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Review

Toward the Inclusion of Waste Materials at Road Upper Layers: Integrative Exploration of Critical Aspects

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Abstract: Nowadays, recycling in pavement engineering is not a novelty. Utilization of recycled aggregates and other waste materials for the asphalt layers appeared as a well-established approach during the last decades, at least at a research level, in favor of preservation of natural resources, economical balance in road construction and reconstruction, and overall pavement sustainability. The focus on the asphalt layers does make sense based on the fact that these layers are to be more frequently replaced in the framework of periodical pavement maintenance or rehabilitation. Taking as a fact that mainly laboratory-scale studies and limited field trials have already proven the performance-based viability of using alternative materials in the asphalt layers, including waste plastic, waste glass, steel slag, waste tires in the form of rubber, reclaimed asphalt pavement (RAP), etc., this study tries to identify additional critical aspects and reasons why recycled materials are not consistently selected and uniformly applied during construction and reconstruction activities in real practice. A comprehensive discussion for interdisciplinary issues is provided with respect to (i) the challenge of comparing the performance of asphalt mixtures containing recycling materials with a reference condition status, related to mechanical testing, (ii) the aspect of recycled material availability versus peculiar conditions applied to some countries, related to socioeconomical issues, (iii) the unawareness of the actual lifecycle assessment of pavement structures with recycled mixtures, related to environmental assessment, and (iv) some legislative and health issues that could make pavement engineers reluctant to extensively use non-conventional materials. After a multi-parametric discussion, some useful remarks for fostering further research are given together with the ambition to bridge the gap between research and practice toward a greener future in pavement engineering.

Keywords: recycling; waste materials; RAP; surface layers; local material availability; lifecycle assessment; safety; legislation

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1. Introduction

Ever since the pavement engineering society started investing in the research of recycled material incorporation into conventional pavement mixtures, a major concern is to avoid downgrading mixture quality [1–3]. Systematic experiments, primarily conducted in laboratories and, to a lesser extent, in the field, have confirmed that, when compared to control mixtures made of conventional materials, non-conventional mixtures, including waste plastic, crumb rubber, waste glass, steel slag, and reclaimed asphalt pavement (RAP), can perform as well as or even better against fatigue, rutting, and moisture damage [4–9]. It is observed that most of the relevant studies concentrate on problems concerning these materials' mechanical performance and structural contribution. In contrast, even though

surface layers are often replaced within the context of a maintenance and rehabilitation (M&R) plan, serviceability concerns and functional characteristics (such as texture, skid resistance, etc.) are more infrequently studied and hence have received less attention [10,11].

In any case, it is expected that the diversity of waste materials' properties can indeed produce some controversial results, as per the performance of non-conventional mixtures, something that justifies why related research consistently revives. On the other hand, it might be anticipated that practitioners do follow these research trends and try to broadly apply this knowledge in the field through an extended use of these materials [12]. However, this is yet to be achieved so far. Therefore, this study tries to integrate additional critical aspects and reasons, apart from those related to the mechanical testing of these materials, about why recycled mixtures are not consistently selected and uniformly applied during construction and reconstruction activities in real practice.

The motivation for this objective is two-fold. The first has to do with the frequency of asphalt layers' maintenance and/or rehabilitation. In other words, the surface layer, in particular, exhibits an increased potential for inclusion of recycled or other waste materials, because of the periodical surface interventions that can take place during a pavement's lifespan [1,13]. In real practice, road operators are unwilling to move forward with expensive and extensive full-depth interventions. Therefore, surface treatments are typically applied to most pavements, provided that structural soundness over time is ensured. Aligned with the concept of long-life pavements (LLPs) [14], or perpetual pavements [15], frequent surface layer interventions usually include minor maintenance measures, like crack sealing, or the replacement of the surface layer. The latter explains why using non-conventional materials for the surface layers, either locally available from pavement reconstruction activities or from landfilling, does indeed make sense.

Secondly, in fully serviceable pavements, it is important for the surface layer to provide a distress-resistant behavior with both structural and functional features. This indicates that the material mix design for the top layer is an essential step in both the pavement design process and the pavement's operational service life. The absence of specifications together with the related strict behavioral requirements of surface layers can account for the related diversity of research findings. Indeed, these limitations might control the maximum rate of waste materials in the composition of the non-conventional mixtures. Hence, despite the continuously revitalized research, there is still a lot to achieve, until a more broadened and consistent use of these materials at surface-layer mixtures takes place.

So, under these two main arguments, and taking as a fact that mainly laboratory-scale studies and limited field trials have already proven the performance-based viability of using alternative materials in the asphalt layers for surface courses, the present study aims to consolidates issues of a multi-disciplinary nature that are to be overpassed for a greener and eco-friendlier future in pavement engineering. This goal is further enhanced by the fact that the variable recycling rates of alternative mixtures when designing laboratory experiments and/or field trials involve challenges related to the environment, health of working personnel and road users, etc. For example, despite the fact that the majority of utilized RAP refers to the asphalt layers during pavement construction or reconstruction, its actual rate in the mix design of the individual asphalt layers can indeed vary. RAP rates have been reported to vary from 15% to 20% or 20% to 30% for the surface layers [16,17], while an as high as 100% rate has also been mentioned elsewhere [18]. Another example includes the use of plastic, where it has been reported that using plastic at a rate of more than 15% in porous pavements tends to degrade the asphalt mixture performance [19]. This is because plastic's viability is called into doubt, as its performance under extended heat, oxygen, sunshine, and moisture is still unknown [19]. Such remarks can of course raise

regulatory concerns about what can be confidently characterized as rational use of waste materials in asphalt layers.

In the meantime, the recent inclusion of environmental consideration into public procurement, also known as green public procurement (GPP), implies that a comprehensive and official approach to the sustainability analysis of road structures is needed [20]. GPP is a process whereby public authorities seek to procure goods, services, and works with a reduced environmental impact throughout their lifecycle when compared to goods, services, and works with the same primary function that would otherwise be procured. Thus, the engineering community still needs to become knowledgeable about optimal ranges of rates for those recycling materials that should meet both environmental and performance-based criteria to make the roads and pavement structures more viable in the future.

2. Multi-Disciplinary Aspects of Reutilizing Waste Materials

2.1. Condition Status Comparison

Almost everyone engaged in pavement and material engineering should agree that using waste materials can (i) lower the amount of virgin materials needed to produce either hot-mix asphalt (HMA) or warm-mix asphalt (WMA), by either replacing the aggregates or the binder, (ii) lower transportation costs for obtaining and delivering construction materials, (iii) protect natural resources, and (iv) successfully deal with debris accumulation and landfilling [2,16]. However, the behavior of non-conventional materials remains unexplored.

As previously mentioned, the tight performance requirements for surface layers in asphalt pavements, as well as the variety of material types and qualities, make it compulsory to compare the behavior of a non-conventional mix to another one with known material components. In other words, the performance of asphalt mixtures made with traditional components and preparation methods should be acknowledged in advance, since this should serve as a benchmark for evaluating any alternative mixture type. Particular attention must be given to laboratory testing to assess the impact of waste materials on the viscoelastic properties of the binder and mixture, particularly for those waste materials that are anticipated to replace the binder [21]. This is rather important considering that the asphalt mixture behaves in a viscoelastic manner too; so, waste materials can induce challenges in pavement performance modeling [22–24]. Similar remarks apply for the use of recycling materials in concrete pavements as well [25,26].

It is practically indicated that, based on a number of factors, including the type of road, its traffic volume, the anticipated frequency for M&R activities, etc., if a non-conventional material deteriorates the behavior of the final mixture, it should probably be rejected or employed with caution. To this end, the ability to generate reliable outcomes is undoubtedly strengthened by additional "lessons-learned" experience gained from field applications and scientific research.

2.2. Availability, Local Aspects, and Concerns

2.2.1. Waste Materials

The amount of waste material that is readily available within a project's area constitutes the most determinant factor that may stimulate or limit its use [2]. Waste items that, due to their huge volumes, might make landfilling problematic locally, let's say in a particular country, province, etc., might not be the first choice elsewhere, i.e., in a different country or province, etc. Taking the example of waste plastic in countries where an advanced recycling perspective is adopted, its use for asphalt mix design may not be so pronounced as elsewhere. There have been reports claiming that globally, a million plastic bottles are generated every minute [21], but not uniformly across the world. Nevertheless, the

disposal of plastic wastes is a social and environmental concern for many countries because of the non-biodegradable nature of these materials [27,28]. According to Mashaan [29], throughout the second half of the 20th century, the amount of plastic consumed annually increased globally from roughly 5 million to 100 million tons. Therefore, it can be said that in recent decades, plastic has emerged as one of the most significant solid waste products.

On the other hand, the rate at which waste plastic is recycled over the years does not appear to be high enough [3,30]. For instance, just 9% of Australia's plastic consumption in 2017–2018 was recycled [31], whereas 69% of plastic waste was not recycled in the majority of European Union (EU) countries in 2016 [30]. However, the development and the recycling philosophy has moved forward very rapidly in recent years. Indeed, more than 40% of plastic packaging waste was recycled in the EU in 2022 [32]. Australia has set a target recycling rate of 70% for plastic by the end of the year 2025 [33].

Similar remarks can be made for the steel slag and waste glass particles. The EU produces 21.8 million tons of steel slag annually [30,34]. Of this waste, 24% is landfilled after being temporarily kept, which increases the possibility of other uses, like the incorporation in asphalt surface courses. Even within a single country, it can be anticipated that there may be areas with limited or no access to steel slag landfills, thereby being unable to uniformly use this component.

According to Rashad [6], the EU countries, China, and the US are the biggest consumers of glass globally, with 33, 32, and 20 million tons consumed, respectively. Since glass cannot be recycled by nature, it is not practical to fully recover glass after it has reached the end of the useful life, in order to produce new glass. As a result, it can be considered a good substitute for producing other materials. In addition, because it is a non-biodegradable trash, dumping it illegally in landfills and stockpiles might pose a number of hazards to the community [35]. Thus, waste glass recycling can be partially recognized as a closed-loop recycling technique if it can be utilized as an additive in construction engineering materials, such as asphalt mixtures [36].

In the domain of scrap tires, since these are made of non-biodegradable elements too, disposing of them is once again a social issue and an environmental problem in many countries [27,28]. The shredding process of waste tires to obtain crumb rubber is shown in Figure 1. Based on the left part of Figure 1, it appears that the problem of tire landfilling provides sufficient room for targeted research projects seeking to develop workable substitutes that could absorb a significant portion of these waste volumes.



Figure 1. Shredding process of tires from landfills to retrieve crumb rubber.

Of course, again the issue of local peculiarities applies. For example, waste tires are more likely to be produced in locations where newer cars are replacing older ones more frequently. Specifically, it was anticipated that China would produce twice as many new passenger cars between 2016 and 2024, which presents a challenge for recycling the scrap tires of automobiles that need to be replaced [37]. However, re-vulcanizing rubber is a laborious process that must be completed in order to repurpose scrap tires into new cars [38]. This is translated into much more energy-based intensity and financial pores to

support these procedures. Therefore, the power of lifecycle analysis appears as a major concern for the overall suitability assessment of most waste materials.

2.2.2. The Case of RAP

The case of RAP is slightly different in terms of availability. For two main reasons that can account for the entire road network, a sizable fraction of RAP can be regarded as an alternative raw material for asphalt surfacing on a global scale. The first has to do with the category of heavy-duty pavements and the challenge to maintain LLPs. Despite ensuring long-term structural adequacy, the wearing courses often have a shorter service life. Thus, interventions typically concentrate on improving road user safety and comfort, as well as repairing the surface condition of the pavement, like skid resistance and texture [5,39]. Because of this aspect, milling procedures at in-service motorways yield more and more RAP from the milled courses, which increases its potential to be used as an additional source of raw materials to supplement virgin ones during restoration [2].

The second reason for the high availability of RAP is related to the secondary road network. Most of these pavements are, in general, poor in structural integrity and serviceability [13]. Nevertheless, these pavements typically handle low traffic volumes, but they can be of strategic significance for the national and international economy, thereby requiring attention during their maintenance. Again, comprehensive restoration requirements with full-depth interventions are often disregarded as being too expensive and unfeasible. For instance, in Romania, it has been reported that over 24,000 km are in need of renovation, at the very least in their wearing courses [13]. Similar trends apply for other countries as well. Meanwhile, not all the areas of a country have access to completely virgin materials [21], and the price of producing and managing the transportation and procurement of such materials might be prohibitive [16]. Because of this, one can benefit from the increased RAP's availability at the end-of-life disposal phase nearby a road network and exploit it as a feasible alternative.

Based on the previous remarks, Figure 2 and Table 1 self-prove the increased potentiality of recycled asphalt for inclusion into the upper road layers. Its potentiality for lower layers (i.e., bases or sub-bases comprising of unbound granular materials [40]) appears somehow limited, probably because these layers are not so frequently rehabilitated. Nevertheless, despite its availability for the upper layers, engineers face some concerns that they have to balance during the mix design procedures of RAP-based mixtures. The most pronounced are shown in Figure 3 and are well documented elsewhere [16,41–43]. Following Figure 3, the major problem with RAP mixtures (as well as mixtures with other waste additives) is the evaluation of their field performance because of the limited large-scale studies.

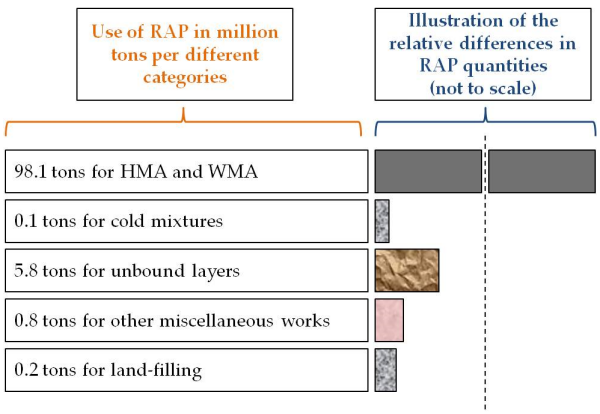


Figure 2. Use of RAP in the road construction sector—USA, year 2022 (adapted from [44]).

Table 1. Distribution of recycled asphalt in the EU, year 2017 (adapted from [45]).

Country	Percentage (%) of Recycled Asphalt for Use in Reconstruction				
	HMA and WMA	Cold Mixtures	Unbound Layers	Other Miscellaneous Works	Landfilling
Austria	60	N/A	N/A	N/A	N/A
Belgium	95	N/A	N/A	N/A	N/A
Czech Republic	14	30	20	10	26
Denmark	66	0	8	0	26
Finland	100	0	0	0	0
France	70	N/A	N/A	N/A	N/A
Germany	84	0	16	0	0
Hungary	95	0	0	4	1
Italy	23	N/A	N/A	N/A	N/A
Netherlands	71	11	0	0	18
Norway	30	1	0	0	0
Slovakia	96	2	1	1	0
Slovenia	24	6	10	0	60
Spain	83	0	14	0	3

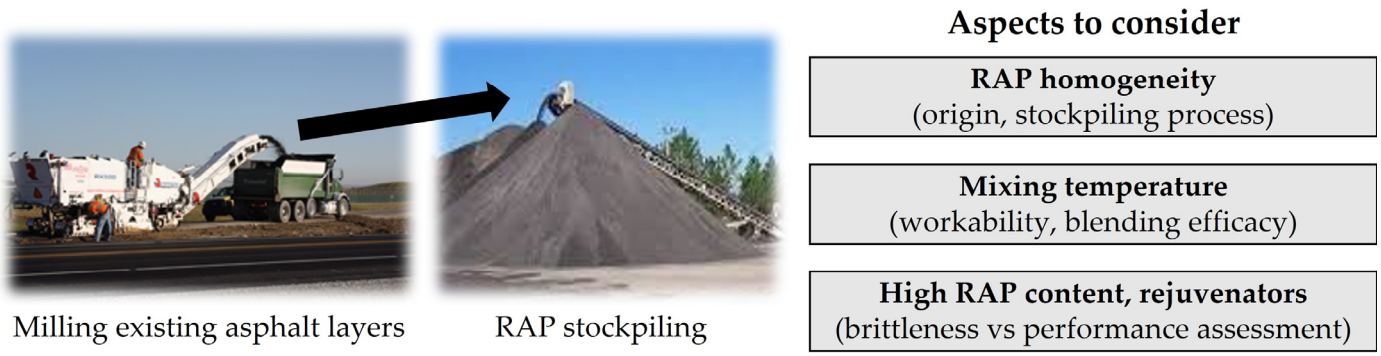


Figure 3. Main issues with RAP performance.

From some illustrative examples, controversial results can be found in the literature that should not make road engineers reluctant to invest in recycling material technology; rather, they should stimulate even more field-scale studies. Gong et al. [46] reported that the use of RAP for surface rehabilitation of pavements may have a negative long-term influence on pavement performance; however, there may not be much of an effect on wheel path and non-wheel path longitudinal cracking. On the other hand, Hand et al. [18] determined that low-volume roads in North Nevada with surface layers of 100% RAP had satisfactory field performance since, over the course of their lifetime, these roads required little to no maintenance. The aforementioned statements underscore the significance of field observations in providing additional insights into the performance characteristics of recycled mixtures and in enhancing laboratory processes designed to complement the comprehension of the influence of RAP and/or other waste materials on pavement performance.

Again, the significance of conducting a cost–benefit analysis is pinpointed once more in order to provide more integrated proof of whether recycling in the pavement sector is more privileged than recycling in other industries [30].

2.3. Lifecycle Assessment

As a follow-up to the previous section, another crucial factor to take into account while using recycling material in pavement engineering is the economic pillar. Costs include both those associated with road users and those that have an impact on road agencies

and operators [21]. Evaluations of the adaptability of current manufacturing methods and equipment should be carried out, together with comparisons with virgin material supply and recycled material processing [1]. A focused technological shift and a significant advancement in the relevant standards and/or recommendations can be sparked by such research. Until now, lifecycle analysis (LCA) seemed to be a complete instrument that was vital to support performance analysis of recycled mixtures and enable more thorough decision-making, while embracing recycling viewpoints [47–50].

Some of the environmental benefits of using recycling materials include the natural resource preservation, the reduction of air acidification and photochemical haze caused by the usage of plastic, as well as the elimination of transportation costs associated with waste milling products to landfills [51]. Mantalovas and Di Mino [48] have recently developed the Environmental Sustainability and Circularity Index (ESCI), which ranks the various degrees of circularity of a recyclable material. There are also cases where LCA of asphalt mixes for wearing courses might not support the use of a specific combination of materials despite the mechanical performance benefits. For example, in a study from Farina et al. [47], wearing course mixtures made up of CR and RAP were compared in terms of their environmental impact with traditional pavement mixtures. For a proper planning and construction of wet rubberized mixtures, considerable environmental advantages were achieved, followed by marginal improvements after RAP addition. On the contrary, the researchers did not report environmental advantages for dry processed mixtures.

From the above example, it appears that the LCA can lead to controversial results. The fact is that LCA is only occasionally performed and is used even more infrequently in the analysis of a research project. Nonetheless, it should be mentioned that the main barrier to producing trustworthy LCA inventory data is the need to take into account a number of assumptions, whether or not they are conservative. In addition, the use of international LCA tools envisages the risk of using assumptions that are only of location-specific applicability, thereby leading to results with limited prediction accuracy. Again, the issue of field-scale experiments is emphasized so that more reliable LCA can be jointly performed. Overall, LCA needs to be more methodologically retrofitted through regular investigations and holistic comparisons (Figure 4).

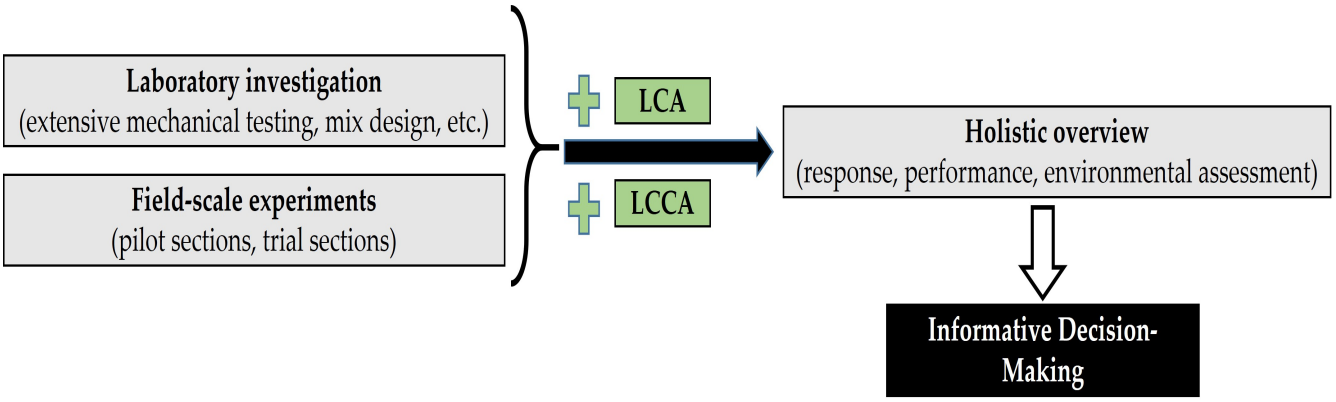


Figure 4. The role of lifecycle analysis in the consideration of recycled materials.

Going a step beyond LCA, the aspect of cost is almost overlooked in the related research. Indeed, lifecycle cost analysis (LCCA) studies are often rarer than LCA studies employing recycled solid waste materials. According to Li et al. [52], two critical elements—the analysis period and the discount rate—must be taken into account to ensure the effectiveness of an economic analysis. First and foremost, it is essential to choose a representative study period that allows for careful consideration of the use phase. The decision-makers' subjectivity affects the precise selection of the analysis period, which

can range from 20 to 50 years [53]. An even shorter analysis period could probably fail to account for long-term cost reductions realized during the pavement's operation phase, which is when M&R planning actually dominates. In conclusion, strong recommendations for carrying out economic analysis as a supplement to traditional LCA are given in the international literature in support of a more informative selection and implementation of recycled materials into asphalt mixtures for surface layers [52,54].

2.4. Legislative and Health Concerns

Another crucial factor that can limit the extensive use of recycled materials into asphalt mixtures is the compliance with all applicable local laws, as well as any upcoming legislation [30]. For instance, the resistance to a wide implementation of RAP in surface courses due to legal constraints has already been acknowledged previously [1]. Therefore, the current levels of utilization exhibit variance, since some countries either partially permit or fully restrict the use of waste materials. For instance, according to Anthonissen et al. [55], RAP use is prohibited in surface courses that adhere to Belgium's Flemish Road Standard SB250 v3.1. Other safety considerations do exist for the case of glass, as in urban road environments, glass particles can harm automobiles and/or hurt people, because of the danger of being dislodged by moving vehicles over a pavement surface [56]. Because of this, there is a propensity to "not trust" waste glass when it comes to applying it in heavy-duty motorways with fast-moving vehicles [36]. Conversely, it appears that parking spaces and quieter roads are better cases for using waste glass.

Surface courses may also be subject to even stricter legislation because of possible leachates and health issues from waste material use, tire–pavement noise, etc., which is particularly important in urban and suburban areas. The investigation of recycled materials in pavement construction and reconstruction projects shall not exclude such components that are strictly related to the quality of living of human beings [55]. Indeed, Figure 5 shows the example of the mechanism of groundwater table leaching. Pollutants that may seep from the pavement's surface into the underlying soils and groundwater aquifers can endanger ecosystems and the environment. This factor has not received the research attention it deserves. Shortly after construction and up to the "end-of-life" phase of the pavements, leaching is a persistent worry pertaining to the pavement's lifespan [57].

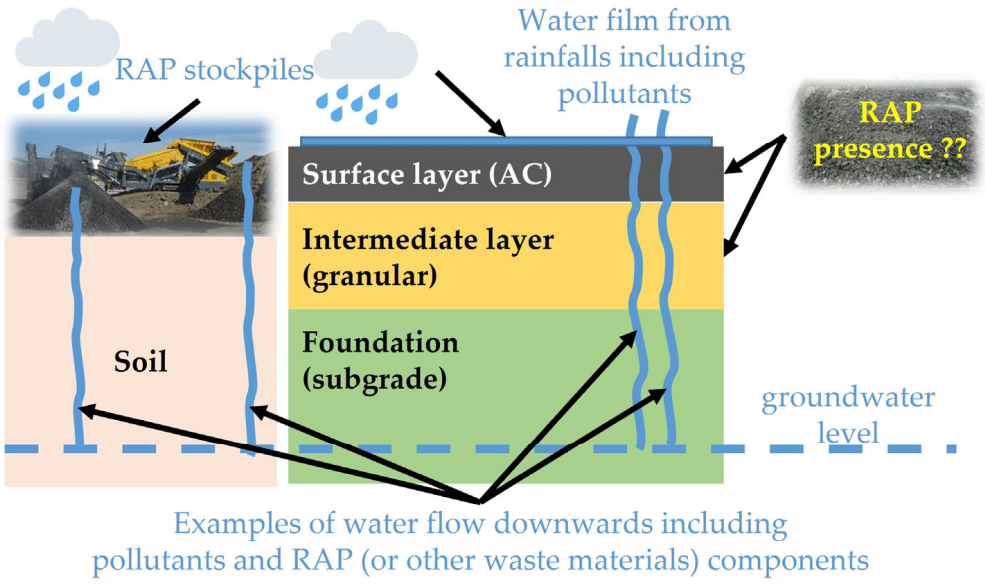


Figure 5. The leaching mechanism for the case of RAP.

Leaching can occur from the usage of waste materials in asphalt pavements as well as from their disposal or stockpiling, which makes the assessment of the leaching potential rather difficult. While leaching potential can be evaluated using laboratory and field testing, the latter is uncommon and challenging due to the extended time required to finish the assessment and form meaningful conclusions.

According to pertinent research, in order to create more accurate simulations, it is imperative to take into account as many environmental factors as possible that are close to the recycled pavement, such as humidity, frequency of rainfall, air temperature, and wind speed. Lastly, leaching needs to be evaluated in conjunction with the effects of the soil layers surrounding the pavement and in the space between the pavement and the groundwater table [57].

Governments, businesses, and academia may all work together to more efficiently develop and create new test protocols and evaluation techniques. In addition to the performance standards, it is important to consider any possible harm to the health and safety of paving crews and other employees. Legislative issues about the use of waste materials that need to be taken into account can be undoubtedly raised by such reasons [18]. From this perspective, any reluctancies about using waste materials or unawareness of good practices could be replaced by a robust and informative knowledge background.

Finally, the aspect of GPP, mentioned earlier, is again recalled toward a greener lifecycle of recycled mixtures. Wherever applied, GPP aims to establish minimum environmental criteria. Thus, in road engineering, GPP can even promote a minimum rate of recycled materials within the road construction layers and consequently foster the development of virtuous practices. This is an issue that definitively affects both road engineers and designers, as well as the road stakeholders.

3. Discussion and Future Directions

So far, it has become clear that recycling in pavements gathers a multitude of issues that are to be solved and systematically handled so that greener pavements can become the majority of road structures in the near future. In Figure 6, several disciplines are illustrated that need to collaborate toward addressing current challenges and transforming them into future opportunities. Such challenges and opportunities encompass three major categories, i.e., technical, environmental, and implementation perspectives.

In more detail, from the scope of the material science and engineering discipline, it appears that different waste materials require a different perspective, depending on the characteristic of each material. For example, the reuse of RAP involves understanding the characteristics of the aged asphalt binder and aggregates, followed by the need to assess the quality and properties of RAP and determine how it may affect the performance of the recycled asphalt mixture. Another example includes the use of plastic, where its physical properties need to be studied to ensure compatibility with asphalt, as well as the way it may affect the mix's stability, flexibility, and resistance to cracking and deformation.

From the pavement design perspective, engineers should be aware about the structural performance of pavements and analyze how the inclusion of RAP, glass, etc., impacts the strength, fatigue resistance, rutting, cracking, and overall longevity of road structures. In the meantime, the design of asphalt mixtures that incorporate recycled materials requires careful selection of binder types, aggregate gradations, and mixing temperatures. Advanced techniques, such as WMA or high-performance additives, may be used to ensure proper performance [58]. The role of chemical engineering is also important. Modification of RAP with additives, such as rejuvenators, is something common that restores its properties. Chemical engineers need to understand how the components in recycled materials interact

with the asphalt binder at the molecular level to ensure the formation of a stable mixture that can withstand the stresses and environmental conditions encountered on road surfaces [59].

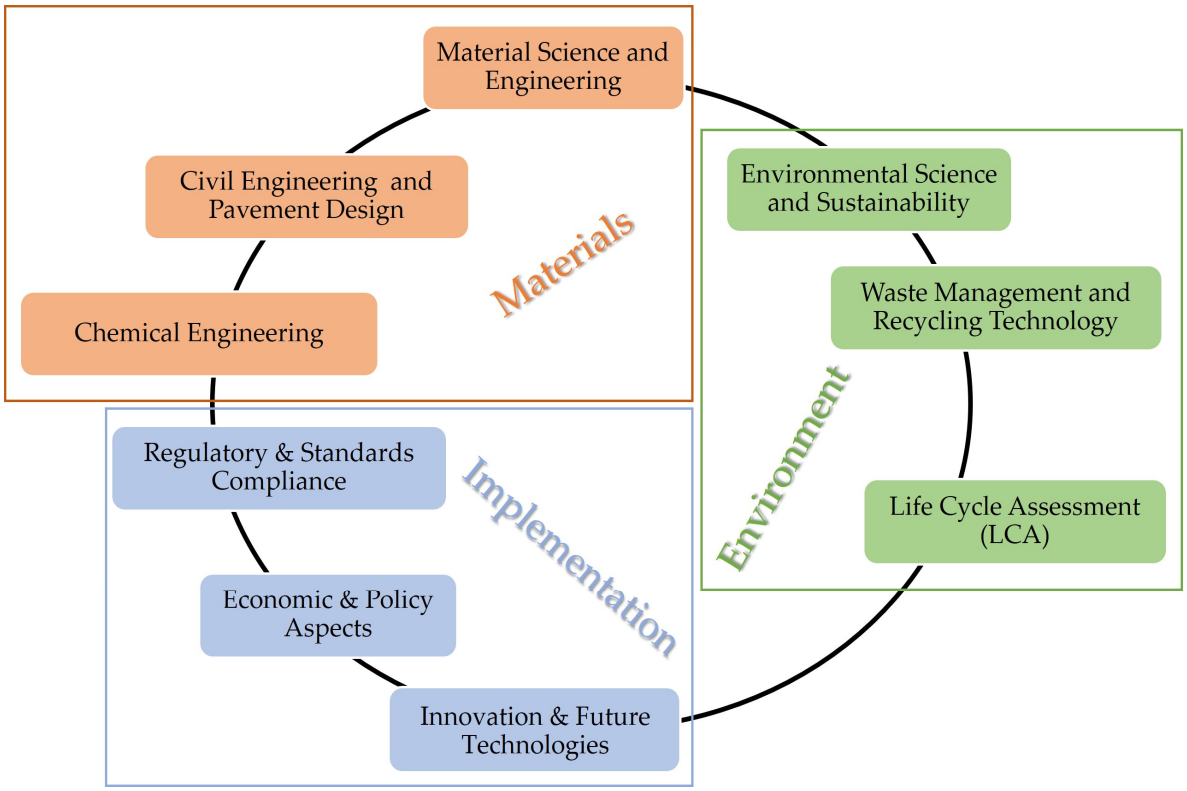


Figure 6. Multi-disciplinary factors affecting recycling in road surfaces.

Furthermore, from the environmental point of view, the reuse of waste materials in asphalt can significantly reduce the environmental footprint by diverting materials from landfills, promoting circular economy practices, and conserving raw materials (e.g., aggregates and binder). Incorporating recycled materials like RAP and plastics can reduce the need for energy-intensive processes (e.g., extracting virgin materials and refining new binder), which can lower the overall carbon footprint of asphalt production. So, research in this field explores how various waste materials can help in mitigating pollutants, such as leachate from landfills, while simultaneously providing a sustainable solution for waste management (i.e., pollution control).

To maximize the potential of the aforementioned activities, efficient systems must be in place to collect, sort, and process the waste materials. For instance, glass must be crushed to an appropriate size, and plastics need to be sorted by type. There are several complex processes and treatment procedures requiring advanced knowhow that could involve grinding, melting, or chemical treatment to adapt the waste materials for asphalt mix production. Provided that a robust recycling procedure is achievable, the environmental impact analysis can assess the incorporation of recycled materials over the entire lifecycle of the asphalt pavement—from production to end-of-life disposal. Being a multi-disciplinary approach, LCA indeed helps assess the net environmental benefits of using RAP, glass, etc., in pavement mixtures.

Moving toward a full-scale implementation, regulatory compliance reveals that the use of waste materials in asphalt pavements must comply with national and international quality standards. These standards ensure that the final pavement product is safe, durable, and meets the performance criteria. Regulations may set limits on the percentage of recycled materials allowed in pavement layers, particularly concerning the performance

and safety of road users and working personnel during construction and/or reconstruction. Additional regulatory frameworks govern the use of recycled materials in construction, especially related to the release of pollutants or leachates into the environment. Compliance with these regulations is critical for ensuring sustainability. Of course, governmental stakeholders may introduce policies or incentives to encourage the use of recycled materials in infrastructure projects [60,61]. These policies may include tax credits, subsidies, or mandates on recycling content in construction projects.

Again, the issue of economic cost-effectiveness arises, since the processing and treatment of waste materials can involve additional costs, which need to be carefully balanced while determining the feasibility of using waste materials in asphalt. Given the tough policy development, the future toward innovation is robustly paved, supporting research on pioneering aspects, like the use of nanotechnology to improve the properties of recycled mixtures [62,63], or the use of advanced sensors to monitor the performance of pavements with recycled content, i.e., instrumentation. The exploration of cutting-edge materials, such as self-healing asphalt or high-durability mixtures, could further enhance the potential of waste materials in pavements, making them more sustainable and long-lasting [64].

4. Conclusions

4.1. Main Remarks

Recycling patterns in pavement structures can differ based on the types of materials and the amounts used in conventional mixtures. Primary reasons for repurposing waste materials include recovering energy, practicing sustainable resource conservation, and minimizing the use of landfills for waste disposal, which in turn reduces transportation costs and required space. By implementing a new "end-of-life" approach for waste materials, the pavement industry is reinforcing the principles of the circular economy. Based on the rationale of this review, the following remarks can be made:

- Despite the existing studies on recycled mixtures mainly in laboratories and/or field-scale tests (to a lesser extent), the lack of specific requirements and documented guidelines consistently fuels the need for new research efforts on a continuous basis.
- An examination of nearby waste materials, the assessment of local availabilities, local peculiarities, health, and other safety concerns, and the comparison of recycling options can lead to investments on in-place or in-plant facilities for asphalt pavement recycling.
- In this context, collaboration between researchers and practitioners can be promoted for innovative processes that convert waste into construction materials. It is also advisable to thoroughly examine the cost-effectiveness through the perspective of LCA/LCCA studies as well, for a more informative decision-making.
- The issues of environmental sensitivity and circular economy are highlighted so that the use of waste materials into road construction can guarantee the sustainability of the future road infrastructures.

4.2. Prospects

Ultimately, the optimal way to further stimulate a more broadened utilization of waste materials toward a greener and eco-friendlier future in pavement engineering is to enhance the existing legislative system and foster collaboration between local governments, academia, and industry. From such synergies, it could become more feasible to create specific technical guidelines and/or specifications for the incorporation of waste materials into asphalt mixtures. This implies that there is a need for standardization in determining proper material sources, dosages, conducting laboratory tests, setting evaluation criteria, defining quality acceptance levels, etc. Additionally, conducting experimental trials

on small sections of roads (i.e., pilot sections) could provide valuable insights into the performance of recycled materials in asphalt pavements under actual traffic and environmental conditions. This factor can assist in enhancing and firmly establishing legislative aspects for performance-based material requirements and specifications through an integrated approach.

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