

Article

Waste Plastic in Asphalt Mixtures via the Dry Method: A Bibliometric Analysis

Isabella M. Bueno  and Jamilla E. S. L. Teixeira * 

Department of Civil and Environmental Engineering, University of Nebraska-Lincoln (UNL),
Lincoln, NE 68588, USA; ibueno2@huskers.unl.edu

* Correspondence: jamilla.teixeira@unl.edu

Abstract: Although waste plastic (WP) application as a paving material has drawn increasing attention from scholars, there is a lack of studies that summarize the latest development of WP research. Considering there is no standard procedure to incorporate WPs in asphalt mixtures, it is important to document the major findings from the available literature to identify knowledge gaps to tackle in future research and advance knowledge on this subject. Using a bibliometric analysis method, this study carries out a holistic review of WP articles published from 2003 to 2023, focusing on incorporating WP in asphalt mixtures via the dry method. This study particularly focused on identifying and evaluating individual types of WP mostly used in asphalt mixtures via the dry method and how their most common characteristics (size, shape, and melting point) affect the mixing procedure and the overall mixture's performance. The analysis highlighted China, the USA, and India as leading countries in WP-related publications. Typically, low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyethylene terephthalate (PET) were the most utilized WPs in the dry method. Smaller WP particle sizes (<2.36 mm) were considered more suitable in asphalt mixtures. In general, studies employing procedures involving WP melting, typically by introducing WP to pre-heated aggregates at temperatures surpassing its melting point, resulted in improved asphalt mixtures with enhanced resistance to rutting, cracking, and moisture damage. In this context, positive performance outcomes were notably observed in studies using HDPE or LDPE, potentially because of their low melting point. The key knowledge gaps identified were the lack of a consistent procedure applicable across studies, a feasibility assessment for scaling laboratory-based procedures to field applications, and laboratory evaluations utilizing advanced performance tests as suggested in the Balance Mix Design (BMD) approaches.



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Keywords: bibliometric analysis; waste plastic; asphalt mixture; dry method

1. Introduction

There is a global concern regarding the lack of sustainable alternatives to minimize the accumulation and deposition of mismanaged waste plastics (WPs) in the environment [1]. According to Ritchie et al. [2], the amount of plastic generated globally has doubled in the last two decades, accounting for 460 million tons in 2019. During that year, less than 10% of all plastic generated was recycled, while 19% was incinerated, 49% was disposed of in landfills, and the remaining was considered mismanaged WPs, including all waste burned in open pits, dumped into the ocean, or disposed of in dumpsites. Figure 1 shows the distribution of mismanaged WPs in the world in 2019.

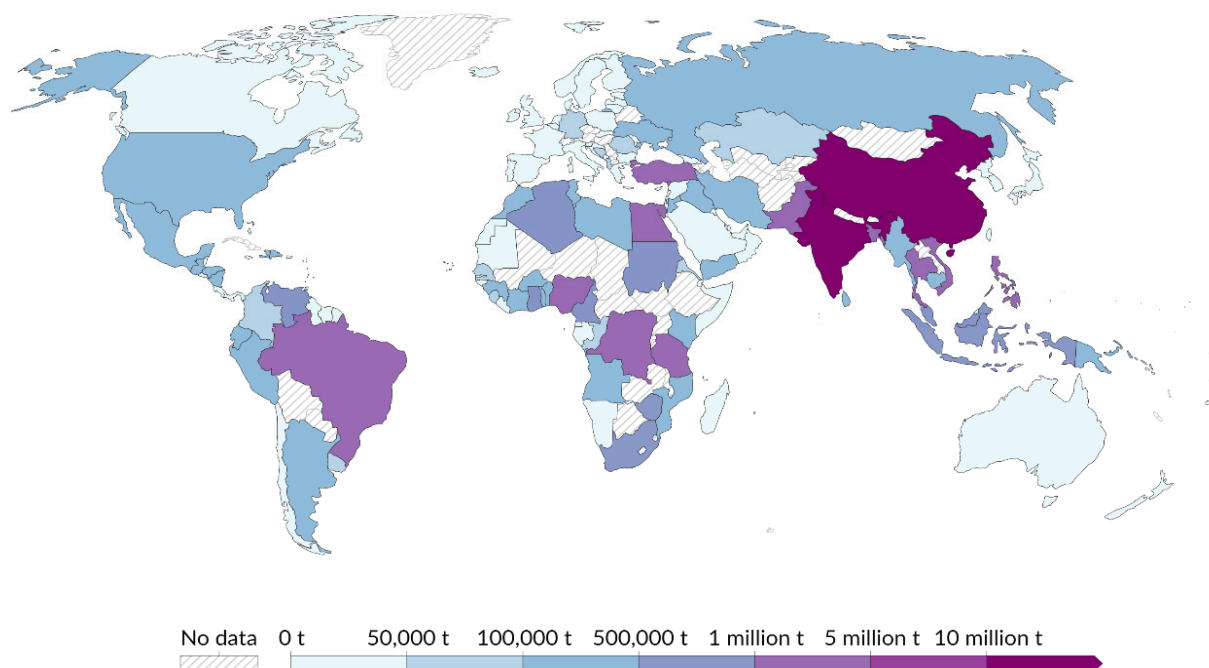


Figure 1. Global mismanaged waste plastic in 2019 (Meijer et al. [3], processed by Our World in Data).

In 2019, China and India were identified as the biggest producers of mismanaged waste plastic, generating over 12 million tons of WP. Brazil and some African countries such as Nigeria, the Democratic Republic of Congo, Egypt, and Tanzania accounted for 1 to 3 million tons each [2]. Lower amounts of mismanaged WPs were identified in the United States (about 267,569 tons); however, its recycling rate still represents a concern. In 2018, only 8.7% of all plastic generated in the country was recycled, while 75% ended up in landfills [4].

The amount of plastic generated in the world may have increased exponentially over the last three years because of the COVID-19 pandemic. Peng et al. [5] estimated that between 2020 and 2021, the amount of WP increased by approximately 8 million tons compared with the typical generation rates. The main sources were hospital medical waste, test kits to detect the COVID-19 virus, personal protective equipment (i.e., masks, gloves, and face shields), and packaging (from online shopping, food, and hand sanitizer containers). During the pandemic, Sharma et al. [6] also estimated that the world production of packaging and medical products made from plastic has increased by 44.8% and 13.2%, respectively.

Because of the substantial volume of plastic produced and mishandled WPs, along with the paving industry's successful track record of reusing waste materials in road construction, utilizing WPs for paving purposes presents itself as a viable alternative solution. Many recent research works have been conducted to evaluate the feasibility of WP addition into hot mixture asphalt (HMA) [7–11]. In this case, WP can be used to modify the asphalt binder [7,8,11], to replace a portion of the aggregates in the mixture [7,9], as a mixture modifier (additive) [7], or a combination of these [7,10]. Although promising results have been found, many knowledge gaps remain regarding the optimized use of WPs in HMA.

In brief, WPs can be added to HMA using two main approaches, dry and wet methods. In the dry method, WP is added directly to the aggregates, as an aggregate replacement or as an additive, acting as a reinforcement in the mix. In the wet method, WP is added directly into the binder, aiming to produce a polymer-modified asphalt (PMA). In this case, the WP acts as a binder modifier [9–14]. The majority of studies show that both addition methods can lead to modified HMAs with improved performance, showing enhanced Marshall stability, rutting, and stiffness [9,10,14–16]. The wet procedure can become more

expensive in comparison to the dry method since it often requires either pre-processing WPs to produce very small particle sizes or changes in current asphalt plants such as the inclusion of agitation systems inside the binder tanks to reduce the separation tendency between the binder and the WP [7,17]. Regarding sustainability aspects concerning the number of WPs re-used or post-secondary effects, the dry procedure can lead to a larger number of WPs incorporated into the HMA in comparison with the wet method. Also, the use of WP as an aggregate replacement can help minimize the amount of microplastics released into the environment since the WP particles are placed deeper within the pavement layers. [18,19]. One concern regarding the use of the dry process is the lack of normative guidance and a standard procedure [7].

WPs recommended for paving applications are mostly thermoplastic types, i.e., their chemical structure allows them to melt when heated and solidify when cooled. Thermoplastics include polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), acrylonitrile butadiene styrene (ABS), and polyethylene (PE). PE is further classified into high-density polyethylene (HDPE) and low-density polyethylene (LDPE) based on the differences in crystallinity and branching in their polymer chain, leading to differences in the material's density [20]. Regarding the use of WPs for HMA applications, PET, HDPE, LDPE, and PP are the most explored [12].

Many properties of WPs must be considered when selecting the proper addition method. Specific gravity, for example, is related to compatibility/incompatibility between WP and both the binder and aggregates, affecting the mixture's volumetric parameters and the interaction among the mixture's components [7,10]. The melting point of WPs also plays an important role in the selection of the procedure. Plastics with higher melting points (i.e., above 160 °C), such as PET and PP, are generally used in the dry process. That is because the melting point is usually higher than the binder's mixing temperature, which makes it hard for the WP to be blended with the binder if added through the wet process. [7].

Another crucial property is the particle size and shape of WPs. Plastic can be added to HMA in many shapes with varied sizes, such as powder (0.035–0.25 mm) [21,22], pellets (5–10 mm) [23], fibers (6.5–30 mm) [24–26], flakes (0.63–10 mm) [27–30], or granules (0.3–0.6 mm) [31,32]. WPs can also go through some processes for size reduction, such as shredding, grinding, crushing, and cutting [10,33–35]. Smaller particle sizes lead to more homogenous blends in both wet and dry methods. Powdered WP is the best option for the wet method because it provides a larger surface area per unit mass of plastic, facilitating the melting of the WP [13]. The dry process accepts bigger sizes of WPs than the wet method, and different shapes can be used. Nonetheless, the smaller the particle size, the better the distribution of aggregates and the binder during the mixing process [7]. Movilla-Quesada et al. [36] even suggest that to achieve better coating of aggregates with WP and better performance in the presence of water, the ideal particle size in the dry method should be smaller than 2 mm.

As mentioned, the dry method allows for a larger quantity of WP to be incorporated into HMA, which can be relevant when it comes to reducing the amount of mismanaged WP released into the environment. However, there is no standard procedure when it comes to adding WP through the dry process. This is a knowledge gap that needs to be addressed. Different mixing approaches have been proposed to incorporate WP into HMA through the dry processes, which vary mainly according to the necessity of pre-heating aggregates, mixing temperatures, and the instant WP should be added during the mixing procedure. It is crucial to understand how and why each approach is utilized and their respective outcomes.

Considering the aforementioned literature review, it is necessary to perform a holistic evaluation of the effects of WP in asphalt mixtures and document the major findings from the available literature to identify knowledge gaps to tackle in future research and advance knowledge on this subject. Therefore, this paper aims to conduct a bibliometric analysis, a social network analysis, and an in-depth content analysis, focusing on the dry process of using WP in HMA. This analysis will provide research trends, the relevancy of the topic

nowadays, and different incorporation approaches used based on the type of WP, aiming to identify the main divergences in the suggested approaches and how various types of WPs might interact with the other HMA constituents. This could help establish the most appropriate mixing procedure since there are still no standards for this addition method.

2. Data Collection and Research Procedure

2.1. Sample Source and Extraction

In this study, the Web of Science (WoS) database was selected to gather preliminary information on WPs because of its extensive repository comprising over twenty-one thousand peer-reviewed journal articles, books, and conference proceedings across various fields including science, social sciences, and humane disciplines [37]. It is important to establish the topic and keywords that address the full scope of this research. Since the scope of this research is the addition of WP in asphalt mixtures, the topics searched for in the database were “waste plastic” and “asphalt mixtures”. The keywords chosen were “waste plastic”, “asphalt” (both as “must be included” in all publications), and “pavements”, which “should be included” in the publications (it was not a mandatory keyword). The term “asphalt” includes many possibilities, such as “asphalt mixtures”, “asphalt concrete”, and “hot mix asphalt”, which are all part of this research. This procedure helped eliminate articles that were not related to the topic of interest.

The initial search resulted in 145 technical documents. To further refine the search, the publications were restricted to peer-reviewed journal articles only, resulting in 124 papers. This restriction was used to eliminate conference papers, theses, dissertations, and books, focusing only on peer-reviewed papers published in journals. Similar restrictions were applied by other bibliometric analyses on WP recycling [38] and asphalt pavements [39]. Subsequently, a screening process was employed, involving a quick analysis by reading their titles and abstracts to determine if they were related to incorporating WP in asphalt mixtures, resulting in the elimination of a total of 5 articles from the list of papers gathered to perform the bibliometric analysis, leading to a total of 119 papers used in the bibliometric analysis.

2.2. Social Network Analysis, Initial Bibliometric Analysis, and In-Depth Content Analysis

An initial bibliometric and social network analysis was performed following a similar procedure adopted by Wu et al. [40] but applied to other types of waste material. For that, graphs and network maps were plotted using the software VOS viewer (version 1.6.20) and Microsoft Excel (version 16.84). This visual representation depicted the various aspects of the results, including geographic distribution, co-occurrence of keywords, co-authorship, published journals, and publication over the years and by type of plastic.

After that, a comprehensive literature review was conducted. This review encompassed various aspects, including the prevalent types of WPs utilized for paving application, key characteristics of WPs (such as size, shape, and percentage of use in HMA), methods of WP incorporation (whether wet, dry, or other), and their respective detailed procedures (order of material addition, mixing temperature, compaction techniques, etc.). Additionally, the overall implications on HMA performance resulting from WP addition were verified. A flowchart of the research procedure employed herein is shown in Figure 2.

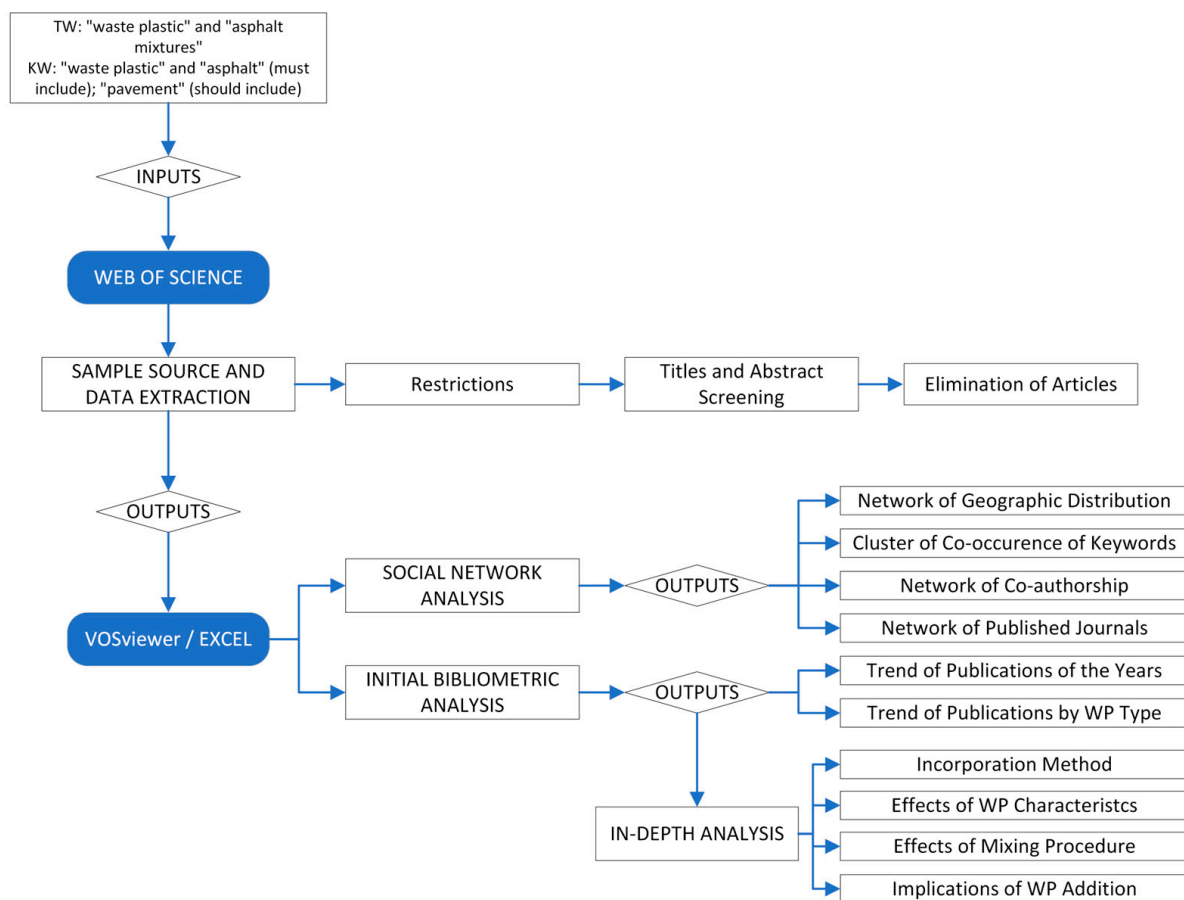


Figure 2. Research procedure.

3. Results and Discussion

3.1. Geographic Distribution

In total, 43 countries contributed to publications on the use of WP in asphalt mixtures. Figure 3 represents the social network map of the bibliometric coupling organized by country, in which each node (25 in total) consists of a country with at least two publications. The map also shows the links between various countries, indicating that a single publication could have authors from different places in the world. Closer nodes and thicker links represent a higher frequency of publications containing authors from those countries [39].

China (represented as “Peoples r China” in Figure 3) and the USA represent the countries with the highest number of publications, accounting for 26 and 19, respectively (publications with at least one author from those countries). India also plays an important role when it comes to publications regarding the use of WP in asphalt mixtures, accounting for 17 publications. As mentioned, China and India correspond to the largest producers of mismanaged waste plastic globally. The high number of publications from those countries can represent the necessity to search for new ways to manage their plastic waste. Regarding the USA, their plastic management systems consist of landfilling the highest amount of plastic and combusting the remaining amount. Therefore, the landfilling rate has grown over the years, while the recycling rate has never been higher than 10% [4]. Researching new alternatives, such as using WP for paving applications, can help reduce the amount that is landfilled.

Similar trends were observed in a report study conducted by NCAT [7] in 2021, which showed that the United States, India, Australia, and China were the countries with the highest numbers of publications.

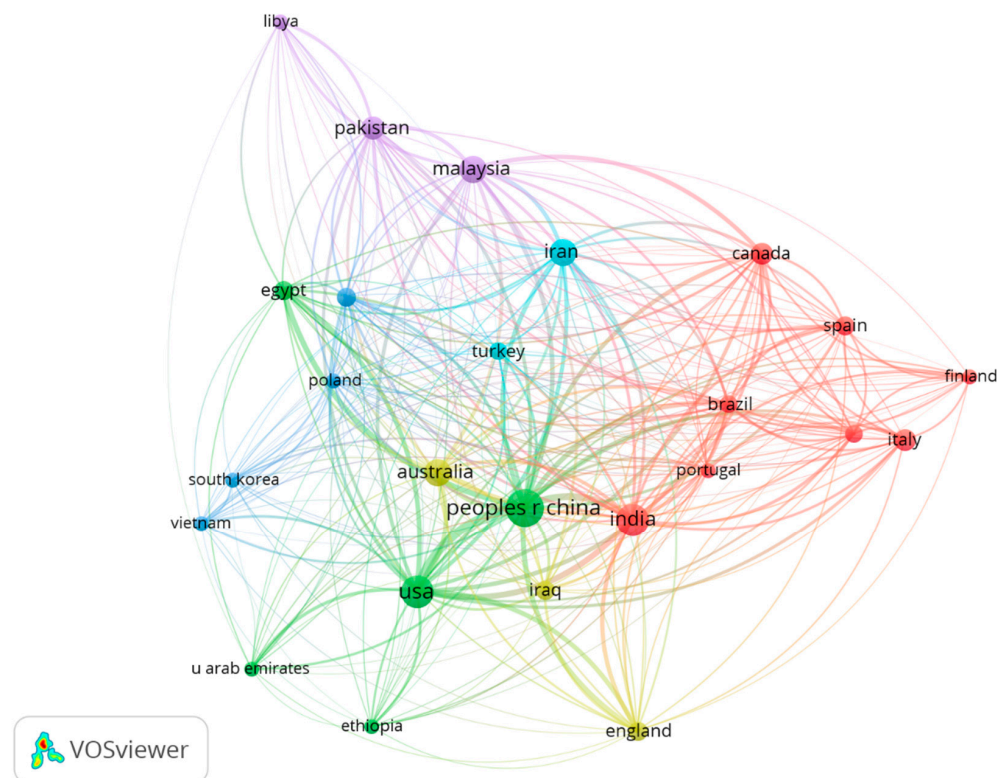


Figure 3. Network map of the geographic distribution of the publications, according to WoS.

3.2. Keywords Cluster Analysis

Figure 4 shows a network map representation of the keywords that co-occurred at least five times in all publications, totaling 21 keywords. The node size corresponds to the occurrence frequency of the keyword. The links illustrate terms that appeared together in the same publications. Closer nodes and thicker links represent the frequency of the co-occurrence of the keywords [39].

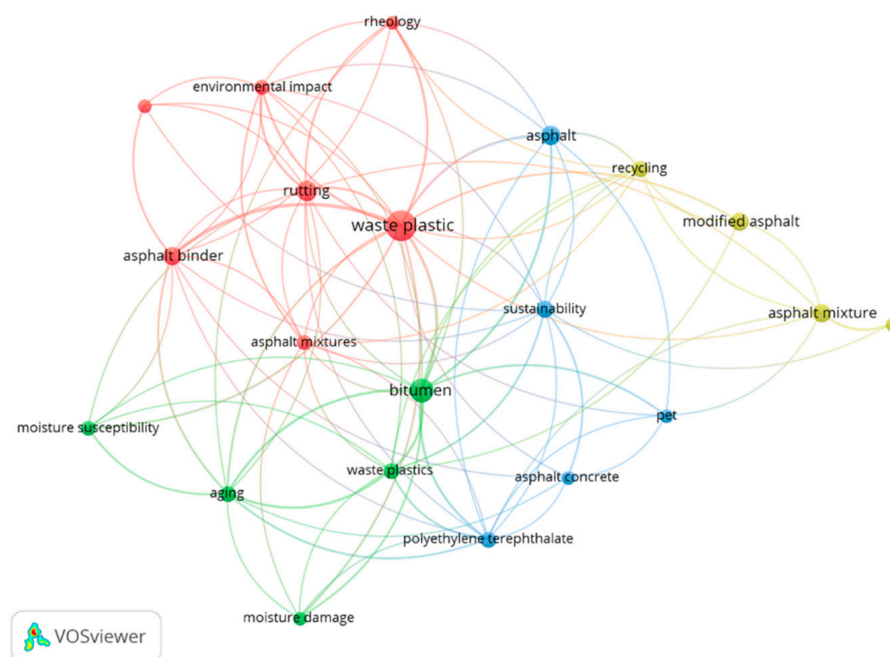


Figure 4. Network map of the most used keywords on the publications, according to WoS.

As mentioned, the keywords established as mandatory in all papers were “waste plastic” and “asphalt”. “Waste plastic” represented the most used keyword, given by the size of the node. The word “asphalt” enabled the occurrence of similar terms containing keywords such as “asphalt concrete”, “asphalt mixture”, “modified asphalt”, “asphalt mixtures”, and “asphalt binder”. There were also keywords related to the mixture’s performance, including “moisture susceptibility”, “moisture damage”, and “rutting”, which could indicate the improvement in those parameters by the addition of WP. Also, only one type of WP was used as a keyword (PET), indicating the possibility of it being the most researched plastic waste. Terms related to binders were also utilized, such as “bitumen” (the second most used keyword), “rheology”, and “aging”, which could represent a higher tendency of publications on binder modification using the wet process in comparison with the dry process. Finally, words related to sustainability were also present.

3.3. Co-Authorship Cluster Analysis

The network map of co-authorship is given in Figure 5. This analysis considered authors with a minimum amount of three publications. The nodes show the names of the authors and the lines represent co-authorship relationships. Each color corresponds to authors who worked together in the same publication. For example, authors in the green cluster did not collaborate with authors in the red cluster. In total, 406 authors contributed to the research on the use of WP in asphalt mixtures. Twenty-six authors matched the thresholds, which were divided into eight different connections (clusters). Given the size of the node, the yellow cluster accounted for the largest number of publications, followed by the dark blue cluster. All publications in the yellow cluster were affiliated with a Malaysian university, while the ones from the dark blue cluster were affiliated with an American university.

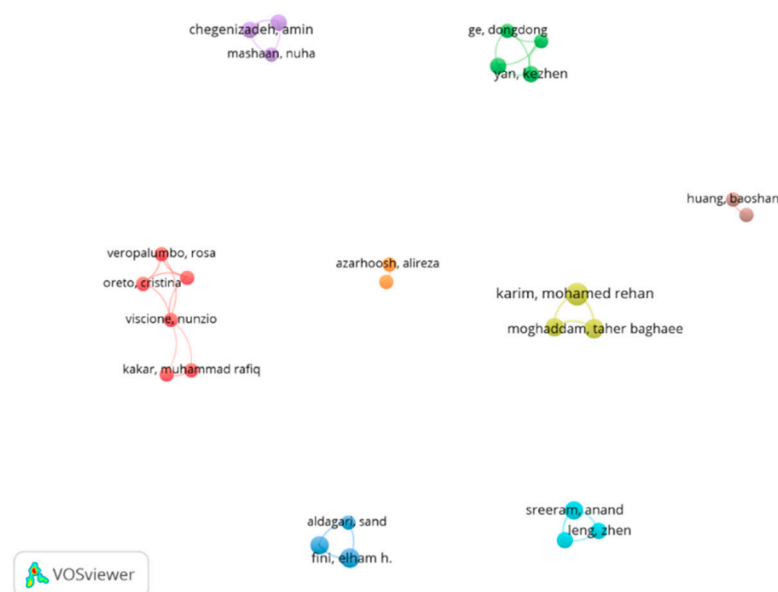


Figure 5. Network map of co-authorship, according to WoS.

Karim, M. R. was the most productive author with eight publications [27–29,33,41–44] and over 600 citations (yellow cluster), followed by Moghaddam, T. B. [27–29,33,41,42] (yellow cluster) and Fini, E. H. [31,32,45–48] (dark blue cluster) with six publications each. Karim, M. R. and Moghaddam, T. B. were mainly focused on researching the incorporation of PET WPs (plastic bottles) through the dry approach. Fini, E. H., however, focused on the wet procedure, proposing modified binders by PET and PE. Table 1 lists the six most productive authors regarding the topic. Sreeram, A. is a member of the cyan cluster, with five publications [12,49–52]. His work also focused on incorporating WP through the wet

procedure using PET and PS. Here, it is possible to see the tendency for the research works to use PET, as seen previously in the keywords analysis. All the remaining authors had fewer than five publications.

Table 1. Most productive authors on the use of WP in asphalt mixtures, according to WoS.

Cluster	Author	Documents	Citations	Country	Affiliated University
Yellow	Karim, M. R.	8	695	Malaysia	Universiti of Malaya
	Moghaddam, T. B.	6	341		
	Soltani, M.	5	234		
Dark blue	Fini, E. H.	6	95	United States	Arizona State University
	Kabir, S.F.	5	95		
Cyan	Sreeram, A.	1	0	England	University of Cambridge
		4	388	China	Hong Kong Polytechnic University

Malaysia appears as an emerging hub for researching the use of WP in paving applications. Malaysia is the fourth country with the most publications on the topic, only behind China, the United States, and India. Even though the country generates over 10 times less mismanaged WP than China and India, the percentage that reaches the ocean is 15 times higher compared with China, leading to water pollution of 1070 rivers [3]. Researching new WP management solutions can likely help to overcome this problem.

3.4. Number of Articles Published by Scientific Journals

In total, 54 scientific journals published papers on the theme. The network map considering all scientific journals with at least two publications is given in Figure 6. The most used platform was *Construction and Building Materials*, with 25 publications (21.01%), 786 citations, and an impact factor of 7.4 (2022), which is considered an almost excellent score. According to Tsai [53], an impact factor (IP) is an average of the number of citations received in a determinate year, considering articles published in the two preceding years. An IP higher than 10 is an excellent score, between 3 and 10 is a good score, and less than 1 is an average score.

Materials and *Journal of Cleaner Production* were the second and third scientific journals with the most published papers, with nine (7.56%) and seven (5.88%) publications, respectively, far fewer than the amount published by *Construction and Building Materials*. The main research areas were *Engineering*, *Materials Science*, and *Construction Building Technology*. The links between the journals are related to authors who published articles in more than one journal. It is possible to see a centralization tendency in just one journal. Spreading publications among different journals can help disseminate knowledge on the theme, instead of keeping it focused in only one place.

Table 2 shows the 11 scientific journals with the highest number of published articles regarding the topic of WP in asphalt mixtures, with the total number of citations of those articles, impact factor (IF), and quartile rank (QR). The top 11 journals were responsible for 67 research papers, accounting for 56.30% of all the publications. It can be noticed that they had impact factors higher than 3, which represents a good frequency of citation and demonstrates the importance of those journals within their field [53]. Journals such as the *Journal of Production and Resources*, *Conservation*, and *Recycling* were even considered excellent sources because of their high impact factors (higher than 10).

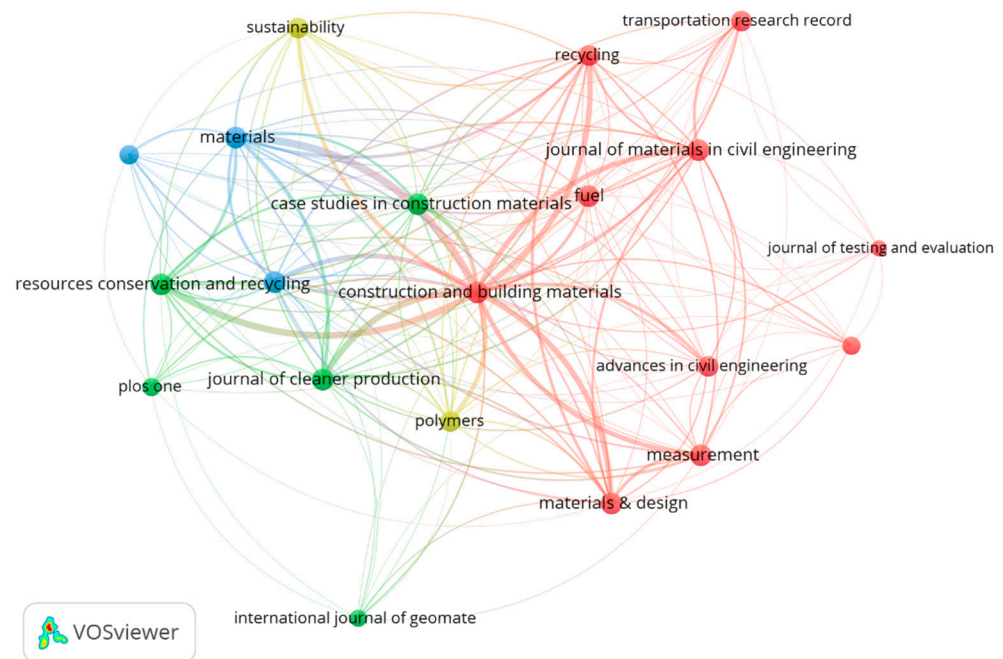


Figure 6. Network map of scientific journals, according to WoS.

Table 2. Most relevant scientific journals on the use of WP in asphalt mixtures, according to WoS.

Journal	Number of Publications	Citations	IF/QR (2023)
Construction and Building Materials	25	786	7.7/Q1
Materials	9	70	3.7/Q2
Journal of Cleaner Production	7	417	11.1/Q1
Journal of Materials in Civil Engineering	4	40	3.7/Q1
Resources, Conservation, and Recycling	4	76	13.7/Q1
Road Materials and Pavement Design	4	78	3.8/Q1
Materials & Design	3	374	8.4/Q1
Polymers	3	21	5/Q2
Recycling	3	20	4.3/Q2
Sustainability	3	14	3.9/Q2
Fuel	2	173	8.3/Q1

3.5. Publications over the Years

Figure 7 represents the temporal evolution of publications on asphalt mixtures with WP, according to the incorporation method used. The numbers on the middle section of each bar represents the number of publications according to the procedure used. The dry procedure accounts for 36.13% of all publications, while the wet procedure accounts for 45.38%. This matches the higher numbers of keywords used regarding binder modification (Figure 4). The remaining publications were either a literature review on the use of WP in asphalt mixtures (10.08%), a methodology that tested both wet and dry methods (1.68%), a different type of incorporation method under the “other” category (i.e., semi-wet, WP dissolved in tall oil pitch before mixing with the binder, and Pyrolysis wax WP added to the binder) (5.04%), and a methodology not specified by the author (1.68%).

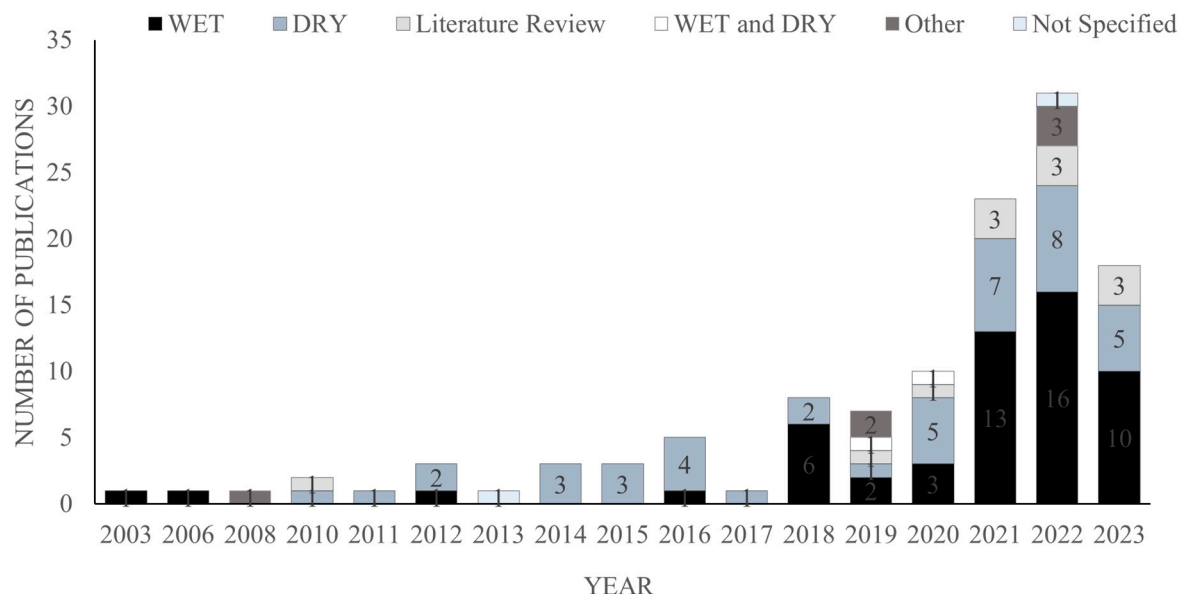


Figure 7. Number of publications over the years on the use of WP in asphalt mixtures, divided by incorporation method, according to WoS.

It is evident that this is still a very new topic since the earliest publication is dated 20 years ago. Also, it is possible to see a growing tendency in the number of publications starting from 2018. One of the reasons can be the unprecedented ban imposed by China in 2017. China used to be one of the major importers of solid waste in the world, importing over 8 million tons of plastic annually until 2017 when it decided to mitigate the situation by banning its import. Following that decision, there was a sharp decline in global plastic waste trade flow, resulting in changes in the treatment structure of many countries and enormous but unexamined impacts on global environmental sustainability [54]. Therefore, countries and regions that exported their waste to China needed to find new ways to manage their waste. Given that the paving application is an alternative solution, this could explain the increase in scientific research regarding this topic.

There was a large increase in the number of publications in the last three years, representing 60.50% of all the reviewed papers. This could be due to the increase in plastic production during the COVID-19 pandemic. With a higher amount of mismanaged WP, new alternatives needed to be found to treat the WP.

Additionally, similar trends were observed in the report conducted by NCAT [7] in 2021. The report showed that the largest number of documents was released from 2017 to 2021 and that the wet process was the most researched incorporation method.

3.6. Publications by Type of WPs

Figure 8 shows the number of publications considering each type of WP and incorporation method. The numbers on the middle section of each bar represents the number of publications according to the procedure used; since one publication may have tested more than one type of WP, the total amount of relative publications may be different than 119. For each type of WP shown in Figure 8, the mixture contained only WP, aggregates, and an asphalt binder (no additives). The “other” category stands for mixtures that blended WP with other components that could also cause variability in the mixture, such as crumb rubber, wax, Reclaimed Asphalt Pavement (RAP), Recycled Concrete Aggregates (RCAs), basalt fiber, graphene, vegetable oils, or any other type of additives.

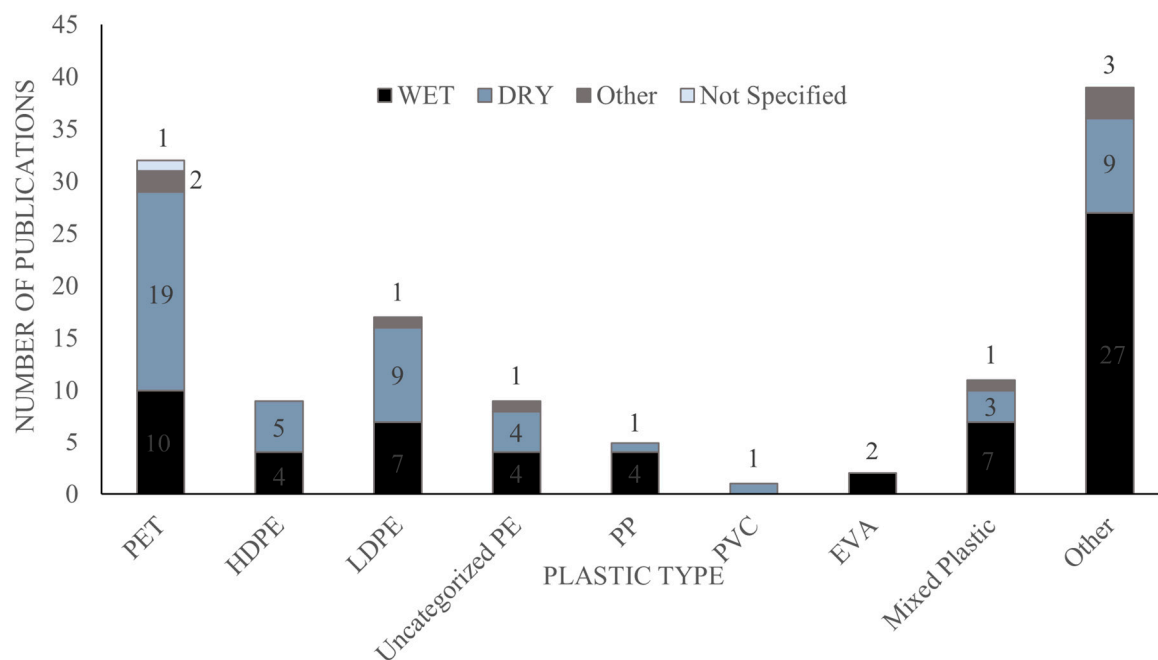


Figure 8. The number of journal article publications considering each type of WP, according to WoS.

PET was the most researched plastic, with 32 publications. As expected, most of those publications focused on the dry procedure, probably because of its higher melting point. Polyethylene, in general, was also a very important research topic, with 35 publications (9 for HDPE and 17 for LDPE). For PE, the number of publications on wet and dry procedures was similar; however, the dry approach stands out slightly. PP represented a controversial result. PP has a higher melting point than most binders' blending temperature; still, 75% of all papers regarding its use in asphalt mixtures applied the wet procedure. Ethylene-vinyl acetate (EVA) is not among the plastics most utilized in paving applications but still has some publications on its use in asphalt mixtures. For mixed plastic and "other", the wet method was the most used approach. As mentioned, the "other" incorporation method category included the semi-wet procedure, WP dissolved in tall oil pitch before mixing with the binder, and Pyrolysis wax WP added to the binder.

Considering only the types of plastics most explored in paving applications (HDPE, LDPE, PET, and PP), the dry procedure was the most used incorporation method, except for PP. This indicates a necessity to evaluate the approach utilized by every author to comprehend how the characteristics of the WP and the mixing procedure used affected the final performance of the mixture.

The results shown in Figure 8 differ from the literature review conducted by NCAT [7] in 2021. That report showed that PE was the most researched WP, with 105 documents. This difference can be related to the documents analyzed. NACT [7] evaluated all kinds of documents regarding WP addition, including journal articles, research reports, trade publications, magazine articles, newsletters, technical guidance, and personal email communications. The bibliometric analysis conducted in this paper only included peer-reviewed journal articles. Also, NCAT [7] did not consider WP by type of incorporation method.

Table 3 shows the five most cited publications on the topic. Considering the publications, PET was again the most researched WP, being investigated in four papers. This confirms the tendency observed in the keywords network map (Figure 4) and the high number of publications on this type of plastic (Figure 8). Although the dry approach was not the most researched method over the years, it was the most relevant method among the five publications. These results reiterate the importance of better understanding this non-standardized methodology and its effect on the mixture.

Table 3. Most important publications on the use of WP in asphalt mixtures, according to WoS.

Title	Reference	Citations	Incorporation Method	WP
Using waste plastic bottles as an additive for stone mastic asphalt	Ahmadinia et al., 2011 [43]	195	DRY	PET
Production of a sustainable paving material through the chemical recycling of waste PET into crumb rubber-modified asphalt	Leng et al., 2018 [49]	188	WET	PET
Performance evaluation of the utilization of waste polyethylene terephthalate (PET) in stone mastic asphalt	Ahmadinia et al., 2012 [44]	159	DRY	PET
Effect of waste polymer addition on the rheology of modified bitumen	García-Morales et al., 2006 [55]	148	WET	EVA/EVA + LDPE
Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes	Modarres and Hamed, 2014 [56]	133	DRY	PET

3.7. In-Depth Content Analysis

To perform a comprehensive evaluation of WP addition in asphalt mixtures via the dry method, it was necessary to collect data from publications that used WP only and no other type of materials or additives besides the conventional ones (natural aggregates and binder) that could cause variability in the mixture such as crumb rubber, RAP, RCA, wax, and others. Therefore, in this part of the study, a total of 27 papers were analyzed (1 paper could have tested more than one type of WP). The focus of this analysis was to identify the size and shape of WP, the percentage of WP addition, and the mixing procedure used. As mentioned before, there is no standard procedure, and the procedure used varies among papers. Differences in additional methods have a significant effect on WP behavior in HMA. Therefore, the analysis of the content is focused on those differences found in each type of WP studied.

3.7.1. Polyethylene Terephthalate (PET)

PET is a polyester thermoplastic resin, used mainly for beverage bottles. It is a result of the polymerization between ethylene glycol and terephthalic acid, with a chemical composition of $C_{10}H_8O_4$. Its chemical structure can be semi-crystalline, amorphous, or a mixture of both. As mentioned, the melting point of PET (around 250 °C) is higher than most binders' mixing temperatures. Utilizing it through the wet procedure could cause excessive binder oxidation, compromising the mixture. Therefore, most papers consider its use following the dry method (as shown in Figure 8) [57–59]. Table 4 presents the materials and procedures adopted by different authors for the use of PET in asphalt mixtures through the dry approach.

As noted, many different procedures were used, which were differentiated mainly by the order in which the materials were added to the mixture and the temperatures used. To simplify, the procedures can be divided into four types as follows: (a) WP added after blending the pre-heated binder and aggregates (to pre-heated mixture); (b) WP added to pre-heated aggregates before mixing with the binder; (c) WP added to non-pre-heated aggregates before mixing with the binder, and (d) other methods. Non-pre-heated aggregates refer to not pre-heating the aggregates prior to WP addition.

Table 4. Different approaches for the use of PET in asphalt mixtures following the dry method.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Moghaddam et al. [27]	1	<2.36	Flakes	0.1–1% (+0.1%), by weight of aggregates	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 130 °C. Step 2. WP was then added to the mixture.
Moghaddam et al. [28]				0.5% and 1%, by weight of aggregate	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 130 °C. Step 2. WP was then added to the mixture.
Moghaddam et al. [29]				0.2–1% (+0.2%), by weight of aggregate	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 160 °C. Step 2. WP was then added to the mixture.
Moghaddam et al. [33]			Crushed	0.2–1% (+0.2%), by weight of aggregates	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 130 °C. Step 2. WP was then added to the mixture.
Moghaddam et al. [41]				0.5% and 1%, by weight of aggregates	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 160 °C. Step 2. Pre-heated WP was then added to the mixture.
Ferreira et al. [60]	1	>12.5	Micro PET	2% and 4% (by weight of sand) and 8% (by weight and volume of sand)	N.S.
Herraiz et al. [61]			N.S.	0.5–2% (+0.5%) and 4% by weight of aggregate	N.S.
Ziari, et al. [34]			Cut	0.25–1% (+0.5%), by weight of aggregate	Step 1. Pre-heated aggregates at 180 °C were mixed with a pre-heated binder at 150 °C. Step 2. WP was then added to the mixture.
Esfandabad et al. [62]			Granules	30, 50, 70, and 100% (replacing by volume pass. #4 and retained #8 aggregate)	N.S.
Xiao et al. [63]			Powdered	3.22%, 3.28%, and 2.89% by weight of aggregate	Step 1. Sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 270 °C to melt the WP.
Mabui et al. [64]	1	>12.5	N.S.	0.5–2.5% (+0.5%), by total weight of aggregate	N.S.

Table 4. Cont.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Modarres and Hamed [56]	2	<2.36	Crushed	2–10% (+2%), by the weight of binder	The binder and aggregates were mixed before adding the WP.
Taherkhani, and Arshadi [65]				2–10% (+2%), by the weight of binder	Step 1. Pre-heated aggregates at 200 °C were mixed with a pre-heated binder at 150 °C. Step 2. WP was then added to the mixture.
Ahmadinia et al. [43]			N.S.	2–10% (+2%), by the weight of binder	Step 1. Pre-heated aggregates at 200 °C were mixed with a pre-heated binder at 150 °C. Step 2. WP was then added to the mixture.
Ahmadinia et al. [44]					Added to pre-heated aggregates at 200 °C.
Modarres and Hamed, [66]				2–10% (+2%), by the weight of binder	N.S.
El-Naga and Ragab, [67]	3	N.S.	Crushed	10–15% (+1%) by the weight of binder	Step 1. Melted WP at 300 °C. Step 2. Melted WP was added to pre-heated aggregates at 250 °C. Step 3. Then, the pre-heated binder at 140 °C was added to the mixture.
Movilla-Quesada et al. [30]		<2.36	Flakes	6–22% (+4%) by weight of the binder	N.S.
Abdo et al. [26]		>12.5	Fibers	0.5% and 1% by weight of the mixture	WP was added to aggregates before mixing with the binder.

Notes: N.S. = not specified; 1 = aggregate replacement; 2 = partial substitution for bitumen; 3 = additive.

(a) WP added to a pre-heated mixture:

Many authors utilized this procedure, with differences noted in particle sizes, mixing and pre-heating temperatures, and addition methods. Moghaddam et al. [27–29,33,41] opted to use fine PET, which was added after mixing pre-heated aggregates at 160 °C with a pre-heated binder (at 130 °C or 160 °C, depending on the type of binder). Then, everything was mixed at 160° to 165 °C. Moghaddam et al. [31] stated that the main reason behind this procedure was that mixing an aggregate with PET would cause the aggregate surface to be coated by the molten part of PET (PET would melt partially), which could eventually contribute to less adherence between aggregate particles and the asphalt cement. It was observed that a higher PET content decreased the stiffness of the mixture, where the optimum content to enhance this parameter was between 0.1% and 0.2% by weight of the aggregates. Additionally, PET incorporation provided a longer fatigue life but reduced indirect tensile strength and the Marshall quotient, especially for PET in flakes, which also increased permanent deformation.

Similarly, Ziari et al. [34] evaluated the use of PET as an aggregate replacement but used a coarse particle size (>12.5 mm) and a higher pre-heating temperature. The coarse PET did not result in many significant improvements in mixture performance, as it was only able to increase flow number and reduce rut depth by only 1cm in comparison with the control mixture. Ahmadinia et al. [43] and Taherkhani and Arshadi [65] investigated fine WP (<2.36 mm) as a partial substitute for bitumen, utilizing the same pre-heating temperatures but different WP shapes. Ahmadinia et al. [43], who did not specify the PET shape used, stated that the use of 6% WP by weight of the binder was the optimum content as it increased the resilient modulus and Marshall quotient of the mixture. Taherkhani and Arshadi [65] verified that crushed PET decreased rutting resistance and the flow number, which was even more noticeable for coarse particles and higher PET content. The mixing procedure caused the amorphous part of PET to melt while the crystalline part remained intact. Having partially melted and partially solid PET over the aggregates decreased binder–aggregate adhesion, reducing the mixture’s resistance.

Modarres and Hamedei [66] followed a similar procedure as Ahmadinia et al. [43] and Taherkhani and Arshadi [65]. They used the same particle size (fine PET) and a similar mixing temperature and addition method, but they did not specify the pre-heating temperatures used. They verified that only 2% PET by weight of the binder was able to increase the indirect tensile strength and resilient modulus of the mixture. An improvement in the resilient modulus was also observed by Ahmadinia et al. [43]; however, both cases presented different values for the optimum content of WP. The difference in the optimum content can be due to the particle shape and the pre-heating temperature of binders and aggregates.

(b) WP added to pre-heated aggregates before mixing with the binder:

Ahmadinia et al. [44] added PET to pre-heated aggregates at a temperature below its melting point so that the WP would not melt. The optimum content, ranging from 4 to 6% PET by weight of the binder, was able to improve the resilient modulus and rutting resistance of the mixture. However, it was verified that WP addition did not improve moisture damage resistance.

(c) WP added to non-pre-heated aggregates before mixing with the binder:

Abdo et al. [26] followed the procedure of adding WP to non-pre-heated aggregates but used coarse PET. The blend was then heated before mixing with the binder. They stated that larger PET fibers became stiffer during the mixing process, and after compaction, they started to stick out of the samples. Additionally, it was noticed that PET addition increased tensile strength, especially for binder AC 60–70, enhancing both rutting and cracking resistance and increasing the flow number at intermediate and higher temperatures. Also, Abdo et al. [26] were the only ones to evaluate a mixture’s performance using a test recommended by the new Balance Mix Design (BMD). Since there was a concern regarding the mixture’s performance under low temperatures because of higher stiffness, the mixture

was tested using the semi-circular bending (SCB) test, which concluded that PET addition led to sudden failure at low temperatures. However, regarding the addition of WP, the optimum content was 0.5% (or 1% for hot regions) by the weight of the mixture.

Xiao et al. [63] added PET to aggregates in powdered form. For that, the authors sprayed water over the aggregate surface, making it easier for the WP to stick to it. Then, the aggregates treated with PET powder were heated, allowing the PET to melt. Based on surface free energy measurements of polar and non-polar components, the authors concluded that the plastic coating increased the polar components of the aggregate surface, increasing the dry adhesion energy between asphalt and aggregate. As a result, the PET-treated mixtures presented improved moisture damage resistance with a reduced debonding tendency. Even though some positive results were observed, the authors reported that among all types of WPs tested, PET showed the least effective coating, which could be related to the fact that it had not melted completely.

It is important to note that the procedure used by Ahmadinia et al. [44] did not improve moisture damage resistance, while the powdered PET used by Xiao et al. [63] did (even if not completely melted) because of the ability of PET powder to coat the aggregate's surface, thus improving the dry adhesion energy. In the study by Ahmadinia et al. [44], the WP did not coat the aggregate and acted as another particle in the mixture.

(d) Other methods:

El-Naga and Ragab [67] added melted PET (size not specified) to pre-heated aggregates before mixing with a binder. The PET was melted using a special container. This procedure led to a mixture of WP-coated aggregates. The studied mixtures presented higher stiffness than the control (with no PET) and good indirect tensile strength and rutting resistance. The optimum content of WP was suggested to be 12% by weight of the binder.

Other publications also showed improvement in some parameters after incorporating PET; however, it was not possible to associate them with the procedure adopted since the used procedure was not specified. Herraiz et al. [61] did not specify size, shape, or mixing temperature, but they stated that up to 2% PET by weight of aggregates could improve the stiffness of the mixture. Mabui et al. [8] and Modarres and Hamed [66] verified that PET (up to 2% by weight of aggregates) addition increased the indirect tensile strength and resilient modulus of the mixture. Movilla-Quesada et al. [30] and Ferreira et al. [60] verified that the addition of fine PET reduced the resilient modulus and increased the air voids in the mixture. Ferreira et al. [60] also stated that WP reduced indirect tensile strength but improved moisture damage resistance, which was also noticed by Esfandabad et al. [62].

It is possible to see that different procedures and WP characteristics could influence the performance of the mixture. Still, lower percentages of PET (0.1–0.2% by weight of aggregates) seem to be more suitable for enhancing some HMA properties. The optimum content depends on the size and procedure adopted. In most cases, WP addition increased the indirect tensile strength, resilient modulus, rutting resistance, and stiffness of the mixtures. It is important to note that PET in flakes, as used by Moghaddam et al. [27–29] and Movilla-Quesada et al. [30], had a negative effect on the mixture's performance. To improve moisture damage resistance, plastic coating, and melted PET seems like the best option. Adding PET to the pre-heated mixture appeared to result in fewer improvements in the mixture's performance.

3.7.2. High-Density Polyethylene (HDPE)

HDPE is a type of thermoplastic plastometer that can be used in paving applications to reduce permanent deformation and increase the rigidity of the mixture. It is produced from ethylene, which has a chemical formula of $(C_2H_4)_n$ and high crystallinity (around 80–90%) [8]. HDPE can be found in plastic cups, milk and shampoo bottles, and pipes. Because of its low melting point, between 130 °C and 149 °C, it can be used as a binder modifier [13,68]. However, as shown in Figure 8, the number of publications regarding the dry procedure is higher in comparison with the wet method. Table 5 presents the

procedures followed by different authors on the use of HDPE in asphalt mixtures through the dry approach.

Table 5. Different approaches for the use of HDPE in asphalt mixtures, following the dry method.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al. [22]	1	<2.36	Powder	0.4–1.2% (+0.4%) (for 35 μ m) and 0.5–2% (+0.5%) for 75 μ m) by weight of aggregates	WP + ethanol solution (fluidized bed) sprayed over pre-heated aggregates at 180–190 °C, resulting in plastic-coated aggregates.
Xiao et al. [63]		N.S.	Powder	2.34, 2.29, and 2.01% by weight of aggregates	Step 1. WP was sprayed over wet aggregates (0.5% of water). Step 2. The mixture was heated at 180 °C to melt the WP.
Xiao et al. [69]				0.5–2% (+0.5%) by weight of aggregates	A WP + ethanol solution (fluidized bed) was sprayed over pre-heated aggregates at 180–190 °C, resulting in plastic-coated aggregates.
Ullah et al. [9]		N.S.	N.S.	5, 15, and 25% by weight of aggregates	N.S.
Haider et al. [14]	2	N.S.	N.S.	9% by weight of the binder	Added to aggregates before mixing with the binder.

Notes: N.S. = not specified; 1 = aggregate replacement; 2 = partial substitution for bitumen.

For HDPE, two different procedures were used in the reviewed papers as follows: (a) WP added to non-pre-heated aggregates before mixing with the binder; and (b) other methods. Non-pre-heated aggregates refer to not pre-heating the aggregates prior to WP addition.

(a) WP added to non-pre-heated aggregates before mixing with the binder:

Haider et al. [14] added HDPE to non-pre-heated aggregates before mixing with the binder (the aggregate and WP blend were heated prior to mixing). They did not specify the mixing temperature, particle size, or shape, so it was not possible to establish if the WP melted or not during the mixing process. However, they were able to compare the effects of adding the WP through wet and dry methods. It was observed that the aggregates had the worst binder–aggregate adhesion when WP was added using the dry approach. Nevertheless, the incorporation of HDPE through the dry process improved the mixture’s rutting resistance and reduced its stability loss.

As already mentioned, Xiao et al. [63] added powdered WP to wet aggregates before putting them in the oven to melt the WP. The plastic coating increased the polar components of the aggregate surface, increasing the dry adhesion energy between the asphalt and aggregate, improving wettability, moisture damage resistance, and energy ratio, and reducing debonding tendency. In comparison with PET, HDPE showed the best coating, which could be related to its low melting point, making it easier for the WP to melt completely.

(b) Other methods:

Xiao et al. [22,69] sprayed powdered HDPE, using a fluidized bed (ethanol solution), over pre-heated aggregates at 180 °C. The chosen pre-heating temperature was much higher than the WP’s melting point to ensure that the HDPE would melt and coat the aggregates. The incorporation of WP following this procedure was able to improve moisture damage resistance by increasing binder–aggregate adhesion. Also, smaller particle sizes were more efficient in the coating process.

Ullah et al. [9] also evaluated HDPE following the dry methodology; however, they did not describe the mixing process, particle size, or shape. The addition of HDPE in-

creased rutting resistance, and the higher the WP content, the smaller the rut depth. The authors suggested that 15% HDPE by weight of the aggregates seemed to be the optimum WP content to improve HMA's Marshall stability and flow and increase dynamic modulus values.

Regardless of the mixing procedure used, the incorporation of HDPE into HMA seems to have positive impacts on the mixture's performance, especially for moisture damage resistance. One of the potential reasons is that since it is easier to coat aggregates with HDPE because of its low melting point, plastic-coated aggregates would be less sensitive to moisture damage. The percentage utilized depends on the procedure adopted. For powdered HDPE, the percentages ranged from 0.5% to 2.5% by weight of aggregates, while for other cases, the optimum content was around 15% by weight of aggregates (no procedure defined) or 9% by weight of the binder.

3.7.3. Low-Density Polyethylene (LDPE)

Similar to HDPE, LDPE is also a type of thermoplastic plastometer that can be used in paving applications to reduce permanent deformation and increase the rigidity of the mixture. It has the same chemical composition as HDPE but with longer, linear, and flexible ethylene chains, presenting lower crystallinity (around 55–65%) [8]. LDPE can be found in packaging films and plastic bags. LDPE has the lowest melting point out of the most used WPs in asphalt mixtures (between 110 °C and 120 °C), which indicates a huge potential for binder modification. Lower melting points require lower mixing speed, making the process more economical [13,68]. Still, more research has been conducted on the use of LDPE through the dry method, as shown in Figure 8, suggesting a necessity to comprehend the different procedures adopted. Table 6 presents the procedures followed by different authors for the use of LDPE in asphalt mixtures through the dry approach.

Table 6. Different approaches for the use of LDPE in asphalt mixtures, following the dry method.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al. [22]	1	<2.36	Powder	0.4–1.2% (+0.4%) (for 35 µm) and 0.5–2% (+0.5) (for 75 µm) by weight of aggregates	A WP + ethanol solution (fluidized bed) was sprayed over pre-heated aggregates at 180–190 °C.
Xiao et al. [63]		N.S.	Powder	2.17, 2.21, and 1.95% by weight of aggregates	Step 1. WP was sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 160 °C to melt the WP.
Xiao et al. [69]				0.5–2% (+0.5%) by weight of aggregates	A WP + ethanol solution (fluidized bed) was sprayed over pre-heated aggregates at 180–190 °C.
Radeef et al. [10]		4.75–12.5	Shredded	1.0% by weight of aggregates	Step 1. Added to pre-heated coarse aggregates at 180 °C. Step 2. A small amount of binder was mixed with coarse-coated aggregates before adding fine aggregates and the remaining binder.
Ullah et al. [9]		N.S.	N.S.	5–25% (+10%) by weight of aggregates	N.S.
Assefa [70]		2.36–4.75	Shredded	6–18% (+3%) by the weight of OBC	Added to pre-heated aggregates at 165 °C.

Table 6. Cont.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Almeida et al. [16]	2	N.S.	Flakes	2–8% (+2%) by weight of binder	N.S.
Almeida et al. [71]				6.0% by weight of the binder	N.S.
Haider et al. [14]			N.S.	9% by weight of the binder	Added to aggregates before mixing with the binder.

Notes: N.S. = not specified; 1 = aggregate replacement; 2 = partial substitution for bitumen.

For LDPE, four different procedures were used in the reviewed papers including the following: (a) WP added to pre-heated coarse aggregates before mixing with the fine aggregates and binder; (b) WP added to pre-heated aggregates before mixing with the binder; (c) WP added to non-pre-heated aggregates before mixing with the binder; and (d) other methods. Non-pre-heated aggregates refer to not pre-heating the aggregates prior to WP addition.

(a) WP added to pre-heated coarse aggregates before mixing with the fine aggregates and binder:

Radeef et al. [10] developed a procedure called the “Enhanced Dry Method”, which consisted of adding the WP only to pre-heated coarse aggregates before adding a small portion of the optimum binder content to the WP pre-treated coarse aggregates. With this procedure, a thin layer of modified binder was created on the surface of the coarse aggregates, boosting the plastic–asphalt digestion process [72]. After that, the remaining binder and fine aggregates were added to the mixture. The analysis of Marshall properties indicated that the mixture with coarse LDPE showed higher stability but reduced stiffness by 4.70%. All mixtures were conditioned to verify moisture damage resistance and aging effects. The mixtures with plastic-coated aggregates showed less susceptibility to moisture damage. Also, the WP addition increased the resilient modulus of the mixtures, especially after long-term aging. Additionally, LDPE increased the creep stiffness even for unconditioned samples, with values ranging from 340 to 390 MPa in comparison with values from 210 to 310 MPa for the control mixture. Finally, the Wheel Tracking Test was used to evaluate the rutting potential of the mixture. Mixtures with LDPE addition presented reduced rut depths, which increased resistance to permanent deformation. The mixtures after long-term aging showed even higher performance regarding rutting resistance.

(b) WP added to pre-heated aggregates before mixing with the binder:

Assefa [70] added shredded LDPE to pre-heated aggregates at a temperature higher than their melting point, resulting in plastic-coated aggregates. The mixture showed enhanced properties, such as increased Marshall stability, flow, stiffness, and moisture damage resistance.

(c) WP added to non-pre-heated aggregates before mixing with the binder:

Haider et al. [14] added LDPE to non-pre-heated aggregates. The blend was then heated before mixing with the binder. However, no details were provided regarding the mixing temperature, and WP particle size and shape, making it difficult to infer if the WP melted or not during the mixing process. The authors compared the effects of both wet and dry methods. The dry method promoted higher coating loss in comparison with the wet method. However, the incorporation of LDPE through the dry process improved the mixture’s rutting resistance and reduced stability loss. The use of basic aggregates showed less coating loss and higher resistance to moisture damage.

As mentioned, Xiao et al. [63] added powdered WP to wet aggregates before putting the mixture in the oven to melt the WP, which resulted in plastic-coated aggregates. The plastic coating increased the polar components of the aggregate surface, increasing the dry adhesion energy between asphalt and aggregate, improving wettability, moisture damage

resistance, and energy ratio, and reducing debonding tendency. In comparison, LDPE showed great coating efficiency since it melted completely, being only behind HDPE.

(d) Other methods:

Xiao et al. [22,69] sprayed powdered LDPE, using a fluidized bed of water and ethanol, over pre-heated aggregates at 180 °C. The chosen pre-heating temperature was way higher than the WP's melting point to ensure that the LDPE would melt and coat the aggregates. WP addition using this procedure improved moisture damage resistance by increasing binder–aggregate adhesion. Also, smaller particle sizes were more efficient in the coating process.

Ullah et al. [9] also evaluated the use of LDPE WP in HMA via the dry process. However, the paper does not provide information regarding the mixing process, particle size, and shape. The authors reported that the addition of LDPE increased rutting resistance, showing smaller rut depth as the WP content increased. They found that 15% of LDPE by weight of the aggregates was the optimum content to improve HMA Marshall stability and flow and increase stiffness values (resilient modulus and dynamic modulus).

Almeida et al. [16] also added LDPE (in flakes) following the dry approach but did not specify the mixing procedure. The WP reduced moisture damage resistance and workability of the mixture while increasing stiffness. After aging, the mixture showed higher fatigue and rutting resistance, as noticed previously by Radeef et al. [10]. The optimum content was reported as 6% by weight of the binder.

Additionally, Almeida et al. [71] evaluated the effects of LDPE (in flakes) in warm mix asphalts (WMAs) and hot mix asphalts (HMAs) but did not describe the mixing procedure adopted. For WMAs, WP addition increased the Marshall stability, stiffness, rutting, and fatigue resistance of the mixture. It also increased moisture susceptibility and air voids while decreasing flow and indirect tensile strength. For HMAs, LDPE addition increased all the parameters evaluated in their study, such as Marshall stability and flow, indirect tensile strength, stiffness, and fatigue and rutting resistance.

Considering that LDPE is a particle (not melted) and a coating on aggregates (melted), it seems to have positive impacts on the mixture's performance. However, it is important to note that for LDPE as flakes, WP had a negative influence on some parameters, which was also observed for PET as flakes. It is easier to coat aggregates with LDPE because of its low melting point. For coated aggregates, the improvements in moisture damage resistance were noticeable. Also, WP addition was able to improve rutting resistance in most cases. The percentage utilized depends on the procedure adopted. For powdered LDPE, the percentages ranged from 0.5% to 2.2% by weight of aggregates, while for other cases, the optimum content was around 15% by weight of aggregates or 6% by weight of the binder. Mixtures with LDPE after long-term aging showed even greater performance.

3.7.4. Polypropylene (PP)

Polypropylene is a semi-crystalline (around 40–60%) vinyl thermoplastic plastometer derived from propylene with the chemical formula of $(C_3H_6)_n$. It is commonly used for food packaging, microwave-safe containers, and pipes, and with a higher melting point than HDPE and LDPE (around 160°). Studies on the use of PP as a binder modifier reported mixing temperatures up to 190 °C, which could cause premature aging of the binder [68,73]. Therefore, even though Figure 8 reports that 75% of all the reviewed publications utilized PP following the wet approach, the dry method might be used more often. Only one study was found in the literature that attempted to use PP as aggregate replacement in HMA. Table 7 presents the procedures followed in this study.

Table 7. Different approaches for the use of PP in asphalt mixtures, following the dry method.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al. [63]	1	N.S.	Powder	2.11, 2.15, and 1.90% by weight of aggregates	Step 1. WP was sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 190 °C to melt the WP.

Notes: N.S. = not specified; 1 = aggregate replacement.

The study by Xiao et al. [63] followed a procedure in which (a) melted WP was used to coat aggregates before mixing with the binder. The authors sprayed powdered WP over wet aggregates before heating the plastic-coated aggregates in an oven to melt the WP. The plastic coating increased the polar components of the aggregate surface, increasing the dry adhesion energy between asphalt and aggregate, improving wettability, moisture damage resistance, and the energy ratio, and reducing debonding tendency. Considering the types of WP evaluated in their study (i.e., PET, HDPE, LDPE, PP, and PVC), PP showed the third-best result, only behind LDPE and HDPE. This could be related to its higher melting point, making it harder for the WP to melt completely and cover the aggregates. Like other powdered WPs, the percentage indicated was around 2% by weight of aggregates.

3.7.5. Polyvinyl Chloride (PVC)

Polyvinyl chloride is a thermoplastic with long repeating chains of vinyl chloride, with both amorphous and crystalline phases and a chemical formula of $(C_2H_3Cl)_n$ [74]. This WP needs special attention when utilized in paving applications. Since it has a high melting point, which varies from 150 °C to 298 °C, heating the WP at such elevated temperatures could produce harmful chlorine-based dioxide emissions because of the vinyl chloride present in its composition [7]. Therefore, PVC is not indicated for use in HMAs, which could also explain the lack of publications on the topic. Only Xiao et al. [63] evaluated its use, as shown in Table 8.

Table 8. Different approaches for the use of PVC in asphalt mixtures, following the dry method.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al. [63]	1	N.S.	Powder	3.23, 3.30, and 2.91% by weight of aggregates	Step 1. WP was sprayed over wet aggregates (0.5% of water). Step 2. The mixture was heated at 180 °C to melt the WP.

Notes: N.S. = not specified; 1 = aggregate replacement.

Xiao et al. [63] used the same procedure as for the other WPs (PET, HDPE, LDPE, and PP), which consisted of spraying powdered WP over aggregates (non-pre-heated) before heating the coated aggregates to melt the WP. The same performance improvements were observed for PVC including enhanced wettability, moisture damage resistance, energy ratio, and reduced debonding tendency. However, PVC was the least effective coating, similar to PET.

3.7.6. Summary of the Procedures Used to Add WP in the Dry Method

Figure 9 shows a summary of all procedures adopted by the authors who followed the dry methodology. After analyzing each paper individually, it was concluded that the two most used WP addition procedures are *WP to pre-heated mixture* or *WP added to non-pre-heated aggregates*. However, the first procedure was only utilized with PET, probably

because of its high melting point. As mentioned by Moghaddam et al. [29], adding PET to aggregates would cause the aggregate surface to be coated by partially molten PET, which could reduce the adhesion of binder and aggregates. Furthermore, the negative results found in the studies indicate that this procedure was not the most effective in improving the performance of mixtures with PET addition.

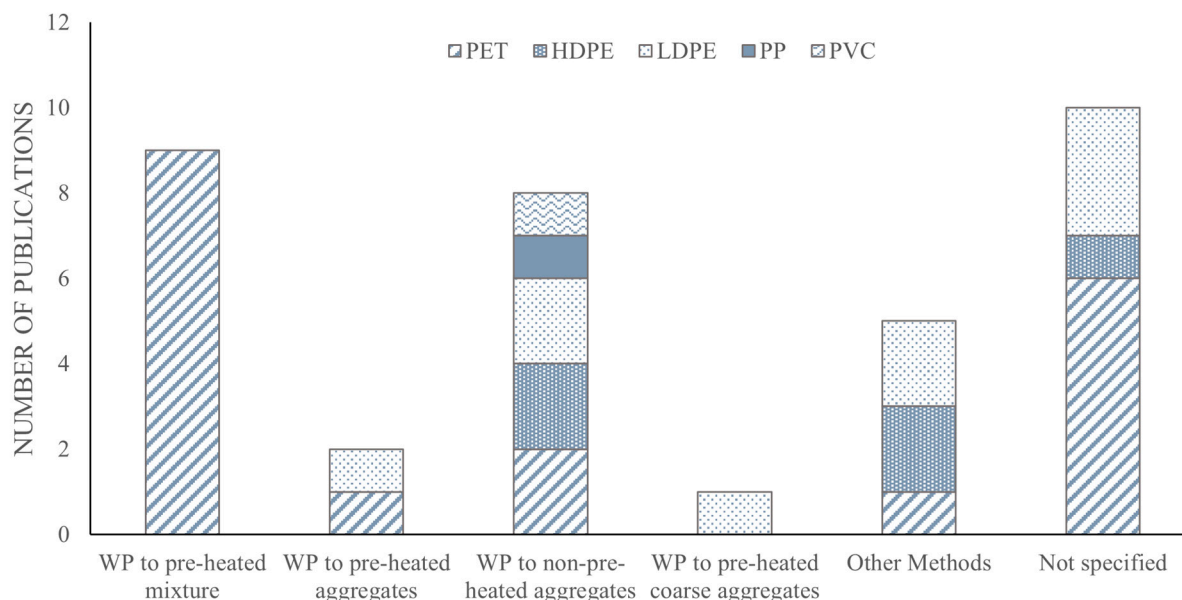


Figure 9. Summary of the addition methods adopted by the authors who followed the dry procedure.

For HDPE and LDPE, the most common procedures were either adding powdered WP, using a fluidized bed, to pre-heated aggregates at a temperature higher than the WP's melting point, allowing the aggregate surface to be coated by plastic (under "other methods"), or adding the WP to non-pre-heated aggregates before placing the blend into the oven to melt the WP and coat the aggregates. For PVC and PP, the only utilized procedure was adding WP to non-pre-heated aggregates and placing the blend into the oven to melt the WP, which also resulted in plastic-coated aggregates.

Therefore, the most adopted procedures targeted the production of plastic-coated aggregates. These procedures included adding WP to pre-heated aggregates, adding WP to pre-heated coarse aggregates, melting WP before adding to the aggregates, and melting WP over aggregates (both aggregates and WP in the oven at a temperature higher than the plastic's melting point). Coating the aggregates with plastic shows improvements in many parameters, especially moisture damage resistance. Those procedures can be more challenging for PET because of its high melting point, but El-Naga and Ragab [67] and Xiao et al. [69] managed to produce PET-coated aggregates with satisfactory results.

Also, evaluating the WP chemical composition and melting point is necessary to establish the best mixing procedure. A higher degree of orientation in the polymer chemical structure causes higher glass transition temperatures (going from brittle to viscous behavior), higher service temperatures (the maximum temperature at which the WP can be exposed for a long period with no significative consequences), and, consequently, higher melting points [59]. As previously mentioned, melting points higher than the binder's mixing temperature are not recommended for the wet procedure, which is the case of PP and PET. For mixed plastic, the performance of the mixture can be compromised by the difference between melting points, which can result in some plastics not melting, while others reach their decomposition temperature [8].

It is important to mention that the chemical composition can influence the WP crystallinity levels, which can affect the interaction between the WP and the binder. Although HDPE has a low melting point (below the binder's mixing temperature), it shows high

crystallinity (over 80%), compromising its ability to be immersed into the binder, which makes it appropriate for use through the dry process [8].

4. Final Conclusions

This study presents a literature review followed by a bibliometric analysis, utilizing the Web of Science database, of 119 publications regarding the use of waste plastic in paving applications. The evolution of the theme over the years demonstrates that this is still a very new topic, with 60.5% of all the reviewed papers being published in the last three years. This growing tendency can be attributed to the increase in plastic generation during the COVID-19 pandemic in 2020. A growing trend in publications on WPs for paving applications was observed, especially after 2018, which can be attributed to the search for new practices to manage wastes globally and also to the increasing amount of WPs generated during the COVID-19 pandemic. The countries and author affiliations that contributed to the publications were China, the United States, and India. China and India have the largest numbers of mismanaged waste plastic in the world, which could indicate a need to evaluate alternative ways of waste management.

The bibliometric analysis was important in the investigation of the relevance of this topic across the globe, which correlated this theme with the necessity of WP management alternatives. Additionally, the analysis addressed many knowledge gaps regarding WP addition. Since there is no normative guidance for the use of the dry methodology, it was necessary to gather information to better comprehend how each procedure was adopted and how the WP characteristics affect the final performance of the mixture. The key conclusions from this in-depth analysis were as follows:

- **Particle Size:** Smaller particle sizes (<2.36 mm) seemed to enhance the mixtures' properties at a higher rate than larger particles. This could be related to their potential better distribution in HMA, presenting better mixture homogeneity. Smaller particles also appeared to be more effective in the aggregate-coating process, which represented the best alternative to enhance the mixture's performance, especially regarding moisture damage resistance.
- **Particle Shape:** WP in flakes showed the worst performance, contributing to lower stiffness, indirect tensile strength, and moisture damage resistance. However, it was not possible to determine the best WP shape since many papers did not report that information or presented the WP processing instead (shredding, cutting, gridding, or crushing).
- **Type of WP:** Even though PET was used in the majority of the publications gathered in this study, the use of PE (LDPE or HDPE) stands out in terms of enhanced HMA performance.

The addition of PET in HMA enhanced some properties, but many other performance parameters were reduced. Additionally, the pre-heating temperature needs to be selected very carefully. High pre-heating temperatures, but still lower than the PET's melting point, can cause WP to melt partially. In this case, partially molten and partially solid PET can decrease the mixture's performance because of its effects on binder–aggregate adhesion. It is worth noting that PET was the least effective coating alongside PVC, mainly related to its high melting point.

The use of PE (HDPE or LDPE) was able to improve a mixture's performance independently of the procedure used. However, coating aggregates with melted PE was an adequate procedure to enhance moisture damage resistance. Because of its low melting point, PE types of WPs provided a more effective coating in comparison with PET and PVC. The optimum contents of PE ranged from 0.5% to 2.5% by weight of aggregates for plastic-coated aggregates or 6–9% by weight of the binder.

The use of powdered PP effectively enhanced HMA performance. The findings suggested that opting for powdered PP could be viable among WP types. The optimal content ranged between 1.90% and 2.15% by aggregate weight. However, the limited number of studies constrains precise recommendations for the preferred shape and size.

PVC represented the least effective WP for incorporation in HMA in comparison with HDPE, LDPE, and PP. This could be related to its higher melting point, making it harder to melt and cover the aggregates. Also, this WP is not indicated for HMAs because of toxic emissions when it is heated up to high temperatures.

- Procedure: Employing a method resulting in plastic-coated aggregates appeared to be the most beneficial for improving asphalt mixture performance. Various approaches were observed including adding WP to pre-heated aggregates, pre-heated coarse aggregates, melting WP before aggregate inclusion, and combining aggregates and WP in an oven for melting. This method consistently proved to be highly effective across all types of WP, enhancing stiffness and rutting resistance and reducing moisture susceptibility by improving binder–aggregate adhesion.

Overall, the utilization of WPs displays the potential to enhance asphalt mixture performance, potentially contributing to sustainable infrastructure solutions and providing an alternative strategy for plastic waste management. However, it is crucial to note that while the reviewed studies aimed to evaluate critical pavement distress such as moisture damage, rutting, and cracking, 92% of the papers gathered herein did not adhere to procedures recommended by the Balanced Mix Design (BMD) protocols for assessing mixture performance. Those papers mainly focused on checking volumetric parameters instead of performance criteria. Further research is necessary to validate and extrapolate these findings and to better correlate mixing procedures and addition methods to the performance of the asphalt mixture, which can lead to a possibly standardized methodology for the dry process.

Furthermore, plastics with higher melting points are recommended for the dry methodology (PET and PP), while plastics with low melting points, such as LDPE, are recommended for both wet and dry methodologies. It is important to mention that WPs with high crystallinity, such as HDPE, are more difficult to add through the wet procedure because of incompatibility between the binder and WP, even though they present a low melting point.

Recommendations for Future Works

The key knowledge gaps identified were the lack of a standard procedure applicable across studies, a feasibility assessment for scaling laboratory-based procedures to field applications, and laboratory evaluations considering performance-based parameters suggested in current BMD approaches. Additionally, there is a lack of studies addressing how the physical–chemical–thermodynamical characteristics of WPs, such as the melting point, crystallinity, and surface free energy, can affect plastic coatings, the interactions among all components of the mixture, and the final performance of the HMA. Finally, aggregate mineralogy can also play an important role in establishing the most suitable materials for recycled mixtures with WP, which still requires further studies.

Several researchers, including the authors of this study, are actively working to address some of these topics. Finally, the feasibility of implementing the mixing procedures in asphalt plants, alongside establishing the proper pre-heating temperatures and correct time for WP addition needs to be studied. Because of the lack of standard procedures, future works should augment and broaden the scope of this bibliometric analysis, thus contributing to the ongoing advancement in this field.

Finally, it is important to address the possible limitations of bibliometric analysis. Regarding the database, other sources could provide additional or even different journal articles on the topic, resulting in different trends than the ones obtained from the WoS database. Although the keywords were chosen to represent the research topic best, they could be a limiting factor if they identified a low number of documents published on the use of WP in asphalt mixtures. Future recommendations include broadening this research by including different databases, such as Scopus, including different keywords, and changing the requirements from “must include” to “should include” to avoid excluding relevant papers.

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References

- Lebreton, L.; Andrady, A. Future Scenarios of Global Plastic Waste Generation and Disposal. *Palgrave Commun.* **2019**, *5*, 6. [CrossRef]
- Ritchie, H.; Samborska, V.; Roser, M. Plastic Pollution. Our World in Data. Available online: <https://ourworldindata.org/plastic-pollution> (accessed on 7 November 2023).
- Meijer, L.J.; Van Emmerik, T.; Van Der Ent, R.; Schmidt, C.; Lebreton, L. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.* **2021**, *7*, eaaz5803. [CrossRef] [PubMed]
- Environmental Protection Agency EPA. Facts and Figures about Materials, Waste and Recycling, Plastics: Material-specific Data. 2023. Available online: <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data> (accessed on 22 June 2023).
- Peng, Y.; Wu, P.; Scharup, A.T.; Zhang, Y. Plastic waste release caused by COVID-19 and its fate in the global ocean. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2111530118. [CrossRef] [PubMed]
- Sharma, H.B.; Vanapalli, K.R.; Cheela, V.S.; Ranjan, V.P.; Jaglan, A.K.; Dubey, B.; Goel, S.; Bhattacharya, J. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. *Resour. Conserv. Recycl.* **2020**, *162*, 105052. [CrossRef] [PubMed]
- NCAT; WRI; GHK; Dow. *Performance Properties of Laboratory Produced Recycled Plastic Modified (RPM) Asphalt Binders and Mixtures*; NCHRP Project 9-66 Interim Report; National Center of Asphalt Technology: Auburn, AL, USA, 2021.
- Xu, F.; Zhao, Y.; Li, K. Using Waste Plastics as Asphalt Modifier: A Review. *Materials* **2022**, *15*, 110. [CrossRef] [PubMed]
- Ullah, S.; Raheel, M.; Khan, R.; Khan, M.T. Characterization of physical & mechanical properties of asphalt concrete containing low- & high-density polyethylene waste as aggregates. *Constr. Build. Mater.* **2021**, *301*, 124127. [CrossRef]
- Radeef, H.R.; Hassan, N.A.; Katman, H.Y.; Mahmud, M.Z.H.; Abidin, A.R.Z.; Ismail, C.R. The mechanical response of dry-process polymer wastes modified asphalt under ageing and moisture damage. *Case Stud. Constr. Mater.* **2022**, *16*, e00913. [CrossRef]
- Li, H.; Hao, G.; Zhou, L.; Wang, S.; Zhao, G.; Zhang, Y.; Temitope, A.A. Effect of different waste plastic modifiers on conventional asphalt performance: Optimal preparation parameters determination and mechanism analysis. *Environ. Sci. Pollut. Res.* **2023**, *30*, 89910–89926. [CrossRef]
- Ashish, P.K.; Sreeram, A.; Xu, X.; Chandrasekar, P.; Jagadeesh, A.; Adwani, D.; Padhan, R.K. Closing the Loop: Harnessing waste plastics for sustainable asphalt mixtures—A comprehensive review. *Constr. Build. Mater.* **2023**, *400*, 132858. [CrossRef]
- Duarte, G.M.; Faxina, A.L. Asphalt concrete mixtures modified with polymeric waste by the wet and dry processes: A literature review. *Constr. Build. Mater.* **2021**, *312*, 125408. [CrossRef]
- Haider, S.; Hafeez, I.; Jamal, Ullah, R. Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures. *Constr. Build. Mater.* **2020**, *235*, 117496. [CrossRef]
- Mashaan, N.S.; Chegenizadeh, A.; Nikraz, H.; Rezagholilou, A. Investigating the engineering properties of asphalt binder modified with waste plastic polymer. *Ain Shams Eng. J.* **2021**, *12*, 1569–1574. [CrossRef]
- Almeida, A.; Capitão, S.; Bandeira, R.; Fonseca, M.; Picado-Santos, L. Performance of AC mixtures containing flakes of LDPE plastic film collected from urban waste considering ageing. *Constr. Build. Mater.* **2020**, *232*, 117253. [CrossRef]
- Yin, F.; Turner, P.; Moraes, R. *Storage Stability Testing of Asphalt Binders Containing Recycled Polyethylene Materials (Phase II-B Study)*; NCAT Report; National Center of Asphalt Technology: Auburn, AL, USA, 2019.
- Lu, D.X.; Giustozzi, F. Recycled Plastics As Synthetic Coarse and Fine Asphalt Aggregate. *Int. J. Pavement Eng.* **2022**, *24*, 2068550. [CrossRef]
- Enfrin, M.; Myszk, R.; Giustozzi, F. Paving Roads with Recycled Plastics: Microplastic Pollution or Eco-Friendly Solution? *J. Hazard. Mater.* **2022**, *437*, 129334. [CrossRef] [PubMed]
- Sam, S.T.; Nuradibah, M.A.; Ismail, H.; Noriman, N.Z.; Ragunathan, S. Recent advances in polyolefins/natural polymer blends used for packaging application. *Polym. Technol. Eng.* **2014**, *53*, 631–644. [CrossRef]
- Veropalumbo, R.; Oretto, C.; Viscione, N.; Biancardo, S.A.; Russo, F. Environmental assessment of asphalt mastics containing plastic bottles and jet grouting waste. *Environ. Impact Assess. Rev.* **2022**, *93*, 106736. [CrossRef]

22. Xiao, R.; Polaczyk, P.; Huang, B. Mitigating Stripping in Asphalt Mixtures: Pretreatment of Aggregate by Thermoplastic Polyethylene Powder Coating. *Transp. Res. Rec. J. Transp. Res. Board* **2023**, *2678*, 776–787. [\[CrossRef\]](#)
23. Kakar, M.R.; Mikhailenko, P.; Piao, Z.; Bueno, M.; Poulikakos, L. Analysis of waste polyethylene (PE) and its by-products in asphalt binder. *Constr. Build. Mater.* **2021**, *280*, 122492. [\[CrossRef\]](#)
24. Ma, J.; Hesp, S.A.M. Effect of recycled polyethylene terephthalate (PET) fiber on the fracture resistance of asphalt mixtures. *Constr. Build. Mater.* **2022**, *342*, 127944. [\[CrossRef\]](#)
25. Suresha, S.N.; Varghese, G.; Shankar, A.U.R. Properties of cellulose fibres and waste plastic modified porous friction course mixes. *Balt. J. Road Bridg. Eng.* **2010**, *5*, 156–163. [\[CrossRef\]](#)
26. Abu Abdo, A.M.; Jung, S.J. Investigation of reinforcing flexible pavements with waste plastic fibers in Ras Al Khaimah, UAE. *Road Mater. Pavement Des.* **2020**, *21*, 1753–1762. [\[CrossRef\]](#)
27. Moghaddam, T.B.; Soltani, M.; Karim, M.R. Experimental characterization of rutting performance of polyethylene terephthalate modified asphalt mixtures under static and dynamic loads. *Constr. Build. Mater.* **2014**, *65*, 487–494. [\[CrossRef\]](#)
28. Moghaddam, T.B.; Soltani, M.; Karim, M.R. Stiffness modulus of Polyethylene Terephthalate modified asphalt mixture: A statistical analysis of the laboratory testing results. *Mater. Des.* **2015**, *68*, 88–96. [\[CrossRef\]](#)
29. Moghaddam, T.B.; Soltani, M.; Shahraki, H.S.; Shamshirband, S.; Noor, N.B.M.; Karim, M.R. The use of SVM-FFA in estimating fatigue life of polyethylene terephthalate modified asphalt mixtures. *Measurement* **2016**, *90*, 526–533. [\[CrossRef\]](#)
30. Movilla-Quesada, D.; Raposeiras, A.C.; Olavarria, J. Effects of recycled polyethylene terephthalate (PET) on stiffness of hot asphalt mixtures. *Adv. Civ. Eng.* **2019**, *2019*, 6969826. [\[CrossRef\]](#)
31. Aldagari, S.; Kabir, S.F.; Fini, E.H. Investigating aging properties of bitumen modified with polyethylene-terephthalate waste plastic. *Resour. Conserv. Recycl.* **2021**, *173*, 105687. [\[CrossRef\]](#)
32. Aldagari, S.; Kabir, S.F.; Lamanna, A.; Fini, E.H. Functionalized waste plastic granules to enhance sustainability of bituminous composites. *Resour. Conserv. Recycl.* **2022**, *183*, 106353. [\[CrossRef\]](#)
33. Moghaddam, T.B.; Karim, M.R.; Syammaun, T. Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. *Constr. Build. Mater.* **2012**, *34*, 236–242. [\[CrossRef\]](#)
34. Ziari, H.; Kaliji, A.G.; Babagoli, R. Laboratory evaluation of the effect of waste plastic bottle (PET) on rutting performance of hot mix asphalt mixtures. *Pet. Sci. Technol.* **2016**, *34*, 819–823. [\[CrossRef\]](#)
35. Mashaan, N.S.; Chegenizadeh, A.; Nikraz, H. Evaluation of the performance of two australian waste-plastic-modified hot mix asphalts. *Recycling* **2022**, *7*, 16. [\[CrossRef\]](#)
36. Movilla-Quesada, D.; Raposeiras, A.; Silva-Klein, L.; Lastra-González, P.; Castro-Fresno, D. Use of Plastic Scrap in Asphalt Mixtures Added by Dry Method As a Partial Substitute for Bitumen. *Waste Manag.* **2019**, *87*, 751–760. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Clarivate. What is Web of Science Core Collection? Web of Science Platform: Web of Science Core Collection. Available online: <https://clarivate.com/webofsciencelibrary/support/wos/wos-core-collection/> (accessed on 8 November 2023).
38. Armenise, S.; SyieLuing, W.; Ramírez-Velásquez, J.M.; Launay, F.; Wuebben, D.; Ngadi, N.; Rams, J.; Muñoz, M. Plastic waste recycling via pyrolysis: A bibliometric survey and literature review. *J. Anal. Appl. Pyrolysis* **2021**, *158*, 105265. [\[CrossRef\]](#)
39. Pinheiro, C.; Landi, S., Jr.; Lima, O., Jr.; Ribas, L.; Hammes, N.; Segundo, I.R.; Homem, N.C.; Castelo Branco, V.; Freitas, E.; Costa, M.F.; et al. Advancements in phase change materials in asphalt pavements for mitigation of urban heat island effect: Bibliometric analysis and systematic review. *Sensors* **2023**, *23*, 7741. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Wu, H.; Zuo, J.; Zillante, G.; Wang, J.; Yuan, H. Construction and demolition waste research: A bibliometric analysis. *Arch. Sci. Rev.* **2019**, *62*, 354–365. [\[CrossRef\]](#)
41. Moghaddam, T.B.; Soltani, M.; Karim, M.R.; Baaj, H. Optimization of asphalt and modifier contents for polyethylene terephthalate modified asphalt mixtures using response surface methodology. *Measurement* **2015**, *74*, 159–169. [\[CrossRef\]](#)
42. Moghaddam, T.B.; Karim, M.R.; Soltani, M. Utilization of waste plastic bottles in asphalt mixture. *J. Eng. Sci. Technol.* **2013**, *8*, 264–271.
43. Ahmadiania, E.; Zargar, M.; Karim, M.R.; Abdelaziz, M.; Shafigh, P. Using waste plastic bottles as additive for stone mastic asphalt. *Mater. Des.* **2011**, *32*, 4844–4849. [\[CrossRef\]](#)
44. Ahmadiania, E.; Zargar, M.; Karim, M.R.; Abdelaziz, M.; Ahmadiania, E. Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt. *Constr. Build. Mater.* **2012**, *36*, 984–989. [\[CrossRef\]](#)
45. Kabir, S.F.; Sukumaran, S.; Moghtadernejad, S.; Barjasteh, E.; Fini, E.H. End of life plastics to enhance sustainability of pavement construction utilizing a hybrid treatment of bio-oil and carbon coating. *Constr. Build. Mater.* **2021**, *278*, 122444. [\[CrossRef\]](#)
46. Aldagari, S.; Kabir, S.F.; Fini, E.H. A comparative study on efficacy of waste plastic and waste Rubber in bitumen. *Constr. Build. Mater.* **2022**, *325*, 126724. [\[CrossRef\]](#)
47. Kazemi, M.; Kabir, S.F.; Fini, E.H. State of the art in recycling waste thermoplastics and thermosets and their applications in construction. *Resour. Conserv. Recycl.* **2021**, *174*, 105776. [\[CrossRef\]](#)
48. Hung, A.M.; Li, M.; Wu, G.; Fini, E.H. Effects of Liquefied Waste Plastics on Chemical and Rheological Properties of Bitumen. *J. Transp. Eng. Part B Pavements* **2023**, *149*, 04023003. [\[CrossRef\]](#)
49. Leng, Z.; Padhan, R.K.; Sreeram, A. Production of a sustainable paving material through chemical recycling of waste PET into crumb rubber modified asphalt. *J. Clean. Prod.* **2018**, *180*, 682–688. [\[CrossRef\]](#)
50. Leng, Z.; Sreeram, A.; Padhan, R.K.; Tan, Z. Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP). *J. Clean. Prod.* **2018**, *196*, 615–625. [\[CrossRef\]](#)

51. Padhan, R.K.; Sreeram, A.; Gupta, A. Evaluation of trans-polyoctenamer and cross-linking agents on the performance of waste polystyrene modified asphalt. *Road Mater. Pavement Des.* **2020**, *21*, 1170–1182. [CrossRef]
52. Xu, X.; Leng, Z.; Lan, J.; Wang, W.; Yu, J.; Bai, Y.; Sreeram, A.; Hu, J. Sustainable practice in pavement engineering through value-added collective recycling of waste plastic and waste tyre rubber. *Engineering* **2021**, *7*, 857–867. [CrossRef]
53. Tsai, S.J. What's a Good Impact Factor? (Ranking in 27 Categories). SCI. 2022. Available online: <https://www.scijournal.org/articles/good-impact-factor> (accessed on 11 November 2023).
54. Wen, Z.; Xie, Y.; Chen, M.; Dinga, C.D. China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. *Nat. Commun.* **2021**, *12*, 425. [CrossRef] [PubMed]
55. García-Morales, M.; Partal, P.; Navarro, F.; Gallegos, C. Effect of waste polymer addition on the rheology of modified bitumen. *Fuel* **2006**, *85*, 936–943. [CrossRef]
56. Modarres, A.; Hamed, H. Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. *Mater. Des.* **2014**, *61*, 8–15. [CrossRef]
57. Chin, C.; Damen, P.M.M. *Viability of Using Recycled Plastics in Asphalt and Sprayed Sealing Applications*; Austroads (No. AP-T351-19); ARRB Group Limited: Melbourne, Australia, 2019.
58. Aghayan, I.; Khafajeh, R. Recycling of PET in Asphalt Concrete. In *Use of Recycled Plastics in Eco-Efficient Concrete*; Woodhead Publishing: Sawston, CA, USA, 2019; pp. 269–285.
59. Nistico, R. Polyethylene terephthalate (PET) in the packaging industry. *Polym. Test.* **2020**, *90*, 106707. [CrossRef]
60. Ferreira, J.W.d.S.; Marroquin, J.F.R.; Felix, J.F.; Farias, M.M.; Casagrande, M.D.T. The feasibility of recycled micro polyethylene terephthalate (PET) replacing natural sand in hot-mix asphalt. *Constr. Build. Mater.* **2022**, *330*, 127276. [CrossRef]
61. Herráiz, T.R.; Domingo, L.M.; Martínez, J.H.A.; Prieto, J.M.B.; Herráiz, J.I.R. New Environmental bituminous mixture for slab track design in tram networks. *Adv. Struct. Eng.* **2015**, *18*, 2117–2127. [CrossRef]
62. Esfandabad, A.S.; Motevalizadeh, S.M.; Sedghi, R.; Ayar, P.; Asgharzadeh, S.M. Fracture and mechanical properties of asphalt mixtures containing granular polyethylene terephthalate (PET). *Constr. Build. Mater.* **2020**, *259*, 120410. [CrossRef]
63. Xiao, R.; Shen, Z.; Polaczyk, P.; Huang, B. Thermodynamic Properties of Aggregate Coated by Different Types of Waste Plastic: Adhesion and Moisture Resistance of Asphalt-Aggregate Systems. *J. Mater. Civ. Eng.* **2023**, *35*, 04023261. [CrossRef]
64. Mabui, D.S.; Tjaronge, M.W.; Adisasmita, S.A.; Pasra, M. Performance of porous asphalt containing modified buton asphalt and plastic waste. *Int. J. Geomate* **2020**, *18*, 118–123. [CrossRef]
65. Taherkhani, H.; Arshadi, M.R. Investigating the creep properties of PET-modified asphalt concrete. *Civ. Eng.-Frastructures J.* **2018**, *51*, 277–292.
66. Modarres, A.; Hamed, H. Developing laboratory fatigue and resilient modulus models for modified asphalt mixes with waste plastic bottles (PET). *Constr. Build. Mater.* **2014**, *68*, 259–267. [CrossRef]
67. El-Naga, I.A.; Ragab, M. Benefits of utilization the recycle polyethylene terephthalate waste plastic materials as a modifier to asphalt mixtures. *Constr. Build. Mater.* **2019**, *219*, 81–90. [CrossRef]
68. Brasileiro, L.; Moreno-Navarro, F.M.M.; Tauste-Martínez, R.; De Matos, J.M.; Rubio-Gamez, M.C. Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A review. *Sustainability* **2019**, *11*, 646. [CrossRef]
69. Xiao, R.; Zhang, M.; Zhong, J.; Baumgardner, G.L.; Huang, B. Waste Plastic Powder Coating on Acidic Aggregates: A New Hydrophobic Coating Technology to Build Moisture-Resistant Asphalt Mixtures. *Transp. Res. Rec. J. Transp. Res. Board* **2023**, 03611981231193413. [CrossRef]
70. Assefa, N. Evaluation of the effect of recycled waste plastic bags on mechanical properties of hot mix asphalt mixtures for road construction. *Sustain. Environ.* **2021**, *7*, 1957649. [CrossRef]
71. Almeida, A.; Capitão, S.; Estanqueiro, C.; Picado-Santosc, L. Possibility of incorporating waste plastic film flakes into warm-mix asphalt as a bitumen extender. *Constr. Build. Mater.* **2021**, *291*, 123384. [CrossRef]
72. Radeef, H.R.; Hassan, N.A.; Abidin, A.R.Z.; Mahmud, M.Z.H.; Yusoffa, N.I.M.; Satar, M.K.I.M.; Warid, M.N.M. Enhanced dry process method for modified asphalt containing plastic waste. *Front. Mater.* **2021**, *8*, 700231. [CrossRef]
73. Maddah, H.A. Polypropylene as a promising plastic: A review. *Am. J. Polym. Sci.* **2016**, *6*, 1–11.
74. Materials Properties. Polyvinyl Chloride (PVC). Materials Properties. Available online: <https://material-properties.org/polyvinyl-chloride-pvc> (accessed on 20 May 2024).

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