recycling

Editorial

Special Issue "The Use of Recycled Materials to Promote Pavement Sustainability Performance"

José Neves [1,*] and Ana Cristina Freire [2,*]

1 CERIS, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
2 LNEC, National Laboratory for Civil Engineering, Av. do Brasil 101, 1700-066 Lisbon, Portugal
* Correspondence: jose.manuel.neves@tecnico.ulisboa.pt (J.N.); acfreire@lnec.pt (A.C.F.)

1. Introduction

Recycling road pavement materials allows for a more sustainable use of raw materials and contributes to creating a circular economy. The entire life cycle of the pavement products, focusing on their design, promoting circular economy processes, and fostering sustainable consumption, aims to ensure that the resources used are kept in the economy for as long as possible. Carrying out recycling policies may significantly impact civil engineering activities, including the construction and exploitation of transport infrastructure. Pavement engineering can also contribute to successfully achieve the sustainable development goals proposed by the United Nations [1], through a global framework supported by sustainable production employing green technologies.

Implementing consumption and production patterns based on recycling and adopting an industrial symbiosis approach can promote sustainable urban development under a carbon-neutral economy through green technologies. Due to intensive research and practice, recycling has been used in road construction, maintenance, and rehabilitation in the last few decades. Recycling pavement materials prevents the extraction of non-renewable resources and minimizes waste production and landfilling. It can save energy and decrease greenhouse gas emissions, thereby reducing pollution. Recycling effectively helps to reduce environmental impacts and combat global climate change.

The purpose of this Special Issue was to collect and publish technical and research papers, including review papers, focusing on the recycling of road pavement materials to promote pavement sustainability performance. Ten papers were published in total covering the use of construction and demolition waste (reclaimed asphalt pavement, recycled concrete aggregate and glass) and industrial waste (plastic and slag). The application of recycled materials concerns bituminous mixtures, concrete mixtures, and non-traditional interlocking blocks or cobbles. The most relevant contributions of each paper are briefly described in the following sections. The papers involved thirty-four authors from eleven countries of Europe (Belgium, Finland, Italy, the Netherlands, and Portugal), Africa (Nigeria), Asia (Malaysia and Saudi Arabia), Australia, and South America (Brazil and Colombia).

2. Use of Construction and Demolition Waste

2.1. Reclaimed Asphalt Pavement

Bituminous pavement courses are designed to present adequate characteristics, in terms of safety and comfort, during its period of life. After this period, construction, maintenance, and rehabilitation operations must be performed and, as a result, very high amounts of reclaimed asphalt pavement (RAP) are usually produced.

Reclaimed asphalt pavement (RAP) is a 100% recycled material obtained from road maintenance and rehabilitation operations. After adequate processing, such as crushing and screening, RAP can present high-quality and well-graded aggregates coated by bituminous mastic, thus becoming a secondary raw material proper to replace bitumen and virgin

check for updates

Citation: Neves, J.; Freire, A.C. Special Issue "The Use of Recycled Materials to Promote Pavement Sustainability Performance". *Recycling* **2022**, *7*, 12. https://doi.org/10.3390/recycling7020012

Received: 8 February 2022
Accepted: 22 February 2022
Published: 23 February 2022

aggregates [2,3]. However, RAP applications, without downgrading, with incorporation in similar applications, still face several barriers, due to some lack of confidence in RAP recycling in new bituminous mixtures. The common maximum RAP incorporation rates vary between 10% and 50%, and between 0% and 20% for wearing courses [3]. The incorporation of high rates of RAP in new bituminous mixtures is still a challenge to be overcome to minimize life cycle costs and environmental impacts.

Vandewalle at al. [2] developed a comparative analysis on a real road pavement section, in which the real applied solutions were compared to alternative ones and were combined with the incorporation of five RAP rates into new bituminous mixtures (0%, 25%, 50%, 75%, 100%), in production, construction, and rehabilitation activities. The life cycle assessment (LCA) methodology was applied, and the results have been expressed in four damage categories: human health, ecosystem quality, climate change, and resources, together with 15 impact factors. The results demonstrated that both recycled and multi-recycled bituminous mixtures led to a decrease in the environmental impact when RAP was reused once or multiple-times. The benefits are greater for higher RAP rates presenting an average decrease of 19%, 23%, 31%, and 33% in all the four impact categories, for a 25%, 50%, 75%, and 100% RAP rate incorporation [2].

Antunes et al. [3] studied high RAP incorporation rates into new bituminous mixtures for wearing courses based on their long-term mechanical behaviour, taking into consideration the RAP bitumen mobilization degree, the evaluation of the RAP fractioning and mixing conditions, and both the mechanical and long-term behaviour of RAP mixtures. The behaviour of high RAP mixtures (75%) and virgin bituminous mixtures was compared. A crude tall oil rejuvenator was used to promote bitumen mobilization. The simulation of the ageing that occurs during mixture production and in-service life was accomplished by short- and long-term oven ageing procedures. The laboratory tests for the mechanical assessment were performed. The RAP bitumen mobilisation degree was evaluated, and a mixing protocol was developed and validated.

As a major conclusion, it was referred that, in general, the high RAP mixtures presented equivalent or even improved behaviours when compared with virgin bituminous mixtures. The performance of the high RAP mixtures presented good results even after ageing, allowing to conclude that these can present good long-term performances.

2.2. Recycled Concrete Aggregate

Since the cement industry is a major contributor to greenhouse emissions on a worldwide level, alternative materials are studied for the partial or complete substitution of cement in concrete. Recycled concrete aggregate (RCA) obtained from the demolition of old reinforced concrete structures is one of the recycled materials that can be reused to produce concrete and thus reduce the negative environmental impact of cement production [4,5]. However, some barriers need to be overcome regarding the use of RCA, namely the low demand for these materials and the costumers' unwillingness to pay more for them [4]. Many studies have considered the partial or complete replacement of cement in concrete. The use of fly ash and other by-products from the energy and mineral industry as additional cementitious materials in cement has a significant potential for reducing the carbon footprint of concrete [5].

Katar et al. [4] evaluated the application of construction demolition waste produced in Riyadh to manufacture high-strength concrete. Self-compacting concrete with 100% natural aggregate and three replacement levels (25%, 50%, 75%) of RCA was produced. Fly ash and a superplasticizer were added to obtain the adequate properties of flowability and cohesion in fresh state mixtures. The authors evaluated both fresh and hardened properties of the mixes, and J-ring, v-funnel, and slump flow tests were performed. Compressive strength tests after seven, 14, and 28 days were performed. The results confirmed that RCA can produce concrete with a reasonable compressive strength, its use being acceptable for structural applications.

Rintala et al. [5] presented a case study as part of the EU-funded research project "Urban Infra Revolution" that estimated the cost prices of four different geopolymer concrete (cement-free binders) with different material compositions and carbon footprints, considering the raw material price fluctuation and the potential impact of carbon emission regulation through carbon price. Two major questions were presented: "What are the benefits of using the materials?" and "How much does it cost?". The authors concluded that the results seem to indicate that carbon pricing, at the actual rates, does not significantly change the cost-price difference between traditional and geopolymer concrete. This means that the cost-competitiveness of low-carbon concrete depends on the material mix type and the availability of critical side streams.

2.3. Glass

Glass waste is suitable for various applications, including in the cement and concrete industries, due to its pozzolanic properties being more intensive in fine-grained form. Megna et al. [6] described research on combining glass and marble wastes to produce a new sustainable mortar for non-structural pavement solutions. Based on the experimental characterization of different types of mortars, the authors have confirmed the pozzolanic properties of the glass waste that led to the production of a hydraulic binder suitable to replace the conventional cement in concrete production.

3. Use of Industrial Waste

3.1. Plastic

Plastic wastes are a major global environmental issue, and their recycling and reuse are becoming more and more investigated. The diversity of plastic properties is enormous, and different approaches can be adopted to incorporate plastic wastes into pavement materials. The types of plastic covered in the Special Issue are polyethylene terephthalate (PET) [7], high-density polyethylene (HDPE) [8], acrylonitrile butadiene styrene (ABS) [9], polystyrene polymers (PS) [9], and low-density recycled polyethylene (LDPE) [10]. The authors have studied plastic waste applications in bituminous mixtures [7], concrete mixtures [8], interlocking plastic blocks [9], and sand/recycled-plastic cobbles [10] for pavements of roads [7,8] and other trafficked areas (e.g., parking areas, sidewalks, bike paths) [9,10].

In general, bituminous mixtures are considered a promising application for plastic wastes to achieve more sustainable pavements. Plastic wastes are being addressed as modifier agents of bituminous binders or as substitutes of aggregates. Mashaan et al. [7] investigated the effect of PET from plastic bottles on modifying a bitumen binder to be used on a 14 mm dense-graded asphalt for wearing course, composed of granite aggregates and a 4.9% optimum binder content. The authors studied the rheological properties of the plastic modified bitumen and the mechanical properties of the plastic modified bituminous mixture. Improved stability and resistance to permanent deformation were observed, more significant for 8% PET by weight of the bituminous mixture.

Other pavement applications of plastic wastes were concrete mixtures [8] and non-conventional blocks or cobbles [9,10]. In these applications, plastic waste was used for partial or total replacement of natural aggregates. Tamrin and Nurdiana [8] studied the incorporation of HDPE lamellar particles from diverse origins in concrete mixes for non-structural pavement applications. The authors concluded that the concrete with a 10 MPa compressive strength had the best resistance to adding HDPE, and 5% and 5×20 mm were the optimal content and size, respectively. Gabriel et al. [9] investigated interlocking plastic pavers composed of 70% ABS and PS from electronic equipment (e.g., computers) and 30% of other polymers and residual materials (e.g., other plastic or metal wastes). The 100% recycled blocks resulted from shredding, agglutination, and pressing procedures performed at specific temperature conditions. The authors carried out laboratory tests that confirmed similar properties compared to traditional blocks made of concrete for light traffic conditions. Sanchez-Echeverri et al. [10] evaluated the use of LDPE from recycled plastic bags to manufacture cobbles with 10 cm × 20 cm × 4 cm dimensions. The cobbles were composed of 25% plastic and 75% sand. The experimental research performed in the laboratory demonstrated the adequacy of the cobbles for pedestrian and lightweight traffic pavements. In complement, those authors also presented a market study to implement a factory in Colombia to produce these recycled cobbles.

3.2. Slag

Slags, in particular steel slag, lead slag cooper slag, and tin slag, are some of the industrial waste materials that have been studied to validate their application as replacement of natural aggregates. Tin slag (TS) is an industrial waste that is accessible and still underutilized. About 2 million tons of this waste is landfilled worldwide. Olukotun et al. [11] studied the use of TS as a substitute for fine aggregates in cement mortar, considering different percentages of incorporation (0%, 25%, 50%, 75%, 100%). Three water/cement ratios of 0.5, 0.55, and 0.6 were used to prepare the tested specimens. Laboratory evaluation was conducted at fresh and hardened states and after 3, 7, and 28 days of water-curing of the testing specimens. The workability and the mechanical properties of mortar specimens were evaluated. According to the results, the authors considered that TS could be applied as a substitute for natural sand to produce mortars, thus promoting a reduction in costs and in natural resource depletion and leading to the sustainability of natural fine aggregates.

4. Final Remarks and Future Trends

The guest editors believe that this group of ten papers, published in this Special Issue, gave a significant contribution to promote the circular economy through the pavement sustainability performance of recycled materials. Other studies, namely regarding the application and validation of different types of alternative raw materials into pavements, may also be published in the following Special Issue: "The Use of Recycled Materials to Promote Pavement Sustainability Performance II".

Funding: This research received no external funding.

Acknowledgments: The guest editors are grateful to the MDPI Editorial Office for the support during peer review and publication of the papers included in the Special Issue. We also thank the authors for deciding to disseminate their investigation in this Special Issue, and the reviewers for their collaboration in ensuring the desired quality of the papers.

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

References

1. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://sdgs.un.org/2030agenda (accessed on 31 January 2022).
2. Vandewalle, D.; Antunes, V.; Neves, J.; Freire, A.C. Assessment of Eco-Friendly Pavement Construction and Maintenance Using Multi-Recycled RAP Mixtures. *Recycling* **2020**, *5*, 17. [CrossRef]
3. Antunes, V.; Neves, J.; Freire, A.C. Performance Assessment of Reclaimed Asphalt Pavement (RAP) in Road Surface Mixtures. *Recycling* **2021**, *6*, 32. [CrossRef]
4. Katar, I.; Ibrahim, Y.; Abdul Malik, M.; Khahro, S.H. Mechanical Properties of Concrete with Recycled Concrete Aggregate and Fly Ash. *Recycling* **2021**, *6*, 23. [CrossRef]
5. Rintala, A.; Havukainen, J.; Abdulkareem, M. Estimating the Cost-Competitiveness of Recycling-Based Geopolymer Concretes. *Recycling* **2021**, *6*, 46. [CrossRef]
6. Megna, B.; Badagliacco, D.; Sanfilippo, C.; Valenza, A. Physical and Mechanical Properties of Sustainable Hydraulic Mortar Based on Marble Slurry with Waste Glass. *Recycling* **2021**, *6*, 37. [CrossRef]
7. Mashaan, N.; Chegenizadeh, A.; Nikraz, H. Laboratory Properties of Waste PET Plastic-Modified Asphalt Mixes. *Recycling* **2021**, *6*, 49. [CrossRef]
8. Tamrin; Nurdiana, J. The Effect of Recycled HDPE Plastic Additions on Concrete Performance. *Recycling* **2021**, *6*, 18. [CrossRef]
9. Gabriel, L.T.; Bianchi, R.F.; Bernardes, A.T. Mechanical Property Assessment of Interlocking Plastic Pavers Manufactured from Electronic Industry Waste in Brazil. *Recycling* **2021**, *6*, 15. [CrossRef]

10. Sanchez-Echeverri, L.A.; Tovar-Perilla, N.J.; Suarez-Puentes, J.G.; Bravo-Cervera, J.E.; Rojas-Parra, D.F. Mechanical and Market Study for Sand/Recycled-Plastic Cobbles in a Medium-Size Colombian City. *Recycling* **2021**, *6*, 17. [CrossRef]
11. Olukotun, N.; Sam, A.R.M.; Lim, N.H.A.S.; Abdulkareem, M.; Mallum, I.; Adebisi, O. Mechanical Properties of Tin Slag Mortar. *Recycling* **2021**, *6*, 42. [CrossRef]