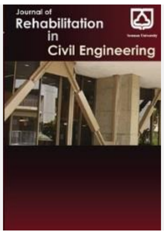

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Incorporating Waste Material in Stone Mastic Asphalt (SMA) Mixtures: A Systematic Literature Review

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ABSTRACT

Waste is one of the largest sources of environmental pollution. This situation is also made worse by waste processing which is only disposed away and piled up in open spaces. Therefore, waste handling and processing are crucial to carry out. One way to achieve those is to use waste material into the stone mastic asphalt (SMA) mixture. Based on this, this paper aims to summarize and review the use of waste materials in SMA mixtures. A systematic literature review technique was used in the research with a database obtained from three reputable sources which explained the effect of adding waste material to the SMA mixture. This paper summarizes the preparation method, mixing method, properties, and environmental perspective analysis regarding the addition of waste material to the SMA mixture. There are also recommendations for further research to explore more deeply the environmental and economic impacts of using different types and volumes of waste in the SMA mixture.

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1. Introduction

Waste can be defined as the products generated by many different human activities, including solid, liquid and gaseous waste [1]. According to World Bank data for 2023, global waste production reached 2.01 billion tons per year [2]. It can be estimated that each individual produces 0.11 to 4.54 kg of waste per day [2]. Waste production by humans is dominated by municipal domestic waste, such as food waste, plastic, textile, and paper [1]. Nevertheless, with a huge amount of waste production, waste treatment in various countries is inadequate. Waste treatment is usually only dumped and stockpiled in open spaces, and some even burn it without any more beneficial treatment. This phenomenon can be seen from 33% of waste is only processed using the open dumping method and 25.5% using landfill (unspecified) which are highly harmful for the environment [2]. Based on this, handling and processing waste is a must to minimize the negative impacts caused.

One approach for achieving this goal is to convert waste into materials in asphalt mixtures. The utilization of recycled/secondary materials. instead of new materials (primary), is expected to help resolve waste problems and decrease the demand for natural resource exploration and exploitation. The use of waste materials is also influenced by the fact that road construction and maintenance work requires large volumes of materials [3–6]. Various types of waste such as polymers [7,8], ashes [9], waste engine oil [10,11] and waste rubber [12] have been explored as additives or substitutes in asphalt mixture, resulting in comparable or even better mix performance values when compared to conventional mixtures.

Furthermore, waste materials can be incorporated into various asphalt mix designs, including stone mastic asphalt (SMA) mixture. SMA is an asphalt mixture that contains high amount of aggregate (approximately 70%) and asphalt (6.0 – 7.0%) in addition to 0.3% cellulose fiber (loosed or pelleted) to prevent drain-down in the mixture [13]. SMA, like other asphalt mixture, is divided into 3 parts: 1) skeleton of coarse aggregate; 2) bituminous mastic; and 3) air voids [14]. This type of mixture was first developed in Germany in 1960 to reduce pavement damage caused by vehicle tires during the snow season [14]. Currently, SMA is widely used in various countries because of it has rutting, crack, and shear resistance capabilities [15]. However, the usage of this type of combination is still less competitive with asphalt concrete (AC) or hot-rolled asphalt (HRA) due to technological issues that contractors have not learned well, and other reasons, although its potential for development and widespread use.

Several studies have been investigated about the SMA mixture performance with incorporating waste materials. Tatarani et al. [16] reported that adding of cigarette butt fiber to SMA increased the indirect tensile strength (ITS) value more than 0.90 MPa. The addition of another waste type, plastic waste in warm SMA mixture, was found to increase the optimum crack resistance by 85% when adding 0.8% plastic waste [17]. The study also showed that the use of plastic waste can reduce production costs and is more environmentally friendly [17]. Polyvinyl chloride (PVC) waste from candy wrappers and pipes added to the SMA mixture, also resulted in an increase in ITS and moisture resistance values [18]. Naser et al. [19] used waste paper and cement kiln dust (CDK) as additives in SMA mixture that can increase Marshall stability and ITS values by 33% and 37% respectively.

Based on the previous explanation, the addition of waste materials in SMA mixes has the potential to improve their performance characteristics prior to their implementation on a larger scale. However, new researchers may find it difficult to identify subjects related to the development of waste materials in SMA mixture. As a result, the objective of the present study is to collect and summarize research data on the potential of adding waste materials to SMA mixture by using systematic literature review technique.

The structure of this article starts with the review method, including data collection, data reduction, data analysis and conclusion. In the next sections, it will be discussion of preparation methods, mixing methods, SMA mixture properties, and environmental perspective analysis regarding the addition of waste into SMA mixture.

2. Method

This article discusses the summary and review results of adding waste to the SMA mixture. Therefore, a systematic literature review technique was used in writing this paper. Figure 1 shows the writing flow used in this paper, starting from data collection, data reduction, data analysis, to drawing conclusions.

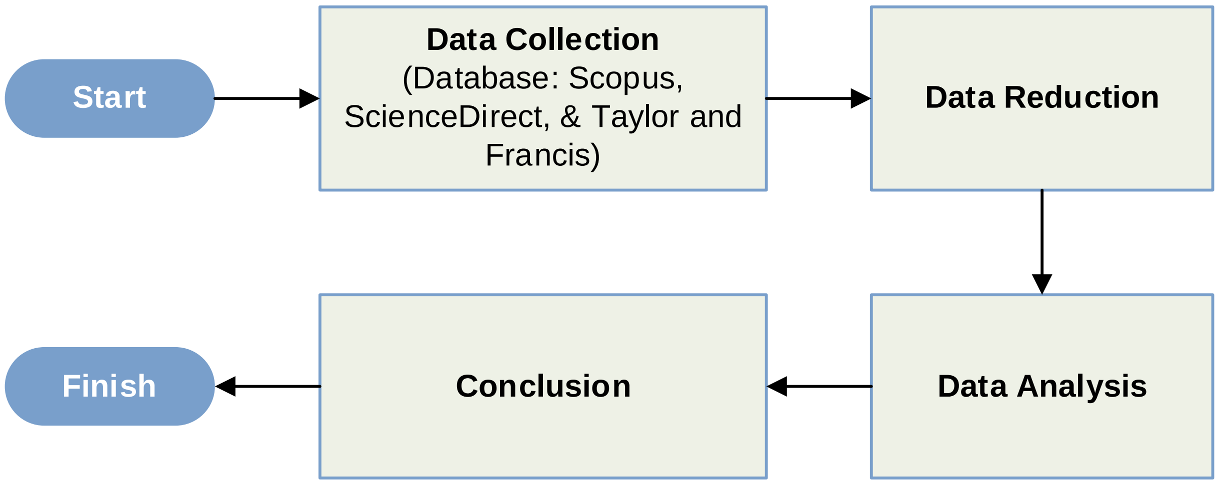

Fig. 1. Paper Writing Flowchart.

The first step is collecting the data from original articles obtained from various databases, such as Scopus.com and ScienceDirect.com using the keywords 'Stone Mastic Asphalt', 'waste material', 'life cycle cost analysis'.

The next step is data reduction by considering the eligibility criteria of the articles obtained using inclusion and exclusion criteria. The inclusion criteria used in this process include: the published scientific literatures were in journals and seminar proceedings indexed by Scopus; were published in the last 10 years (2013 – 2023); only original articles in English; and must be accessible in full text or open access. Meanwhile, the exclusion criteria are a denotation of the inclusion criteria.

Following the completion of the stage, a second selection was taken based on the quality of the research articles that have been collected using the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) method which included abstract reading, abstract and main body skim reading, and main body skim reading [20]. Screening was carried out according to a number of parameters, resulting in 29 articles that may be used as analysis material, as shown by Table 1.

Table 1. Article Identification.

Article ID	Author	Year	Waste Type						Volume	Mixing Method	Adding to	Ref
			Waste Polymer	Ash	Fiber	Recycled Aggregate	Waste Rubber	Waste Oil				
A1	Mashaan et al.	2013	-	-	-	-	✓	-	0, 6, 12, 12, 20% by weight of aggregate	Wet	Bitumen	[21]
A2	Mashaan and Karim	2013	-	-	-	-	✓	-	0, 6, 12, 16, 20% by weight of aggregate	Dry	Aggregate	[22]
A3	Pourtahmasb and Karim	2014	-	-	-	✓	-	-	0,20, 40, 60, 80% by weight of mixture	Dry	Aggregate	[23]
A4	Yadykina et al.	2015	-	-	✓	-	-	-	0.3% by weight of aggregate	Dry	Stabilizing additive	[24]
A5	Sojobi, Nwobodo and Aladegboye	2016	✓	-	-	-	-	-	0, 5, 10, and 20% by weight of bitumen	Wet	Bitumen	[25]
A6	Fernandes, Silva and Oliveira	2018	✓	-	-	✓	✓	✓	6% HDPE 5% SBS 20% CR *by weight of bitumen	Wet	Bitumen	[26]
A7	S. R. M. Fernandes, Silva and Oliveira	2019	✓	-	-	✓	✓	✓	10% EO and 6% HDPE 10% EO and 5% SBS 7.5% EO and 20% CR 15% RB and 6% HDPE 5% RB and 5% SBS 15% RB and 20% CR *by weight of bitumen	Wet	Bitumen	[27]
A8	Morcillo et al.	2019	✓	-	-	-	✓	-	0.5 – 1% greenhouse plastic 0.5 – 1% recycled wires plastic ELT (0.2-0.5%) *by weight of bitumen	Dry	Bitumen	[28]
A9	S. Fernandes, Silva and Oliveira	2019	✓	-	-	-	✓	✓	5, 7.5, 10, 12.5, 15, and 20% motor oil 4, 5, 6% HDPE 4, 5, 6% SBS 5,7.5, 10, 15, 20% crumb rubber *by weight of bitumen	Wet	Bitumen	[29]
A10	Babalghaith et al.	2020	-	-	-	✓	-	-	0, 20. 40, 60, 80, 100% by weight of aggregate	Dry	Aggregate	[30]
A11	Huang et al.	2020	-	-	-	✓	-	-	10, 20, 30, 40, 50% by weight of aggregate	Dry	Aggregate	[31]
A12	Terrones-Saeta et al.	2020	-	-	✓	✓	-	-	15 – 18% by weight of aggregate (aggregate) 0.5% by weight of aggregate (fiber)	Dry	Aggregate; Stabilizing additive	[32]
A13	Parimita	2020	-	-	✓	-	-	-	0.3% by weight of aggregate	Dry	Stabilizing additive	[33]
A14	Tataranni and Sangiorgi	2021	-	-	✓	-	-	-	0, 0.2, 0.3, 0.4% by weight of aggregate	Dry	Stabilizing additive	[16]
A15	Pérez et al.	2021	-	-	-	✓	-	-	100% by weight of aggregate	Dry	Aggregate	[34]
A16	Chegenizadeh, Peters and Nikraz	2021	✓	-	-	-	-	-	0, 2, 4, 6, 8% by weight of bitumen	Wet	Bitumen	[35]
A17	Chegenizadeh et al.	2021	-	-	-	-	✓	-	25% by weight of bitumen	Dry	Bitumen	[36]
A18	Bizarro et al.	2021	-	-	-	✓	-	-	93% by weight of aggregate	Dry	Aggregate	[37]
A19	Noura et al.	2022	-	-	-	-	✓	-	0, 3, 6, 9% by weight of bitumen	Wet	Bitumen	[38]
A20	Mashaan, Chegenizadeh and Nikraz	2022	✓	-	-	-	-	-	6% by weight of bitumen	Wet	Bitumen	[39]

A21	Bieliatynskyi et al.	2022	-	✓	-	-	-	-	NA	Dry	Filler	[40]
A22	Martinez-Soto et al.	2022	-	-	-	-	✓	-	2,500, 3,750, and 5,000 gr/ton	Dry	Stabilizing additive	[41]
A23	Zangooeinia et al.	2023	-	✓	-	-	-	-	100% by weight of filler	Dry	Filler	[42]
A24	Lee, Yun and Minh Le	2023	-	-	-	-	✓	-	6% by weight of bitumen	Wet	Bitumen	[43]
A25	Tayh and Khalif	2023	✓	-	-	-	✓	-	4% PET and PVC 12% CR	Wet	Bitumen	[44]
A26	Vijay, Madinur and Sanganaikar	2023	-	-	✓	-	-	-	5% by weight of mixture	Dry	Filler	[45]
A27	Alshehri, Wahhab and Al-Osta	2023	✓	-	✓	-	-	-	0.3% by weight of aggregate (fiber); 1.5, 3, 4.5, and 6% by weight of bitumen (waste PE)	Wet	Bitumen; Stabilizing additive	[46]
A28	Alshehri et al.	2023	✓	-	-	-	-	-	0, 6, 12, 12, 20% by weight of aggregate	Wet	Bitumen	[47]
A29	Gunka et al.	2023	-	✓	-	-	-	✓	15% by weight of filler	Dry	Filler	[48]

The reduced data were combined and synthesized using narrative synthesis approach. In this phase, the focus of this literature review was divided into several research questions (RQ) such as:

- RQ1: what is the method for preparing waste materials into the SMA mixture?
- RQ2: what is the method for mixing waste materials into the SMA mixture?
- RQ3: what are the mechanical and rheological properties of the bituminous binder and/or SMA mixture with added waste material?
- RQ4: what is the environmental perspective analysis of the SMA mixture with added waste material?

The final phase is to make conclusions after the data has been reviewed with the aim of determining this paper's results and recommendations for additional research.

3. Results and discussion

3.1. SMA mixture composition

Like hot asphalt mixtures, modified SMA mixes in this paper consist of a combination of aggregates, bitumen, stabilizing additives, and waste materials. Aggregates in SMA mixes consist of coarse aggregates, fine aggregates and fillers and obtained from crushed stone with a certain size gradation. All aggregates need to be tested first to determine the characteristics of the material, such as specific gravity, water absorption, and aggregate gradation analysis.

The bituminous binder, which can be obtained from both petroleum and natural sources, is the second component of SMA. Paving grade and polymer-modified bitumen are the types of bitumen produced from petroleum, whereas gilsonite and lake bitumen are examples of natural bitumen. Both types of bitumen must meet several general requirements that are commonly used as asphalt mixtures, such as specific gravity, penetration, softening point, flash point, and ductility [49].

In addition to the two materials above, SMA mixtures also require stabilizer additives that can be obtained from organic or inorganic fibers or polymers [49]. This material can be in the form of fibers or polymers in the form of loose or pelleted factories. This aims to prevent the occurrence of drain-down phenomena or the separation or fall of asphalt mastic with aggregates in SMA mixtures, considering that this mixture has a gap aggregate gradation dominated by coarse aggregates (above No. 16 or 1.18 mm) and contains 6 - 7% asphalt. Therefore, it is also necessary to test the drain-down characteristics based on AASHTO T 305 or ASTM D6390-11 with the results of the drain-down value being the percentage of aggregates covered with asphalt that falls into the test tray and is expressed in percent units.

The last material is waste material that can be used as an additive or substitution of one of the SMA components. This is because the waste sources are diverse and have the potential to be developed into SMA mixtures. Based on Table 1, the collected waste materials can be grouped into six categories of waste types used in the SMA mixture, such as waste polymers [25–29,35,39,44,46,47,50], ashes [40,42,45,48], waste fibers [16,33,45,46,51,52], recycled aggregate [23,26,27,30,34,37,52], waste rubbers [21,22,26–29,38,41,43,44], and waste oil [26,27,29,48].

3.2. Waste materials preparation

Waste polymers

Waste polymers need to shred into a certain size before being mixed into bitumen or aggregate. Based on the results of literature studies, it was found that several types of waste polymers were used, such as polyethylene (PE), polyethylene terephthalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE), styrene-butadiene-styrene (SBS), polyvinyl chloride (PVC), and other plastic types form green houses, wires, and master batches. Only a little literature discusses the size for preparing this material, which ranges from 2 – 50 mm. Table 2 shows the characteristics of waste polymers that can be used for SMA mixtures.

Table 2. Waste Polymers Characteristics.

Article ID	Type of Waste Polymers	Shape	Size (mm)	Ref
A5	PET	Shredded	N/A	[25]
A6	HDPE	Shredded and powdered	N/A	[26]
A7	HDPE	Shredded	N/A	[27]
A8	Green house, wires, and master batches	Shredded	N/A	[53]
A9	HDPE	Shredded and powdered	N/A	[54]
A16	HDPE	Shredded	N/A	[35]
A20	PET	Shredded	N/A	[39]
A25	PET and PVC	Shredded	2.36	[44]
A27	PE	Shredded	N/A	[46]
A28	LDPE	Shredded	20 – 50	[47]

Ashes

Ash waste is also used as an additive and replacement material for filler. Ash waste must be ground to a certain size (0.063 – 0.160 mm). Under certain conditions, such as wastepaper sludge ash (WSA), it must be activated first so that the geopolymer chemical compound can be formed using the chemical activation method. Furthermore, Table **3** shows the characteristics of ash materials that can be used for SMA mixtures.

Table 3. Ashes Characteristics.

Article ID	Type of Ashes	Shape	Size (mm)	Ref
A21	Fly ash	Powdered	0.160	[40]
A23	Calcium Carbide Residue (CCR)	Powdered	0.075	[42]
A26	Bagasse ash	Powdered	0.075	[45]
A29	Wastepaper sludge ash (WSA)	Powdered	0.063 – 0.125	[48]

Waste fibers

Table 4 shows the types and characteristics of fiber waste used in the SMA mixture. This type of waste is usually processed first into powder which can become filler or loose fiber, or a pressing process can be carried out to become pellets which are used as a stabilizing additive (cellulose fiber).

Table 4. Waste Fibers Characteristics.

Article ID	Type of Waste Fibers	Shape	Size (mm)	Ref
A4	Pulp and paper waste	Pressed	N/A	[24]
A12	Cellulose fiber from the papermaking industry	Pressed	N/A	[32]
A13	Coconut and banana fibers	Shredded and loosed	N/A	[33]
A14	Cigarette filter	Shredded and loosed	0.2 – 1.1	[16]
A27	Waste newspaper and jute fiber	Shredded and loosed	N/A	[46]

Recycled aggregate

Recycled aggregate is used as a replacement for some or all the aggregate in SMA mixtures which include coarse aggregate, fine aggregate, and filler. The results of the literature review showed that there are six types of recycled aggregates, such as recycled concrete (RCA), reclaimed asphalt pavement (RAP), chunk clinker, ceramic waste aggregate, electric arc furnace slag (EAFS), and ladle furnace slag (LFS) as shown in Table 5. For each type, there is the same preparatory treatment, namely crushing it first until an aggregate of 0.063 – 14 mm is formed.

Table 5. Recycled Aggregate Characteristics

Article ID	Type of Recycled Aggregate	Shape	Size (mm)	Ref
A3	RCA	Crushed	0.075 – 12.5	[23]
A6	RAP	Crushed	0.063 – 14	[26]
A7	RAP	Crushed	N/A	[27]
A10	Chunk clinker	Crushed	0.075	[55]
A11	Ceramic waste aggregate	Crushed	Max. 13.2	[31]
A12	EAFS and LFS	Crushed	0.063 – 22	[32]
A15	RAP	Crushed	0.063 – 14	[34]
A18	RAP	Crushed	N/A	[37]

Waste rubbers

Incorporating waste rubber in SMA's mixtures consists of using rubber powder and end-life-tire (FiTyre) or crumb rubber (CR) waste. Before use, CR, which is a processed product from FiTyre, is converted into powder which has a size of 4.75 to 0.075 mm with a fiber content of less than 0.5% and a specific gravity of 1.15 ± 0.05 [47]. In more detail, Table 6 shows the characteristics of the use of waste rubber in SMA mixtures.

Waste oils

Waste oils are used as a rejuvenator in mixing waste into asphalt using the wet process method. The types of waste oils used can be seen in Table 7, consisting of engine oil and acid tar. Additionally, acid tar is an oil-refining industrial waste, also applied as an activator in the chemical activation method process.

Table 6. Waste Rubber Characteristics.

Article ID	Type of Waste Rubbers	Shape	Size (mm)	Ref
A1	Tyre rubber (crumb rubber modifier [CRM])	Powdered	N/A	[21]
A2	Tyre rubber (crumb rubber modifier [CRM])	Powdered	0.6	[22]
A6	Crumb rubber	Powdered	N/A	[26]
A7	Crumb rubber	Powdered	N/A	[27]
A8	Crumb rubber	Powdered	N/A	[53]
A9	Crumb rubber	Powdered	N/A	[54]
A17	Crumb rubber	Powdered	N/A	[36]
A19	Rubber powder	Powdered	0.361	[38]
A22	End-life-tyres	Pelleted	N/A	[41]
A24	Crumb rubber	Powdered	N/A	[43]
A25	Recycled tire crumb rubber	Powdered	N/A	[44]

Table 7. Waste Oils Characteristics.

Article ID	Type of Waste Oils	Shape	Size (mm)	Ref
A6	Engine oil and engine oil bottoms	Liquid	N/A	[26]
A7	Engine oil	Liquid	N/A	[27]
A9	Motor oil	Liquid	N/A	[54]
A29	Acid tar	Liquid	N/A	[48]

3.3. Incorporating waste methods

Dry process

Waste is described as an addition added to the aggregate prior to the bitumen pouring process in the dry process technique [16,22,23,28,30,31,33,34,36,37,40–42,45,48,51,52]. Based on the summary results, the volume of waste used is a ratio of the mass percentage of waste over the aggregate. Furthermore, this method is more widely used because it accommodates more waste material. Overall, for all types of waste reviewed, the processing sequence using this method is: preparing waste materials; heating the aggregate and waste material until a certain temperature is reached, then continuing with pouring the liquid asphalt into the mixture of aggregate and waste material; and finally, stirring the mixture until it becomes a homogeneous mixture.

Wet process

Another method, the wet process, is a method of mixing waste materials by mixing directly with bituminous binder to produce a homogeneous mixture. Different from the dry process, this method has several parameters for mixing success consisting of temperature, mixing time, and stirring speed. Based on the results of the literature study, summary data was obtained for various types of waste. To mix crumb rubber requires a mixing temperature of between 160 – 180 ± 5ºC with a mixing rotation speed of 200 – 1,000 rpm [21,26,29,38,44,56], HDPE and SBS waste requires mixing temperature 170 – 180 ºC with a mixing rotation speed of 350 – 600 rpm [26,27,29], PET plastic waste requires a temperature of 160 – 180 ± 5ºC with a mixing rotation speed of 1,000 – 4,000 rpm [39,44], PVC waste 179 ± 5ºC with a mixing rotation speed of 1,000 rpm [44], and LDPE waste a maximum of 200ºC with a mixing rotation speed of 850 rpm [47].

3.4. SMA's mixing methods

Table 8 summarizes the results from previous studies, which state that researchers use different criteria to determine the type of SMA according to the size of the aggregate gradation. This can be seen from the symbols used in their research, such as SMA 8 [48], SMA 10 [35,51], SMA 13 [31], SMA 14 [26], SMA 15 [24] and SMA 20 [21–23,30,38]. Abbreviation "SMA" means the designation of Stone Mastic Asphalt and the number behind means the aggregate size above that number, in millimeters (mm) [49].

Furthermore, blending SMA with additional waste has the same procedure as other hot asphalt mixing methods, such as asphalt concrete (AC) and porous asphalt (PA). The first step is preparing and measuring SMA ingredients according to the job mix formula (JMF), which includes aggregate preparation, bitumen, cellulose fiber, and waste materials. The original and/or waste-based aggregate and bitumen are heated into the oven at a specific temperature and duration. After that, they were mixed manually or with mixer at varying temperatures, depending on the viscosity value of the bitumen used. The review results indicate that the mixing temperature is in the range of 135 and 180ºC. Finally, compacting is carried out using Marshall compactor tools, 50 or 75 blows per side, or a Superpave Gyratory Compactor (SGC).

Table 8. Summary of Mechanical Properties of Each Study

Article ID	Specification Standard for SMA mixture	SMA Type	Mixing Temperature (ºC)	Compaction Temperature (ºC) and Duration (Blows)	Compaction Method
A1	Malaysian Public Works-Road Department (*Jabatan Kerja Raya* [JKR]) 2008	SMA 20	160	160; 50 each side	Marshall compactor tools
A2	Malaysian Public Works-Road Department (*Jabatan Kerja Raya* [JKR]) 2008	SMA 20	160 – 165	160 ± 5; 50 each side	Marshall compactor tools
A3	-	SMA 20	150	145; 50 each side	Marshall compactor tools
A4	-	SMA 10 and SMA 15	-	-	-
A5	-	-	170	160 – 180; -	-
A6	EN 13108–5	SMA 14	30ºC above the mixing temperature of bitumen	-	-
A7	This paper focuses on the discussion of carbon dioxide emissions and heavy metal contamination of SMA using previous research data.				
A8	This paper focuses on the discussion of noise attenuation of SMA mixture.				
A9	EN 13108–5 and EN 12697–34	SMA 14	100°C–180°C, with 10°C increments.	100°C–180°C, with 10°C increments; -	-
A10	Malaysian Public Works-Road Department (*Jabatan Kerja Raya* [JKR]) 2008	SMA 20	150 – 155	140 – 145; 50 each side	Marshall compactor tools
A11	JTG F40–2004	SMA 13	175	160; 50 each side	Marshall compactor tools

A12	Circular Order OC 3/2019	-	180 ± 5	-; 50 each side	Marshall compactor tools
A13	The Ministry of Road Transport and Highways (MORTH) of India – 2013	-	-	-; 50 each side	Marshall compactor tools
A14	District of Bologna technical specification – 2018	-	170	170	Superpave Gyratory Compactor
A15	UNE-EN-12697-2 and the Spanish Specification for Highway Maintenance (PG-4) for mixtures	-	-	-; 50 each side	Marshall compactor tools
A16	AP TI32/09 and Main Road WA specification	-	135 – 160	-	-
A17	AS 2150-2005	SMA 10; SMA 14	180	150 ± 3; -	Marshall compactor tools
A18	Paper ini menjelaskan tentang potential carbon footprint dengan menggunakan metode LCA pada porous asphalt, AC, dan SMA				
A19	-	SMA 20	-	-; 75 each side	Marshall compactor tools
A20	AS/NZ 2891.2.1:2014	-	-	-	-
A21	This paper focuses on the discussion of the addition of waste to the bitumen only and does not mention the mixing temperature.				
A22	This paper focuses on the discussion of the comparison of Life Cost Assessment (LCA) from the use of HMA and SMA.				
A23	-	-	170	140 – 173; 50 each side	Marshall compactor tools
A24	-	SMA 10	165	-	Gyratory Compactor
A25	-	-	40/50 pen = 158 ± 5. Asphalt + PET = 180 ± 5. Asphalt + PVC = 179 ± 5. Asphalt + CR= 183 ± 5.	40/50 pen = 146 ± 5. Asphalt + PET = 168 ± 5. Asphalt + PVC = 167 ± 5. Asphalt + CR= 175 ± 5.	Marshall compactor tools
A26	IRC:SP:79-2008	-	-	-	-
A27	AASHTO R 46, AASHTO M 325, and NCHRP 673	-	SMA base mixes (control mixes) = 161. SMA modified mixes = 195.	SMA base mixes (control mixes) = 148. SMA modified mixes = 184.	Superpave Gyratory Compactor
A28	AASHTO R 46, AASHTO M 325, and NCHRP 673	-	SMA base mixes (control mixes) = 161. SMA modified mixes = 195.	SMA base mixes (control mixes) = 148. SMA modified mixes = 184.	Superpave Gyratory Compactor
A29	-	SMA 8	-	-	-

- = not explained.

3.5. Effect on SMA's mixture's properties

Mechanical properties

The results of the literature study illustrated that the mechanical properties of adding waste material to the SMA mixture are divided into two, such as permanent deformation characteristics and fatigue resistance. There are differences in the results shown depending on the type of waste used. Furthermore, Table 9 shows a complete summary of the mechanical properties.

Table 9. Summary of Mechanical Properties of Each Study

Article ID	Mechanical Properties								
	Marshall Stability	Indirect Tensile Strength (ITS)	Compressive Strength Test	Wheel Tracking Test	Drain down test	Moisture Damage Resistance	Dynamic Creep Test	Indirect Tensile Fatigue Strength (ITFT)	4-point Bending Test
A1	-	↑	-	-	-	-	↑	↑	-
A2	-	↑↓	-	↓	-	-	↓	-	-
A3	↓	-	-	-	-	-	-	-	-
A4	-	-	↓	-	-	-	-	-	-
A5	↑	-	-	-	-	-	-	-	-
A6	-	↑	-	↓	-	-	↑	-	-
A7	-	-	-	-	-	-	-	-	-
A8	-	-	-	-	-	-	-	-	-
A9	-	↑	-	↑↓	-	-	↑	-	-
A10	↑	↑	-	-	↓	-	↑	-	-
A11	-	↑	-	↑	-	-	↑	-	-
A12	↑	-	-	-	-	-	-	-	-
A13	↑↓	-	-	-	-	-	-	-	-
A14	-	↓	-	-	↓	-	-	-	-
A15	↑	-	-	-	-	-	-	-	-
A16	↑↓	-	-	↑	-	-	-	-	↓
A17	↑↓	-	-	↑	-	-	-	-	-
A18	-	-	-	-	-	-	-	-	-
A19	-	↑↓	-	-	-	-	-	-	-
A20	↑	↑↓	-	↑↓	↓	-	-	-	-
A21	-	-	↓	-	-	-	-	-	-
A22	-	-	-	-	-	-	-	-	-
A23	↑	↑↓	-	-	-	-	-	-	-
A24	-	-	-	-	-	-	↑↓	-	-
A25	↑↓	↑↓	-	↑↓	↑↓	↑	-	-	-
A26	↑↓	-	-	-	-	-	-	-	-
A27	-	↑↓	-	↑	-	↑↓	-	-	-
A28	-	↑	-	↑	↓	-	-	-	-
A29	-	-	↑↓	-	-	-	-		-

↑ = increase; ↓ = decrease; ↑↓ = depends on volume of material waste

Permanent deformation characteristics

Permanent deformation (rutting resistance) is the ability of an asphalt mixture to resist changes in shape due to continuous traffic and weather loads [57]. There are several methods used to assess this resistance, consisting of Marshall stability, Indirect Tensile Strength (ITS) test, compressive strength test, wheel tracking test, drain-down test, and moisture damage test. A high Marshall stability value means that the mixture has high stiffness so that it can distribute the load better.

The ITS test usually uses a cylindrical specimen with a diameter of 101.6 mm × 50.8 mm height or a diameter of 150 mm × 75 mm height which is set horizontally, and a load is applied radially to the surface which causes the formation of vertical cracks along the length of the specimen [58]. The review results show differences in ITS values depending on the type of waste used. The higher the ITS value, the better the deformation resistance.

The wheel tracking test is carried out to assess the strength of the asphalt mixture in resisting failure due to weak aggregate composition, the quality of the bituminous binder, and poor adhesion between the binder and the aggregate [57]. Not only that, traffic load, mix design, and weather conditions also influence this parameter value [57]. Table 8 illustrates the average increase in the value of this parameter which is caused by reducing the water voids percentages in the mixture, thereby increasing the resistance to deformation [31,35,36,46,47,54].

Fatigue resistance

Fatigue resistance is a performance assessment of an asphalt mixture in resisting excessive traffic loads, causing excessive horizontal strains in the asphalt layer. There are several methods that can be used to assess this property (based on reported articles), including indirect tensile fatigue test (ITFT), dynamic creep test, and 4-point bending beam test.

The results of ITFT were reported only by Mashaan et al. [21] on the addition of crumb rubber with various test loads given starting from 2,000 N, 2,500 N, and 3,000 N. The results of this research were an increase in the fatigue life value of up to 59%. This indicates an increase in the fatigue life value along with increasing crumb rubber volume. This happens because the crumb rubber is well distributed in the mixture, thus allowing the prevention of cracks and the inhibition of microcrack formation in the modified SMA's mixture [21].

The results of the 4-point bending beam test were only reported by Chegenizadeh, et al. [35] on the addition of HDPE waste which showed an increase in value with the addition of 2% HDPE of 6624 Mpa and 1022 Mpa higher compared to conventional SMA.

Rheological properties

Rheological properties are used to identify the characteristics of bituminous binders that are susceptible to aging due to the influence of temperature, sunlight, oxygen, or a combination of these three factors [59]. Therefore, the aging phenomenon can be prevented through rheological property characterization. To investigate the aging performance, especially for binder mixtures for SMA based on waste materials, the results of the literature review show that there are several procedures used, such as using dynamic shear rheology (DSR) and multiple stressed creep and recovery (MSCR).

Fernandes et al. [54] tested the DSR and MSCR parameters from the addition of waste HDPE, waste motor oil, and CR to SMA's binder. It was found that adding several different types of waste increased the high temperature continuous PG of binders compared to conventional bitumen. The optimum values are 10% waste motor oil and 6% HDPE, 10% waste motor oil and 5% SBS, and 7.5% motor oil and 20% CR. Alshehri et al. [46] also tested the DSR and MSCR parameters when adding LDPE using the wet process method and the resulting addition of 6% recycled plastic showed the maximum volume that met these two parameters so that it could be used as an addition to asphalt binder modification.

Lee et al. [43] tested the MSCR parameters in adding epoxy resin with crumb rubber to the binder. The result is that modified asphalt shows strain recovery and reduced strain under creep loads at MSCR levels of 0.1 and 3.2 kPa compared to the reference binder.

Alshehri et al. [47] tested the elastic recovery (R%) and non-recoverable creep (Jnr) compliance parameters using MSCR respectively on the addition of LDPE using the wet process method. The results obtained were that the addition of several variations of LDPE could not meet the requirements and the Jnr value met the minimum value requirements (3.2 Kpa^{-1}).

3.6. Environmental perspective

Fernandes et al. [27] calculated CO_2 emissions resulting from implementing waste materials (waste engine oil, waste bottom engine oil, and polymer) into SMA mixtures on a large scale. The stages considered are material production, material transportation, mixture production, and mixture transportation. The study concluded that the recycled SMA mixture showed the lowest CO2 equivalent emissions due to the use of RAP material which replaced part of the original aggregate and reduced the amount of new asphalt required. This means that waste materials in asphalt modification and RAP materials contribute to reducing CO_2 equivalent emissions.

Fernandes et al. [29] conducted tests on heavy metals and leachates content in the use of motor oil, HDPE, SBS, and CR waste materials in SMA mixtures using the EN 13473-1 standard. The research results showed that this type of waste has pollutant content values (cadmium, chromium, copper, nickel, lead, and zinc) which is low or less than the established standards.

Morcillo et al. [53] investigated the impact of using end-life-tire (FiTyre) and waste plastics in the SMA mixture on the noise produced by the pavement layer. It was found that the addition of 1.5% crumb rubber from FiTyre processing was the best mixture in reducing noise pollution. This mixture produces a close proximity (CPX) method value with a CPX_p value of 89 dBA compared to the porous asphalt mixture.

Martinez-Soto et al. [41] assessed the use of FiTyre as a fiber in SMA mixtures using the Life Cycle Assessment (LCA) method. The results of this research were that the greater the amount of FiTyre used, the lower the pollutant emissions produced. For example, in the exhaustion of fossil resources category, this waste can produce 40 g lower oil-eq compared to manufactured cellulose fiber. Not only that, in the human toxicity category, FiTyre produces 1.8 times lower emissions 1.4DB-eq (1.9) compared to manufactured cellulose fiber (1.4DB-eq 3.4).

Bizarro et al. [37] also assessed the use of reclaimed asphalt pavement (RAP) using the LCA method. In this study, as much as 93% of RAP was used in SMA mixture modeling. The research results show that there is a potential for reducing the carbon footprint of between 55% and 64%.

Based on the assessment study described, it is known that waste material in the SMA mixture can reduce noise pollution due to tire rotation, energy consumption and greenhouse gas emissions. Fortunately, these results are quite promising, even though they are still on the laboratory scale. Therefore, more research is needed that measures large scale results and long-term emissions related to the service life of such SMA mixtures.

3.7. Recommendations for future research

Recommendations for future research are the researchers can investigate the use of different types of local waste with high volume and variations into SMA blends. Furthermore, numerical study using computer software needs to compare the mechanical properties with numerical estimations of SMA mixtures with waste material substitution. Other calculations on the correlation between SMA mix performance and service life prediction must be conducted for achieve predicted road service lifespans when using this type of mix. Environmental and economic impacts should be thoroughly investigated using life cycle cost analysis (LCCA) and life cost analysis (LCA) on waste utilization in SMA mixtures. Furthermore, public policy research on the use of waste in SMA mix should be performed to develop larger-scale standards, regulations, and implementation strategies.

4. Conclusions

Proper waste management is crucial for addressing the existing issue of experimental contamination. One effective approach is to utilize the waste as an additive or substitute in SMA mixture, which is now the subject of extensive research. The present study aims to conduct a systematic literature review to summarize and review various published research results on the use of waste materials in SMA mixture. The findings of this evaluation demonstrate that the mixture has significant potential for large-scale development and implementation. Therefore, it can be inferred from this information as follows.

- There are 6 categories of waste materials that are frequently used in the manufacture of SMA mixtures, with the most commonly added materials are waste rubbers and polymers.
- The incorporation of waste materials into SMA mixture is categorized into two methods: the dry process and the wet process.
- The use of waste materials has an impact on increasing or decreasing the mechanical and rheological properties of SMA mixtures, depending on the type and volume of waste used.
- The use of waste materials in SMA mixtures has a positive impact on the environment. This is shown by the reduction of CO_2 emission, toxicity levels, and sound reduction resistance.
- The future research should investigate how the utilization of waste materials in SMA affects service life modeling by mechanistic, numerical, and economic techniques.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Christian Hadhinata: conceptualization; methodology; investigation; writing–original draft, review and editing; data curation; data analysis; visualization; software.

Ary Setyawan: methodology; conceptualization; writing–review and editing; supervision; resources.

Florentina Pungky Pramesty: methodology; conceptualization; writing–review and editing; supervision; resources.

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