining the induction and rejuvenation into one product. The author (Tabaković *et al.* [39]) has developed a novel extrinsic self-healing asphalt technology**:** Conductive Alginate Capsules Encapsulating Bitumen Rejuvenator (oil), which reinforce the asphalt pavement by improving its tensile and compressive strength and enhancing its autonomous healing properties via induction heating. The concept combines two existing self-healing asphalt technologies: i) rejuvenator encapsulation and ii) induction heating to create a self-healing system which provides rapid and effective asphalt pavement repair. Initial results [39] demonstrated that capsules have sufficient thermal and mechanical strength to survive the asphalt mixing process and also that it sufficiently heals the asphalt bitumen damage. Initial results also demonstrated that the capsules can improve the mechanical properties of the asphalt mix in terms of improving tensile strength and stiffness. With a capsule content of 20% in pure bitumen, the mix strength of the material increases to 118%. Whereas for mortar bituminous mixtures (bitumen + fine aggregates – sand), the mix strength of the material increases by up to 67%. However, the system does not demonstrate a good healing response for the full asphalt mix. Although the system is still under development, it is necessary to determine the optimal amount of capsules in the mix to initiate induction healing while not diminishing the mechanical and physical properties of the asphalt mix. Wan *et al.* [31, 40] developed a calcium alginate/nano-Fe_3O_4 composite capsules for controlled rejuvenator oil release using microwave heating. Wan *et al.* have shown that Fe_3O_4 alginate capsules encapsulating rejuvenator can successfully be inserted into an asphalt mix and that they distribute evenly throughout the asphalt mix. Wan *et al.* showed that capsules demonstrated superior levels of healing with microwave heating due to the combined effect of thermal induction and rejuvenator healing. Wen *et al*. have shown that hybrid Fe_3O_4 Calcium alginate capsules encapsulating rejuvenator have a higher self-healing capacity (8.6%) when compared to the mix containing pure calcium alginate capsules encapsulating rejuvenator and 19.3% in comparison to standard asphalt mix. The asphalt mix containing 2% of the capsules achieved up to 87.2% healing after 40 seconds healing time.

The idea of the extrinsic self-healing for asphalt pavements (roads) stems from the concept of the "forever open road", motivated by the need to avoid the traffic disruption (and associated risk of accidents) caused by road maintenance activities on busy roads. A challenge for the road industry is how to ensure the safety of road construction workers during the pandemic (keeping them safe from COVID-19 as well as from road traffic). How can road construction workers/crews maintain social distancing from each other and from vehicle, cyclist and pedestrian traffic [41] while also remaining safe from oncoming traffic. In the UK, 175 crashes per month are caused by drivers driving into road-work sites [42]. The USA Centre for Construction Research and Training (CPWR) reported 1,230 fatalities and 324,000 work zone injuries of road construction workers between 2009 and 2018 [43]. These figures show that current methods of road maintenance involve risk and danger for road maintenance workers/crews. Extrinsic self-healing asphalt technology has the potential to reduce the need for road maintenance, thereby reducing risk to road maintenance workers while simultaneously reducing the environmental impact of road construction. It is estimated that extrinsic self-healing asphalt technology could reduce energy consumption and CO_2 emissions by 30% over the lifetime of the road [44]. Extrinsic self-healing asphalt technology has potential to address several of the technical, economic, environmental and safety challenges currently facing the road industry.

2.2 Bio-utilisation: Use of bio oils as bitumen additives and rejuvenators

Bitumen has traditionally been used as a binder in asphalt mixes and is a product of crude oil. The production of crude oil is in decline [8] and the environmental and financial costs of extraction are constantly increasing [7, 8]. There is a need to identify alternatives to bitumen, preferably cheap and sustainable alternatives. An asphalt binder generated from biological sources (Bio-binder) offer an environmentally friendly and economically viable alternative to asphalt bitumen. Consideration has been given to plant based alternatives to bitumen [17], using tall oil, rapeseed oil, soybean oil, sunflower oil, corn oil, used cooking oil, castor oil residues and organic oils. These products are generally mixtures of fatty acids (and esters) [45], Table 1 list some of the plant based oils and their content.

Table 1. Vegetable oils and their content [45].

Type	Content
Sunflower oil	palmitin, stearin, olein and linoleic acids
Soybean oil	Unsaturated fat (triglycerides are the polyunsaturates alpha-linolenic acid and linoleic acid), saturated fat (oleic acid), monounsaturated fat (stearic acid and palmitic acid)
Palm oil	palmitin and olein
Castor oil (from Ricinus plant)	triglyceride of ricinoleic acid
Cashew nut oil (oil from the peel of the nut of the cashew tree)	phenol derivatives with long side chains (anacardic acids, cardol and cardanol)
Cotton seed oil	linoleic acid and olein
Linseed oil	linoleic and linolenic acid and, to a lesser extent, olein

The addition of plant based oil products as a rejuvenator results in a lower viscosity of the resultant binder blend. Several studies have highlighted that these rejuvenators can restore the original properties of bitumen, while also being eco-sustainable [17]. There are no many commercially available plant based asphalt bitumen rejuvenators, some of the commercially available plant based asphalt rejuvenators (see Table 2). It is important to note that all bio-genetic organism, including plants, fall under strict Nagoya regulations which specify how the genetic material can and should be shared between regions [46].

Table 2. Commercially available plant based aged bitumen rejuvenators [45].

Product Name	Producer
Rheofalt HP-AM	Ventraco Chemie
ReJUVN8	Sripath Technologies, LLC
RePLAY 18	BioSpan Technologies Inc.
Hydrogreen S™	PVS Meridian Technologies Inc.
Anova 1817 Rejuvenator	Cargill Industrial Specialities
Biorestor	BioBased Spray Systems LLC

Researchers [47-49] have studied vegetable oil encapsulated rejuvenator within calcium alginate capsule as an extrinsic self-healing system. The studies reported good healing efficiency of the asphalt samples using vegetable oil, but also that it failed to outperform petroleum based rejuvenator.

Despite promising results from several studies using plant-based oils as rejuvenator [17, 47, 49, 50] diverting plants from potential food resources to asphalt production is unacceptable given the increased pressure on food resources globally. Biomass is a promising alternative material source. It is a renewable bio-material source which can be linked to the circular economy whereby industrial by-products and secondary materials, can be used in an alternative bio-binder/rejuvenator production.

Waste Cooking Oil (WCO) holds promise as an alternative source of rejuvenator [51, 52], which is readily available [26], more than 18 million tons of WCO is produced annually worldwide. WCO is considered to have detrimental effects on the environment by altering the oxygen levels of water due to the formation of an impermeable layer on the water surface. Moreover, during the degradation of WCO, toxic compounds are released which may be ingested by aquatic animals and thus potentially re-enter the human food chain [53]. Utilisation of the WCO in roads construction, as aged bitumen rejuvenator, has been studied as an environmental and economic solution to the WCO disposal [14]. Zargar *et al.* [54] studied behaviour of the WCO rejuvenated bitumen and compared with virgin bitumen after using the rolling thin film oven ageing process. They reported that 3–4% WCO content can rejuvenate the aged bitumen of group 40/50 to meet all the physical and rheological tests to a level that is comparable with the original 80/100 bitumen. They further concluded that WCO rejuvenated bitumen has less tendency to short-term ageing, correlated to physical, rheological and chemical ratio, compare with virgin bitumen. These findings highlight WCO as potential replacement for standard petroleum based aged bitumen rejuvenators. To reduce the potential environmental impact on human and animal health and to avoid competition with oils from food sources, WCO presents its self as an ideal material to potentially replace petroleum based bitumen rejuvenating oils.

Lignin, by-product of wood processing, was identified by van Vliet *et al.* as a suitable source of biomass [55] for the production of bio-bitumen blends [56]. Van Vliet *et al.* [56] studied the performance of lignin on rheological properties of the bitumen binders (70/100 pen). Van Vliet *et al.* concluded increasing the amount of lignin has a significant effect on the rheological behaviour of the blend, compared to fresh bitumen. Van Vliet *et al.* reported that lignin-bitumen blends, containing 25% of lignin can increase the bitumen stiffness, resulting in polymer like behaviour of the asphalt binder. This indicates that lignin could be used as bio-polymer modifier in bitumen blends, instead of using the petroleum based polymer modifiers. Currently the road authorities in the Netherlands, in collaboration with road and material research centres (Circular Biobased Delta, Utrecht University, Wageningen University, H4A) are running pilot trials which replace petroleum bitumen with lignin-bitumen blends [57]. Eiffage, a French based company, have successfully developed a commercially available rejuvenator based on the pine wood by-product, named Recytal[58, 59], which is very effective replacement for petroleum based rejuvenators in the asphalt recycling process, both hot and cold.

Microalgae have been considered as an alternative source of bio-fuel [60], but also have potential as an alternative bitumen or asphalt binder [61]. Audo *et al.* [61] have demonstrated that microalgae can be converted into crude oil, which is an ideal material for the production of bio-binder. The bio-oil produced has an equivalent energy value to fossil fuels [62], making it suitable for bio-fuel but also possibly as an asphalt binder source [61]. Maximum biocrude yields in the range of 40%–50% have been reported [61], though they are at an initial stage of development. The BioRePavation project [63] demonstrated that microalgae oil can be used as asphalt binder in the construction of new asphalt mixtures and in the asphalt recycling process. The additional sustainability benefit of microalgae utilisation for production of aged bitumen rejuvenator is that the microalgae cultivation can be linked with the water purification process, where microalgae is cultivated in the water purification system. After processing the microalgae biomass (oil extraction) residue, from the biomass processing, could be used as animal feedstock or land fertiliser, while oil is utilised in the roads construction.

Swine Manure derived bio-binder can solve the dual problems of environmental pollution caused by the accumulation of solid swine waste and replacement petroleum bitumen by sustainable asphalt bitumen binder. Heavy metals found in animal waste can lead to heavy metals leaching into the soil. Improper treatment of swine manure may also result in air pollution by toxic gases (foul odour), soil and water contamination, which can have a significantly negative effect on the environment [64]. Wang *et al.* [64] studied the swine-manure-derived bio-binder. They concluded that the bio binder derived from the swine-manure-derived improves low temperature cracking of an asphalt mix.

In order to extract the oil from any of these alternative biomaterials (that can be used in asphalt production), biomass processing thermal and/or chemical is required, such as rapid pyrolysis, esterification or hydrothermalliquefaction (HTL), flash pyrolysis and co-pyrolysis, [14, 61, 65-69].

There are two major routes for the chemical processing of biomass bio-oils: (i) thermo-chemical and (ii) biochemical. The advantage of thermochemical processes is that the biomass can decompose within a few minutes. Thermochemical techniques include "pyrolysis, gasification, hydrothermal" processes ("hydrothermal gasification, hydrothermal liquefaction, hydrothermal carbonization") and supercritical oxidation. Fermentation, anaerobic digestion and composting are involved in biochemical processes [70]. The biochemical method, however, takes longer to convert biomass, because bacteria and enzymes are needed as catalysts [14]. Bio-oils, in general, have higher oxygen content, viscosity and density in comparison to regular asphalt binder, and this can lead to low heating value, immiscibility with conventional fuels and instability during storage [14]. This challenge can be addressed by processing the bio-oil using techniques like co-pyrolysis and hydro-treating catalytic processes effective in reducing the oxygen content and removal of heavy metals [14].

The use of bio-oils in asphalt production offers an opportunity for the asphalt industry to reduce its negative impact on the environment. Introducing bio-binders into the asphalt pavement production process could reduce the carbon footprint of the asphalt industry. The utilisation of waste biomass, including waste vegetable oils and lignin offer the asphalt industry a source of alternative bio-based asphalt binder and an alternative to crude oil. Replacing petroleum based oils (bitumen) with oils from biomass in asphalt production would make asphalt production part of the circular economy, which is one of the key aims in the EU Circular Economy Action Plan for a cleaner and more competitive Europe [71].

3 Barriers to bio-innovative technology scale up

Researchers have demonstrated the performance levels of bio-inspired technology. Both self-healing asphalt technology and bio-binder/rejuvenator technology can be easily adapted into the current asphalt production process. However, despite the clear technical, environmental and social impetus for adopting these innovative technologies, there is little urgency from the asphalt industry. The barriers to adoption include:

i. Self-healing technology:
   - *Equipment deficit*: although laboratory and on-site results [24, 72-74] demonstrate the clear benefits of induction/microwave and hybrid healing, industry cannot adopt these technologies until induction or microwave vehicles are widely available. The induction or microwave vehicles required must enable asphalt repair while vehicle is in motion if they are to remove the need for road closures. One company (EpionAsphalt [75]) is in the process of developing such an induction vehicle.
   - *Production cost*: when considering microcapsule rejuvenation, two issues arise the first is the efficiency of the healing process [36, 38] and the second is the cost of microcapsule production. The author (A.T.) has received quotes from two European microcapsule producers who estimate that the cost of calcium alginate microcapsule encapsulating bitumen rejuvenator production at €110/kg and €180/kg of dry capsules including rejuvenator. Such high costs could only be justified if the efficiency of self-healing using microcapsules were to be higher than commercial value of the product.

ii. Bio-binder/rejuvenators, there are two issues with biomass utilisation:
   - *Supply chain issues*: The EU is currently phasing out fossil fuels (coal, peat, gas etc.) in energy production. Going forward, traditional power plants will be converted to biomass. This presents a challenge to the prospect of biomass oil production. The EU currently imports biomass (wood) from US to supply its demand for powerplant biomass [76, 77]. Although WCO has shown promising results as

a bitumen rejuvenator, the quality of the product is variable, which impacts on the quality of the bio-rejuvenator. The key challenge with bio-binders, then is ensuring a guaranteed supply of good quality raw material.

- *High energy use*: Biomass processing requires a high amount of energy (thermal and chemical) for oil extraction [78]. However, Steele *et al.* [78] have shown that wood bio-oil production using pyrolysis method results in lower sustainability costs (in terms of energy and emissions [78]). It could be argued that plant and microalgae carbon dioxide absorption during the cultivation process, thereby compensating for the energy used and CO_2 released during the processing stage [79].
- *Cost*: Despite the positive environmental benefits to be derived from the adoption of this technology, economic factors continue to be a key barrier to change in the asphalt industry. Oil based bitumen currently costs between €0.314 - €0.506/kg [80], whereas the cost of bio-oils is much higher. Based on ASAP [81] costings, where a suitable, EU sourced supply of microalgae was sourced, the cost of the biomass ranged from between 20 €/kg – for Spirulina (5% lipid content) to 240 €/kg – for Nannochloropsis paste (40%-50% dry weight lipid content). If the further processing costs of the biomass are factored in, the market value would exceed performance and environmental benefits of the bio-bitumen.

Although research has shown us the potential of bio-inspired technologies to revolutionise the asphalt industry, there is little motivation within the asphalt industry to realise their potential. Encouraging the asphalt industry to explore and implement environmentally-friendly alternatives to crude oil will require incentives and encouragement from policy makers at EU and national levels and should form part of wider climate and enterprise initiatives. It is clear that without incentives/encouragement, the asphalt industry will not embrace bio-innovation or environmentally friendly alternatives to crude oil.

4 Discussion

So, is this the end of the road for the bio-inspired road construction materials and technologies? Possibly!

But we should not ignore the potential benefits of self-healing and bio-binder based technologies. Research has shown that these technologies can improve the physical and mechanical performance of asphalt pavements (roads) and that they can reduce the environmental cost of road construction and maintenance.

So before we walk away from these innovations, we should consider whether some of the barriers are surmountable.

In relation to extrinsic self-healing, although the vehicles to facilitate induction/microwave are not yet readily available, this only prevents its use in full road maintenance, self-healing technology could easily be adopted for asphalt joint repair and/or pothole patching. The high cost of capsule production could be addressed by enabling the creation of lower quality raw materials, i.e. approving raw materials for industrial consumption rather than using food and medicine grade materials.

In relation to bio-binder/rejuvenators the challenges associated with the biomass supply chain could be addressed via regulated cultivation of the biomass, particularly microalgae. Microalgae biomass production can be developed specifically for industrial use, thereby ensuring a secure supply of the biomass necessary for the bio-rejuvenator production.

The second bio-binder challenge relates to the high cost of the microalgae biomass production. The costs presented above refers to the highest quality biomass, cultivated for human consumption (e.g. for use in food and cosmetics). Although the price of these biomass, at €16 for 0.1kg of oil [82] are commercially unviable for the asphalt industry. However, if microalgae cultivation were to be connected to the water purification process (which will result in lower quality product but high lipid yield), the price of the microalgae oil would reduce substantially. Richardson *et al.* [83] demonstrated that by scaling up microalgae production, the price of the oil could be reduced to between 0.44€/kg – 2.84€/kg. They also estimated that the price of biodiesel made from algae oil is 0.62 €/l, which is lower than current price of regular diesel (1.6 €/l) [84]. Thilakaratne *et al.* [85] reported similar findings, where the cost of microalgae biofuel produced using pyrolysis would reduce costs to between €1.3/l and €1.6/l. These findings can be applied to the bio-bitumen and bio-rejuvenator production. Instead of diverting the oil to the biofuel production, it could be diverted to the bio-binder/rejuvenator production. These reduced prices of the bio-bitumen/rejuvenators would render it a feasible replacement for petroleum based bitumen and rejuvenators.

Although not yet commercially viable, these two technologies provide an opportunity for the asphalt industry to begin to evolve from a heavily oil reliant (or dirty industry) towards becoming a smart, low carbon industry which embraces the circular economy.

To date the road/asphalt industry has not embraced technological innovation and has been hesitant to bring this technology from the lab to the road-site. It is understandable that the asphalt industry (as all industry) is motivated primarily in financial/economic terms and market competitiveness [86]. But there is clearly a role for policy incentives connected to environmental goals to encourage take up of new technology.

Porter and van der Linde [87] have highlighted the synergies that exist between industrial competitiveness and environmental preservation. They argue that the imposition of adequate environmental norms and standards will encourage companies to adopt innovations. These innovations will generate environmental benefits, they may also reduce costs add value to their products and processes in other ways, thereby improving competitiveness. So if road owners (overwhelmingly the national government and/or local authorities) begin to demand innovative, more sustainable and environmentally friendly technologies in their road building and road maintenance processes (and build it into their tenders), this is likely to be sufficient motivation for change by the asphalt/road industry.

It is also clear that the discipline of Civil Engineering needs to evolve if it is to keep pace with and lead innovation in asphalt road materials, particularly in relation to environmental concerns. As Griffiths explains [88], the answers to the big global questions cannot be found within single traditional disciplines, such as biology or politics. Civil Engineering must reach out to other disciplines to teach the next generation of engineers the relevance of sustainable practice and the need for environmentally friendly innovation in road construction.

In the future, road material development and the roads design process must seek inter-disciplinary inspiration and collaboration and embrace insights from physics, chemistry and biology, among others. Again, the discipline and industry could learn from researchers, particularly those funded by EC Marie Curie/ERC schemes, who naturally work across disciplinary, geographic boundaries to solve environmental and engineering challenges. At present, clinging to the 'way we have always done things' is holding the asphalt industry and the civil engineering discipline back from realising the full potential of disruptive and innovative bio-materials.

5 Conclusions

In most countries, the road networks are among the most valuable, most significant and most overlooked components of national infrastructure. Industrial concerns around pricing should not be the sole determinant and driver of innovation in the road construction industry, particularly because roads are built primarily with public money [3, 89]. If innovations in asphalt technology can reduce the environmental impact of roads, improve road safety and reduce the level of traffic disruption caused by road maintenance, perhaps should be motivation enough for the adaption, or at least trial, of bio-inspired asphalt technologies.

For this to happen, road owners (overwhelmingly national governments and/or local authorities) should factor in environmental/social impact and/or a willingness to embrace innovation when awarding lucrative contracts for road construction and maintenance. As in many sectors, we cannot simply wait for the asphalt/road industry to decide to adopt bio-technology, as businesses are profit-focussed [86, 87]. However, as statutory bodies with a remit for environmental and societal protection alongside the remit for road network development and maintenance, national governments and road owners are ideally placed to look beyond the immediate financial cost of the road projects and begin to incentivise the use of innovative and more sustainable road paving and maintenance.

The transition to the bio-innovative technology must be systemic, deep and transformative, but we cannot expect industry to lead it. The transition must be led by government statutory bodies, i.e. road owners, in synergy with industry and researchers. Transition must be fast, disruptive and has to be fair, in order to address current societal challenges, such as the UN STG, and climate change goals. It will require an alignment and cooperation of all stakeholders at all levels – researchers, asphalt industry, asphalt industry organisations, national and regional governments and UN. The bleak alternative is that we accept defeat and admit that this is the end of the road for bio-inspired roads.

Authorship statement (CRediT)

Amir Tabaković: Writing – original draft, Methodology, Visualisation, Resources, Funding acquisition.

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Conflict of Interest

Author declares no conflict of interest. The study design; the reference data collection, information and/or review and data analysis; the writing of the manuscript, and the decision to publish the findings are authors sole work as part of the ASAP project. The discussion and views expressed in the views expressed in the manuscript are authors own interpretation of the findings and his own views.

References

[1] Central Intelligence Agency (CIA), Roadways - The World Factbook. 2021: www.cia.gov.
[2] L. Vita, M.C. Marolda, Road Infrastructure - the backbone of transport system. 2008, EU Directorate General for Research and Sustainable Surface Transport, Brussels, Belgium, EU.
[3] Organisation for Economic Co-operation and Development (OECD), Infrastructure Investment (Indicator). 2022.
[4] European Aphalt Pavement Association (EAPA), The Asphalt Paving Industry, A Global Perspective. 2011.
[5] European Asphalt Pavement Association (EAPA), Key figures of the European Asphalt Industry in 2014, in Asphalt in Figures. 2016.
[6] D. O'Pray, Asphalt Cost, A. Tabakovic (Editor) 2019.
[7] J. Leggett, Big oil's looming bubble, in New Internationalist. 2014, 20-21.
[8] J. Worth, Ending the oil age, in New Internationalist. 2014, 12-16.
[9] A. Tabaković, et al., The compartmented alginate fibres optimisation for bitumen rejuvenator encapsulation. Journal of Traffic and Transportation Engineering (English Edition), 2017. https://doi.org/10.1016/j.jtte.2017.01.004
[10] A. Tabaković, Recycled asphalt (RA) for pavements, in Handbook of Recycled Concrete and Demolition Waste, F. Pacheco-Torgal, et al. (Ed.), Woodhead Publishing (2013): 394-423. https://doi.org/10.1533/9780857096906.3.394
[11] A. Tabakovic, The Influence of Recycled Asphalt Pavement on the Fatigue Performance of Asphalt Concrete Base Courses. ASCE Journal of Materials in Civil Engineering (2010) 22(6): 8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000093
[12] J. Brownridge, The role of an asphalt rejuvenator in pavement preservation: use and need for asphalt rejuvenation. In: 1st International Conf. on Pavement Preservation. 2010. Newport Beach, USA.
[13] A. Garcia, J. Jelfs, C.J. Austin, Internal asphalt mixture rejuvenation using capsules. Construction and Building Materials (2015) 101(1): 309-316. https://doi.org/10.1016/j.conbuildmat.2015.10.062
[14] R. Penki, S. Kumar-Rout, Next-generation bitumen: a review on challenges and recent developments in bio-bitumen preparation and usage. Biomass Conversion and Biorefinery, 2021. https://doi.org/10.1007/s13399-021-01803-4

[15] J.F. Su, et al., Investigation the possibility of a new approach of using microcapsules containing waste cooking oil; in-situ rejuvenation. Construction and Building Materials (2015) 74: 83-92. https://doi.org/10.1016/j.conbuildmat.2014.10.018

[16] J.B. Król, et al., Effect of bitumen fluxing using a bio-origin additive. Construction and Building Materials (2016) 114: 194-203. https://doi.org/10.1016/j.conbuildmat.2016.03.086

[17] E. Prosperi, E. Bocci, A Review on Bitumen Aging and Rejuvenation Chemistry: Processes, Materials and Analyses. Sustainability, 2021 13. https://doi.org/10.3390/su13126523

[18] S.A. Miller, et al., Opportunities and challenges for engineering construction materials as carbon sinks. RILEM Technical Letters, (2021) 6: 105-118. https://doi.org/10.21809/rilemtechlett.2021.146

[19] M.H. Faber, GLOBE - Global Consensus on Sustainability in the Built Environment-Report, 2020. https://doi.org/10.1080/10168664.2020.1823753

[20] J.M. Benyus, Biomimicry: Innovation Inspired by Nature. Harper Collins Publishers Inc., 2002.

[21] H. Fisher, Self repairing materials - dream or reality. Natural Science, (2010) 2(8): 873 - 901. https://doi.org/10.4236/ns.2010.28110

[22] D.R. March, G. Li, The biology of fracture healing. British Medical Bulletin (1999) 55(4): 856 - 869. https://doi.org/10.1258/0007142991902673

[23] G. Leegwater, et al. Terms and Definitions on Crack-Healing and Restoration of Mechanical Properties in Bituminous Materials. Cham: Springer International Publishing, 2022. https://doi.org/10.1007/978-3-030-46455-4_6

[24] S. Xu, et al., Self-Healing Asphalt Review: From Idea to Practice. Advanced Materials Interfaces (2018) 5(17): 1800536. https://doi.org/10.1002/admi.201800536

[25] A. García, et al., Electrical conductivity of asphalt mortar containing conductive fibers and fillers. Construction and Building Materials (2009) 21(10): 3175-3181. https://doi.org/10.1016/j.conbuildmat.2009.06.014

[26] A. García, et al., A simple model to define induction heating in asphalt mastic. Construction and Building Materials (2012) 31: 38-46. https://doi.org/10.1016/j.conbuildmat.2011.12.046

[27] Q. Liu, Induction healing of porous asphalt concrete, in Faculty of Civil Engineering and Geosciences. TU Delft, The Netherlands, 2012.

[28] M. Bueno, M. Arraigada, M.N. Partl, Damage detection and artificial healing of asphalt concrete after trafficking with a load simulator. Mechanics of Time-Dependent Materials (2016) 20(3): 265-279. https://doi.org/10.1007/s11043-016-9306-z

[29] J. Norambuena-Contreras, A. Garcia, Self-healing of asphalt mixture by microwave and induction heating. Materials & Design (2016) 106: 404-414. https://doi.org/10.1016/j.matdes.2016.05.095

[30] J. Norambuena-Contreras, et al., Effect of fibres addition on the physical and mechanical properties of asphalt mixtures with crack-healing purposes by microwave radiation. Construction and Building Materials (2016) 127: 369-382. https://doi.org/10.1016/j.conbuildmat.2016.10.005

[31] P. Wan, et al., A novel microwave induced oil release pattern of calcium alginate/ nano-Fe_3O_4 composite capsules for asphalt self-healing. Journal of Cleaner Production (2021) 297: 126721. https://doi.org/10.1016/j.jclepro.2021.126721

[32] A. Tabaković, E. Schlangen, Self-Healing Technology for Asphalt Pavements, in Self-healing Materials, M.D. Hager, S. van der Zwaag, and U.S. Schubert, Editors. Springer International Publishing Switzerland, Cham. 2016: 285-306. https://doi.org/10.1007/12_2015_335

[33] S. Xu, et al., A novel self-healing system: Towards a sustainable porous asphalt. Journal of Cleaner Production (2020) 259: 120815. https://doi.org/10.1016/j.jclepro.2020.120815

[34] V. Loise, et al., A Review on Bitumen Rejuvenation: Mechanisms, Materials, Methods and Perspectives. Applied Sciences (2019) 9(20): 4316. https://doi.org/10.3390/app9204316

[35] A. Tabaković, et al., Reinforcement and healing of asphalt mixtures by rejuvenator encapsulation in alginate compartmented fibres. IOP Smart Materials and Structures, Special Edition on Self Healing Materials (2016) 25. https://doi.org/10.1088/0964-1726/25/8/084003

[36] Xu, S., et al., Calcium alginate capsules encapsulating rejuvenator as healing system for asphalt mastic. Construction and Building Materials (2018) 169: 379-387. https://doi.org/10.1016/j.conbuildmat.2018.01.046

[37] I. Gonzalez-Torre, J. Norambuena-Contreras, Recent advances on self-healing of bituminous materials by the action of encapsulated rejuvenators. Construction and Building Materials (2020) 258: 119568. https://doi.org/10.1016/j.conbuildmat.2020.119568

[38] A. Tabaković, et al., An Evaluation of the Efficiency of Compartmented Alginate Fibres Encapsulating a Rejuvenator as an Asphalt Pavement Healing System. MPDI Applied Sciences (2017) 7. https://doi.org/10.3390/app7070647

[39] A. Tabakovic, J. Mohan, A. Karac, Conductive Compartmented Capsules Encapsulating a Bitumen Rejuvenator. MPDI Processes (2021) 9(8). https://doi.org/10.3390/pr9081361

[40] P. Wan, et al., Self-healing properties of asphalt concrete containing responsive calcium alginate/nano-Fe3O4 composite capsules via microwave irradiation. Construction and Building Materials (2021) 310: 125258. https://doi.org/10.1016/j.conbuildmat.2021.125258

[41] S. Seneviratne, A. Tabaković, Self-healing Asphalt HealRoad Customer Discovery and Needs Analysis Report. 2020: Unpublished.

[42] United Kingdom Government. Road accidents and safety statistics. 2021; Available from: https://www.gov.uk/government/collections/road-accidents-and-safety-statistics.

[43] National Work Zone Safety. Work Zone Fatal Crashes and Fatalities. 2021; Available from: https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national.

[44] A.A. Butt, B. Brigisson, N. Kringos, Optimizing highway lifetime by improving the self-healing capacity of asphalt. Procidia - Social and Behavioural Sciences, Transport Research Arena-2012, 2012. 48: 2190 - 2200. https://doi.org/10.1016/j.sbspro.2012.06.1192

[45] L. De Bock, et al., Categorisation and analysis of rejuvenators for asphalt recycling. A. De Swaef, Woluwedal 42 - 1200 Brussels, 2020.

[46] United Nations Environmental Programme - Secretariat of the Convention on Biological Diversity, Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity, Canada. 2011, 15.

[47] S. Xu, et al., The role of rejuvenators in embedded damage healing for asphalt pavement. Materials & Design (2021) 202: 109564. https://doi.org/10.1016/j.matdes.2021.109564

[48] J.L. Concha, et al., Biocapsules containing low-cost rejuvenators for asphalt self-healing. RILEM Technical Letters (2021) 6: 1-7. https://doi.org/10.21809/rilemtechlett.2021.129

[49] A. Garcia-Hernández, et al., Self-healing of reflective cracks in asphalt mixtures by the action of encapsulated agents. Construction and Building Materials (2020) 252: 118929. https://doi.org/10.1016/j.conbuildmat.2020.118929

[50] J. Ji, et al., Effectiveness of Vegetable Oils as Rejuvenators for Aged Asphalt Binders. Journal of Materials in Civil Engineering (2017) 29(3): D4016003. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001769

[51] R. Saha, et al., Effect of Bio-Oils on Binder and Mix Properties with High RAP Binder Content. Journal of Materials in Civil Engineering (2020) 32(3): 04020007. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003057

[52] C. Rodrigues, et al., Full Recycling of Asphalt Concrete with Waste Cooking Oil as Rejuvenator and LDPE from Urban Waste as Binder Modifier. Sustainability (2020) 12(19): 8222. https://doi.org/10.3390/su12198222

[53] I. Kabir, M.J. Rusli, A. Radam, Households' Awareness, Attitudes and Practices Regarding Waste Cooking Oil Recycling in Petaling, Malaysia. IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT) (2014) 8(10). https://doi.org/10.9790/2402-081034551

[54] M. Zargar, et al., Investigation of the possibility of using waste cooking oil as a rejuvenating agent for aged bitumen. Journal of Hazardous Materials (2012) 233-234: 254-258. https://doi.org/10.1016/j.jhazmat.2012.06.021

[55] G. Gellerstedt, G. Henriksson, Chapter 9 - Lignins: Major Sources, Structure and Properties, in Monomers, Polymers and Composites from Renewable Resources, M.N. Belgacem, A. Gandini (Ed.), Elsevier: Amsterdam, 2008: 201-224. https://doi.org/10.1016/B978-0-08-045316-3.00009-0

[56] D. van Vliet, et al., Lignin as green alternative for bitumen, in 6th Euroasphalt and Eurobitumen Congress, Prague, Czech Republic, 2016. https://doi.org/10.14311/EE.2016.159

[57] Maurits Kuypers. Dutch Zeeland premieres with first stretch of road paved with bio-asphalt. 2020 [accessed 2020 28-09]; Available from: https://innovationorigins.com/en/dutch-zeeland-premieres-with-first-stretch-of-road-paved-with-bio-asphalt/.

[58] F. Lictevout, et al., The EIFFAGE Experience: Industrial Development of a Bio-Based Range and Feedback, in 1st International Workshop on the Use of Biomaterials in Pavements, A.J.d.B.C.E. Chailleux, Editor. 2022: Granada, Spain.
[59] Eiffage. Recytal® ARM. 2020; Available from: https://www.eiffageroute.com/files/live/sites/route/files/Activit%C3%A9s/Solutions/RECYTAL-ARM2500_2020.pdf.
[60] F. Murphy, et al., Biofuel Production in Ireland-An Approach to 2020 Targets with a Focus on Algal Biomass. MPDI Energies (2013) 6: 6391-6412. https://doi.org/10.3390/en6126391
[61] M. Audo, et al., Subcritical Hydrothermal Liquefaction of Microalgae Residues as a Green Route to Alternative Road Binders. ACS Sustainable Chemical Engineering (2015) 3(4): 583-590. https://doi.org/10.1021/acssuschemeng.5b00088
[62] J. Umakanta, K.C. Das, Comparative Evaluation of Thermochemical Liquefaction and Pyrolysis for Bio-Oil Production from Microalgae. Energy & Fuels (2011) 25(11): 5472-5482. https://doi.org/10.1021/ef201373m
[63] French Institute of Science and Technology devoted to Transport Planning and Networks (IFSTTAR). BioRePavation. 2020 [cited 2022 17th February]; Available from: http://biorepavation.ifsttar.fr/.
[64] H. Wang, et al., Effects of pyrolysis temperature and reaction time on the performance of swine-manure-derived bio-binder. Transportation Research Part D: Transport and Environment (2020) 89: 102608. https://doi.org/10.1016/j.trd.2020.102608
[65] M. Zahoor, et al., Recycling asphalt using waste bio-oil: A review of the production processes, properties and future perspectives. Process Safety and Environmental Protection (2021) 147: 1135-1159. https://doi.org/10.1016/j.psep.2021.01.032
[66] X. Yang, et al., Mechanical performance of asphalt mixtures modified by bio-oils derived from waste wood resources. Construction and Building Materials (2014) 51: 424-431. https://doi.org/10.1016/j.conbuildmat.2013.11.017
[67] X. Yang, Z. You, Q. Dai, Performance Evaluation of Asphalt Binder Modified by Bio-oil Generated from Waste Wood Resources. International Journal of Pavement Research and Technology (2013) 6(4).
[68] M.A. Raouf, R.C. Williams, Performance properties of fast pyrolysis Bio-oils modified asphalt, in 5th International Conference Bituminous Mixtures and Pavements, Thessaloniki, Greece, 2011.
[69] D.W.F. Brilman, N. Drabik, M. Wądrzyk, Hydrothermal co-liquefaction of microalgae, wood, and sugar beet pulp. Biomass Conversion and Biorefinery (2017) 7. https://doi.org/10.1007/s13399-017-0241-2
[70] S. Aravind, B. Debabrata, Chapter 2 - Toxic Waste From Municipality, in Energy from Toxic Organic Waste for Heat and Power Generation, D. Barik (Ed.), Woodhead Publishing (2019) 7-16. https://doi.org/10.1016/B978-0-08-102528-4.00002-X
[71] European Commission, A new Circular Economy Action Plan For a cleaner and more competitive Europe COM/2020/98 final, EUR-Lex, 2020.
[72] Consortium, H.P. HEALROAD. 2017 [cited 2022 14-01-2022]; Available from: https://healroad.eu/about-the-project/.
[73] A.G. Hernandez, Self Healing Road. LinkedIn: 2021.
[74] Q. Liu, E. Schlangen, G. van Bochove, The first engineering self-healing asphalt road; How is it performing? In: 4th International Conference on Self-Healing Materials (ICSHM 2013), Ghent, Belgium, 2013
[75] E. Schlangen, M. Mangalla. EpionAsphalt. 2022; Available from: http://www.epionasphalt.com/.
[76] R. Speare-Cole, The Burning Question, in The Guardian Weekly, The Guardian: Spotlight Science. 2021: 2.
[77] European Commission, Brief on biomass for energy in the European Union. 2019.
[78] P. Steele, et al., Life-Cycle Assessment of Pyrolysis Bio-Oil Production*. Forest Products Journal (2012) 62(4): 326-334. https://doi.org/10.13073/FPJ-D-12-00016.1
[79] P. Mooij, TEDxDelft, Microalgae is more important than you think, 2015.
[80] ATDM Co Ltd. Bitumen Price. 2022 [cited 2022 17th February]; Available from: https://atdmco.com/penetration/bitumen-price.html.
[81] European Commission. Advanced Solutions for Asphalt Pavements. CORDIS EU Reserach 2022; Available from: https://cordis.europa.eu/project/id/886828.
[82] Luxplus. Atlantic Kelp & Microalgae Anti-Fatigue Bath Oil. 2022 [cited 2022 10-01-2022]; Comercial Website]. Available from: https://www.luxplus.nl/product/ren-atlantic-kelp-microalgae-anti-fatigue-bath-oil-110-ml?gsmp=1&gclid=CjwKCAiAz--OBhBIEiwAG1rIOvQwI8-8-OLojCwXtA4iyQAfWLU8dy2JqBdi_Yh11L1Cv19XC756CBoCM_YQAvD_BwE.
[83] J.W. Richardson, J.L. Outlaw, M. Allison, The Economics of Microalgae Oil. AgBioForum - The Journal of Agrobiotechnology Management and Economics (2010) 13(2).
[84] Global Petrol Prices. Netherlands Diesel prices, 03-Jan-2022. 2022 [cited 2022 10-01-2022]; Diesel prices]. Available from: https://www.globalpetrolprices.com/Netherlands/diesel_prices/.
[85] R. Thilakaratne, M.M. Wright, R.C. Brown, A techno-economic analysis of microalgae remnant catalytic pyrolysis and upgrading to fuels. Fuel (2014) 128: 104-112. https://doi.org/10.1016/j.fuel.2014.02.077
[86] D. Schreiber, et al., Analysis of Innovation and Its Environmental Impacts on the Chemical Industry. Brazilian Administration Review (2016) 13(1). https://doi.org/10.1590/1807-7692bar2016150120
[87] M.E. Porter, C. van der Linde, Toward a New Conception of the Environment-Competitiveness Relationship. Journal of Economic Perspectives (1995) 9(4): 97-118. https://doi.org/10.1257/jep.9.4.97
[88] A. Griffiths, Multi-discipline courses will help solve emerging global problems, in The Conversation. 2014.
[89] R. Monden, et al., Overview of transport infrastructure expenditures and costs. European Commission Directorate-General for Mobility Transport, 2019.