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A REVIEW OF THE QUALITIES AND UTILIZATION OF WASTE MATERIALS IN WARM MIX ASPHALT CONCRETE

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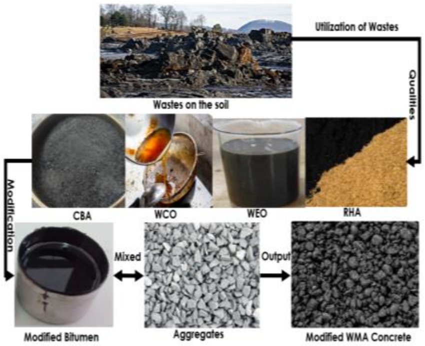
Graphical abstract



Abstract

The amount of unwanted waste produced in recent decades has quickly increased due to rapid population growth, technological advancements, and the widespread use of state-of-the-art products and services in the industry. Different researchers have carried out extensive studies on waste materials. Regretfully, most investigations focus only on the performance of HMA concrete that has been modified using one or two types of waste. Therefore, this study investigates an extensive review of the qualities and utilization of four types of wastes, viz., Coal Bottom Ash (CBA), Waste Cooking Oil (WCO), Waste Engine Oil (WEO), and Rice Husk Ash (RHA), as well as assessing their bibliometric analyses. The wastes that were being investigated showed a notable improvement in Warm Mix Asphalt (WMA) concrete. The WMA technology has successfully reduced the environmental issues of high production and compaction temperatures. The previous publications on CBA, WCO, WEO, and RHA identified 3,914 published documents between 2009 and 2023. Only 32 of these documents were published by Scopus. The academic disciplines of engineering, materials science, environmental sciences, and others have contributed 37%, 29%, 19%, and 15%, respectively, to Scopus publication. The United Kingdom made a significant contribution of 50% to Scopus publication compared to other countries. Furthermore, the findings also revealed that 89.4% (29 documents) were technical articles and only 10.6% (3 documents) were review articles. Further review of the rheological and microscopic properties of the four wastes is needed.

Keywords: Waste materials, asphalt mixtures, asphalt pavements, asphalt binders, WMA technologies, and additives

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Abstrak

Jumlah sisa yang tidak diingini yang dihasilkan dalam beberapa dekad kebelakangan ini telah meningkat dengan cepat disebabkan oleh pertumbuhan penduduk yang pesat, kemajuan teknologi, dan penggunaan meluas produk dan perkhidmatan terkini dalam industri. Penyelidik yang berbeza telah menjalankan kajian meluas mengenai bahan buangan. Malangnya, kebanyakan penyiasatan hanya tertumpu pada prestasi konkrit HMA yang telah diubah suai menggunakan satu atau dua jenis sisa. Oleh itu, kajian ini menyiasat kajian menyeluruh tentang kualiti dan penggunaan empat jenis sisa, iaitu, Abu Bawah Arang Batu (CBA), Minyak Masak Sisa (WCO), Minyak Enjin Sisa (WEO), dan Abu Sekam Padi (RHA), serta menilai analisis bibliometrik mereka. Sisa yang sedang disiasat menunjukkan peningkatan ketara dalam konkrit Warm Mix Asphalt (WMA). Teknologi WMA telah berjaya mengurangkan isu alam sekitar pengeluaran tinggi dan suhu pemadatan. Penerbitan terdahulu mengenai CBA, WCO, WEO dan RHA mengenal pasti 3,914 dokumen yang diterbitkan antara 2009 dan 2023. Hanya 32 daripada dokumen ini diterbitkan oleh Scopus. Disiplin akademik kejuruteraan, sains bahan, sains alam sekitar, dan lain-lain telah menyumbang masing-masing 37%, 29%, 19%, dan 15%, kepada penerbitan Scopus. United Kingdom memberikan sumbangan besar sebanyak 50% kepada penerbitan Scopus berbanding negara lain. Tambahan pula, penemuan juga mendedahkan bahawa 89.4% (29 dokumen) adalah artikel teknikal dan hanya 10.6% (3 dokumen) adalah artikel ulasan. Kajian lanjut mengenai sifat reologi dan mikroskopik keempat-empat sisa diperlukan.

Kata kunci: Bahan buangan, campuran asfalt, turapan asfalt, pengikat asfalt, bahan tambahan campuran hangat

1.0 INTRODUCTION

Fast population expansion, technical breakthroughs, and the industry's adoption of cutting-edge goods and services have all contributed to the recent decades' sharp rise in the quantity of undesired waste production [1]. Previous researchers reported that waste materials can be used as sustainable wastes for asphalt pavements [2, 3, 4]. The issues of excessive waste generation and inadequate disposal have prompted numerous researchers to conduct a series of studies to identify methods for using solid wastes as substitute materials in the management and construction of pavements [5, 6]. Large amounts of various waste products have been produced by the oil sector's cumulative expansion; these products need to be properly disposed of and valued [7]. Researchers worldwide have focused on the challenge, rate of slowness, and high cost of various remediation options for oil industry wastes, as well as the potential use of these wastes in construction sectors [7].

The behaviour of WMA mixtures has been the subject of conflicting results, which can be attributed to the variety of WMA mixture types; the amount of warm mix additive; the type and quantity of additional modifying agents in WMA; and the trial methods used in the evaluation of WMA mixtures and modified binders [8]. Other waste materials have been employed in several countries to produce asphalt concrete [9, 10, 11].

According to Syarif *et al.* [12], a modern worldwide concern that could undoubtedly affect the planet is the waste issue. To ease environmental concerns, reprocessing waste materials is still being researched in many nations. These wastes reduce construction costs, safeguard the environment, and maintain natural resources in addition to improving the performance of hot mix asphalt (HMA) [2, 3]. Four types of waste materials (CBA, WCO, WEO, and RHA) have a range of substantial effects on different qualities of asphalt concrete. On the other hand, the different components of filler materials affect the different qualities of asphaltic concrete [15, 16].

Furthermore, inadequate and increasingly costly provisions for asphalt materials pose a greater challenge to the asphalt industry than ever before [17, 18]. There are grave ecological issues that need to be addressed as a result of the expanded capacity of waste products from the upgraded asphalt sector [19, 20, 21]. The bulk of environmental problems facing the world today may be caused by inadequate and inappropriate waste management techniques and excessive waste production [22]. Recycling of waste materials should be done to supply appropriate substitute materials for pavement construction to lessen the environmental problems related to waste production [23, 24].

A study by Wang *et al.* [25] found that bio-oils significantly increased the rate of repossession of aged asphalt, decreased the compliance of non-repossession creep, and successfully improved the resilience of plasticity and its resistance to long-term deformation. The researchers also found that the most promising effect on crack resistance is provided by aged asphalt and vegetable oil, which have very minor frequency sensitivity. Using waste products would not only be cost-effective but also generate foreign exchange revenue and reduce ecological footprint if managed properly. High demand for pavement and building materials is necessary for the sustainable construction of asphalt concrete using waste materials [18, 26]. This has prompted research on the qualities and utilization of waste materials in WMA concrete as a means of mitigating environmental disposal issues, hence advancing waste product management and reprocessing [19, 27, 28]. This study, which shows advancements in quality and waste material utilization, significantly contributes to many disciplines.

Many countries are now investigating using waste materials to alleviate environmental concerns using WMA technologies. Still, the ecosystem is becoming fairly concerned about them due to their enormous volume of landfill disposal, which has negative consequences on the ecosystem and its inhabitants. Different researchers have carried out extensive studies on waste materials. Regretfully, most investigations focus only on the performance of HMA concrete that has been modified using one or two types of waste. The qualities and utilization of these wastes in WMA concrete during the modification stage and their bibliometric analyses have not been fully investigated. Also, the technologies in the WMA concrete have not been sufficiently clarified. Therefore, this study provides a comprehensive review of the qualities and utilization of four categories of waste materials in WMA concrete in addition to evaluating their bibliometric analyses.

2.0 WASTE MATERIALS

Some studies have been conducted on the utilization of waste materials in various paving mixtures, despite their small particle sizes and gradations [2, 29]. According to Yuechao *et al.* [30], Reddy & Harihanandh [31], and Chindasiriphan *et al.*, [32], a range of waste materials can be utilized to improve the physical stability, rheological, microscopic, durability, and strength of asphalt concrete pavements.

The disposal of waste materials directly into the ecosystem can cause ecological problems [33, 34]. Several rich countries have strict ecological regulations, while many developing countries have very few regulations to protect the ecosystem from environmental impacts [35, 36, 37]. To lower construction costs, a lot of cutting-edge research projects in developing countries had to concentrate on the utilization of low-cost, easily accessible conservative materials, including waste products from industry and agriculture [38, 39]. Furthermore, there is more interest in using these wastes as substitute materials in the pavement sector because of the significant advancement in their annual production and the need for their environmentally responsible disposal [40, 41, 11]. Utilizing waste materials for environmentally friendly constructions would not only be cost-effective but also potentially result in significant foreign exchange earnings and a decrease in environmental pollution [41, 42, 43].

Substantially, the improved thermal qualities of asphalt concrete and the sustainable utilization of cost-effective and replacement wastes in pavement construction have become widespread practices in the asphalt industry, indicating the higher-quality performance of pavement [44]. Therefore, this made a significant contribution to the building industry's attempts to recycle waste materials rather than burning or discarding them. Examples of these wastes include solid goods from cities, businesses, and farms [45, 46]. The potential, ecological compatibility, and behavior of using waste material as a mineral filler or replacement agent in pavement construction are being investigated by some transportation agencies [47, 48]. Consequently, the general solution to waste disposal issues is now to reprocess waste materials into useful products (pollution to solution approach) [49, 50, 51].

Numerous research studies have been conducted on the use of various wastes for pavement construction in different nations [24, 49, 52, 53, 54, 55]. The common waste materials comprise CBA, WCO, WEO, and RHA. A comprehensive review of these wastes is discussed in subsections.

2.1 Qualities and Utilization of CBA

A review of earlier published studies was performed on the exceptional physical qualities of CBA, which involve specific gravity, specific surface area, water absorption of water, and fineness modulus. Zhou *et al.* [56] reported that the CBA's bodily appearance differs from grey to black (Figure 1). Singh & Siddique [57], Shi-Cong & Chi-Sun [58], Rafieizonooz *et al*. [59], and Ahn *et al*. [60] reported that India, China, Malaysia, and South Korea contribute 31.6%, 28.9%, 11.6%, and 4.1%, of the global total CBA water absorption, respectively (Figure 2).

One of the most important physical qualities of CBA is specific surface area. India, Malaysia, and Turkey recorded 600 $m^2\ kg^{-1}$ [61], 316 $m^2\ kg^{-1}$ [62], and 93 $m^2\ kg^{-1}$ [63] of the CBA's specific surface area, respectively. As shown in Figure 3, their quantities account for 60%, 31%, and 9%, respectively. This indicated that India has the main Specific Surface Area (SSA) of CBA compared to Malaysia and Turkey. It is therefore projected that CBA will be used in various disciplines to reduce the high volume of landfill disposal, which has negative consequences on the ecosystem and its inhabitants. The tensile strength, lowest temperature cracking, and rutting strength are undisturbed when finer aggregate is substituted with 10% and 20% CBA by the overall weight of aggregate contents for wearing and binder layers [64, 65, 66].

(a) (b)

Figure 1 Appearance of CBA: (a). original type; (b). ground type [63]

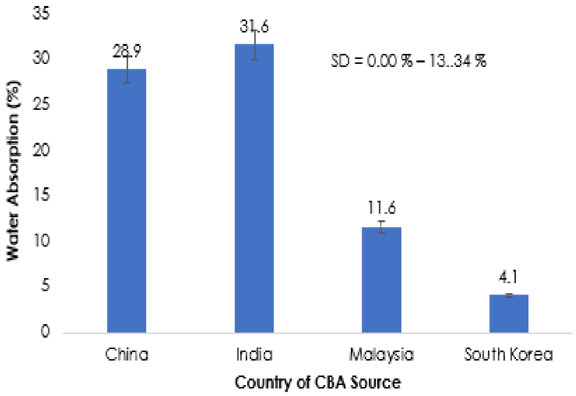


Figure 2 CBA's water absorption by Country

The utilization of CBA possibly conserves the global economy in future construction and may decrease the consumption of natural resources [67]. Mohammed *et al*. [68] reported that using CBA is one of the most efficient techniques for decreasing development expenditures in the construction sector. The researchers discovered that reusing CBA is useful to lessen concerns around its disposal. Goudar *et al*. [69] reported that the primary uses of CBA were in the manufacturing of concrete blocks (52.10%), base layer in the construction of pavements and highways (36.50%), and a smaller percentage of 3.20% as light-weight aggregates (coarse, fine, and filler) in the concrete-making process.

El *et al*. [70] and Al *et al*. [71] also reported that in certain circumstances, such as at a pavement base course, for ice and snow management, and structural fill, this substance (CBA) can be used. Singh [72] examined the effects of substituting CBA for specific sand of different concrete qualities. The study's findings showed how adaptable CBA is for use in production and construction processes. The study also discovered that CBA is also utilized as a coarse material in road construction. Fine aggregates have successfully substituted CBA in the construction of many types of concrete over the last 10 years [56]. Moreover, CBA is utilized in the construction of roads, parks, and jogging trails as surface and base materials for bike pathways [73]. Thus, increasing the utilization of CBA will lower the number of ashes disposed of as wastes that pollute the atmosphere, save costs associated with existing landfills, and enhance the quality of existence.

In the discipline of civil engineering, Kim [67] performed a study of advanced CBA applications and environmental considerations. The results of the review indicated that CBA utilizations may be divided into two categories: simple and advanced. CBA can be used in simple utilizations in place of common building hardware such as gravel, silt, clay, fine sand, and, in some circumstances, cement [67]. Kim and Lee [67], reported that the simple utilizations for CBA include mixed cement, natural materials for clinker, aggregates for cement- and binder-based composites, and geotechnical fillers. The main objective of simple utilization is the use of CBA and the preservation of waste materials.

The advanced utilization of CBA encompasses bacteriological drivers, adsorbents for contaminated trace compounds, sources for non-natural lightweight aggregate making, aggregates for cementitious composites, and geotechnical fill for objectives. Its strong absorption factor and unconventional particle size and shape make CBA a potentially useful material for geotechnical drainage [67].

Several investigations on supplementary substitution waste materials, for example, WCO [27], WEO [74], RHA [75], plastic waste [52], fly Ash (FA) [46], Sawdust Ash (SA) [76], Coconut Shell Ash (CSA) [77], Solid Waste Incineration (SWI) [78], Waste Rubber Tyre (WRT) [79], Glass Fibers (GFs) [80], Groundnut Shell Ash (GSA) [81], cellulose fibers [82], Steel Slag Waste (SSW) [1], and Recycled Rubber (RR) [83], have been utilized to improve the quality of bitumen binders in the pavement construction sectors.

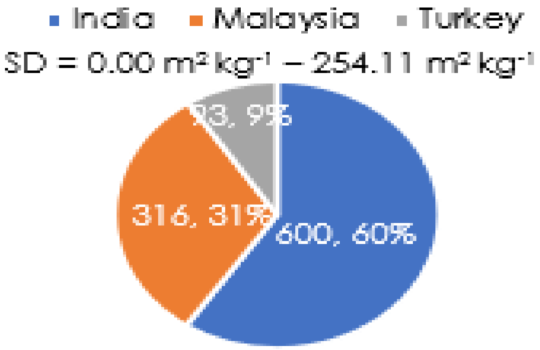


Figure 3 CBA's SSA by Country

The CBA's microstructure can be rejuvenated to a certain degree by supplementary enhancement methods, for instance, milling, sintering, palletization, absorption preservation, and alkaline fusion preservation [56, 84]. According to Consoli *et al.* [85], the unburned CBA percentage's residual angular and sub-angular elements are visible in the standard visual microscopy measurements of the element texture and microscopic morphology, which are opaque (turbid). Figure 6 shows the substance that is incompletely and unburned, as well as the intra-element permeability brought on by element development, which indicates a change from pedospheres to ecospheres [85]. The reduced water-to-cement proportion caused by bottom ash's increased water demand causes the resulting gel substance to have a narrower opening structure [86]. One can find opaque or transparent spherical elements. The elements that are incompletely burnt and break because of internal gas development represent the finer percentage [85].

The main oxides in CBA are silicon oxide (SiO_2), magnesium oxide (MgO), iron oxide (Fe_2O_3), aluminum oxide (Al_2O_3), and calcium oxide (CaO), in ascending order of concentration. According to Ju *et al*. [87], the two principal crystalline types of CBA are silicon inorganic phosphate ($Si3(PO4)_4$) and mullite ($3A1_2O_3 \cdot 2SiO_2$). In addition, CBA is hydrophilic because of its high content of SiO_2 [57] and Si [88]. Potassium oxide (K_2O) has the minimum CBA weight of 2.48 % in the asphaltic mixtures, whereas SiO_2 has the maximum weight of 45.30 %, followed by Fe_2O_3 [89]. Figures 4 and 5 show the main chemical oxides and physical qualities of CBA, respectively. Reviews of the physical and chemical qualities of CBA from the previously published articles are provided in Tables 1 and 2, respectively.

To ensure appropriate performance characteristics over its design lifespan, contemporary durable concrete is being developed using a rejuvenated product, which is a deliberate component of the flourishing construction industry nowadays [73]. Adverse environmental circumstances, like acid and sulphate attacks, can occasionally have an impact on structures built using concrete-incorporated CBA [73]. The way that the use of CBA as a rejuvenator impacts the hardness performance of concrete is something that engineers should be particularly aware of. The durability of concrete that uses CBA as a viable waste material is influenced by the following aspects [73]: (i) resistance to acid, (ii) resistance to sulphate, and (iii) resistance to other toughness characteristics. CBA should therefore be just as resistant to environmental factors and deterioration as state-of-the-art materials.

Table 1 Review of the CBA's chemical qualities from the previously published articles

Reference	**Country of CBA source**	**Weight of CBA (%)**			
		SiO_2	**Al_2O_3**	**Fe_2O_3**	**LOI**
[61]	India	45.40	18.10	19.90	-
[90]	Australia	54.00	25.00	4.00	2.00
[91]	Brazil	57.00	24.00	8.00	5.00
[92]	China	59.90	22.90	7.90	4.00
[93]	Cyprus	55.10	28.10	8.30	3.90
[94]	Europe	64.50	15.90	7.80	11.90
[95]	Hong Kong	52.10	18.30	12.00	4.10
[80, 81]	India	57.80	21.60	8.60	5.80
[98]	Mauritius	-	-	-	11.00
[99]	Niger	62.30	27.20	3.60	-
[100]	South Korea	28.00 – 44.20	31.30 – 31.50	8.30 – 8.90	0.40
[101]	Spain	50.00	27.00	8.30	1.90
[102]	Sri Lanka	44.70	23.80	4.20	15.20
[103]	Thailand	46.00	22.30	10.60	4.00
[104]	Turkey	51.50	18.80	9.60	10.90
[89, 90]	USA	58.70	20.10	6.20	0.80
[107]	-	49.20	16.60	3.53	26.10
[69]	-	79.20	14.80	2.90	1.60
[108]	-	60.30	19.50	11.80	-
[109]	-	66.90	17.70	6.50	2.70
[110]	-	34.40	10.00	18.40	3.50
[111]	-	56.00	26.70	5.80	4.60
[97, 98]	-	45.30	18.10	19.30	0.40
[114]	-	42.60	15.40	17.90	-
[115]	-	38.10	10.90	20.90	19.50
[116]	-	49.40	15.20	7.00	-
[117]	-	44.20	31.50	8.00	-
[118]	-	26.20	15.80	14.20	7.70
[119]	-	36.80	18.30	15.50	2.00
[105, 106]	-	52.60	20.90	9.10	8.60
[107, 108, 109, 110, 111]	Others	40.00 – 55.60	15.00 – 28.80	8.00 – 9.00	1.60 – 8.10

Table 2 Review of the CBA's physical qualities from the previously published articles

Reference	Country of CBA source	Fineness modulus	Water absorption (%)	Specific gravity	SSA (m²/kg)
[67]	-	2.36	5.40	1.87	-
[63]	Turkey	-	-	2.20	93
[57]	India	1.40	31.60	1.40	-
[58]	China	1.80	28.90	2.20	-
[59]	Malaysia	3.40	11.60	1.90	-
[60]	South Korea	5.60	4.10	1.90	-
[61]	India	2.40	8.10	1.90	600
[62]	Malaysia	2.90	1.00	2.60	316
[93]	Cyprus	-	-	1.40	-
[94]	Europe	-	-	2.00	-
[95]	Hong Kong	3.30	11.20	2.20	-
[96]	India	1.60	-	1.90	-
[98]	Mauritius	3.70	26.00	1.80	-
[99]	Niger	2.70	20.20	2.20	-
[103]	Thailand	2.10	6.80	2.10	-
[106]	USA	-	-	2.80	859 - 1102
[69]	India	-	5.50	2.10	-
[109]	-	1.50	6.80	2.10	-
[110]	Indonesia	-	-	2.30	-
[127]	-	1.57	31.50	1.39	-
[86]	-	-	2.77	1.80	-
[128]	-	2.08	5.40	1.94	-
[129]	Malaysia	-	-	2.60	-
[130]	Spain	-	-	-	4050
[131]	Sri Lanka	-	-	2.70	809
[132]	Taiwan	2.60 – 2.80	-	1.80 – 2.40	-
[133]	Turkey	-	-	2.20	93
[134]	-	1.90	-	2.30	1620
[135]	-	-	-	22.40 – 2.50	2235 - 464
[136]	-	-	-	2.40	384
[137]	-	-	-	2.40 – 2.50	384 – 464
[138]	-	-	-	2.40	384
[109, 111, 125, 126]	Others	1.50	6.80	2.10 – 2.50	3463 - 7799

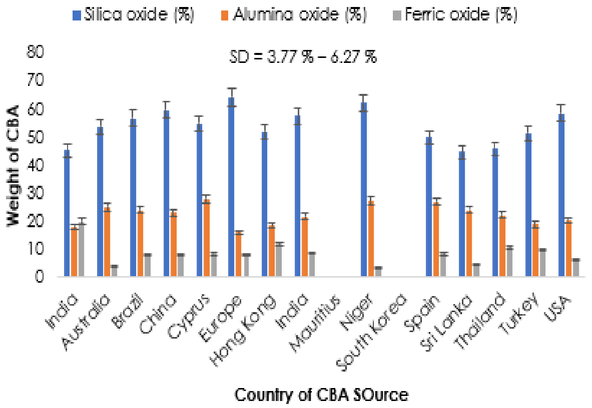


Figure 4 CBA's main chemical oxides (for more information, see Table 1)

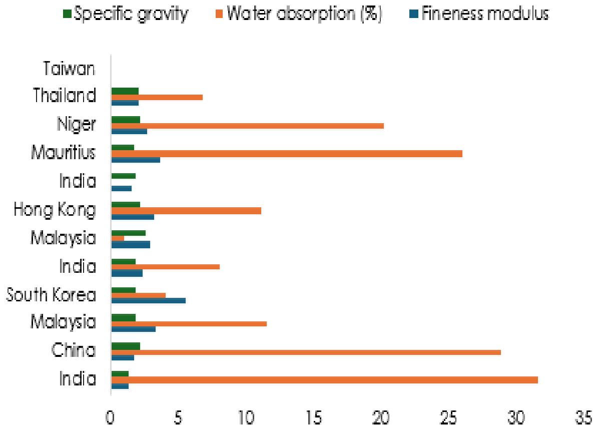


Figure 5 CBA's main physical qualities (for more information, see Table 2)

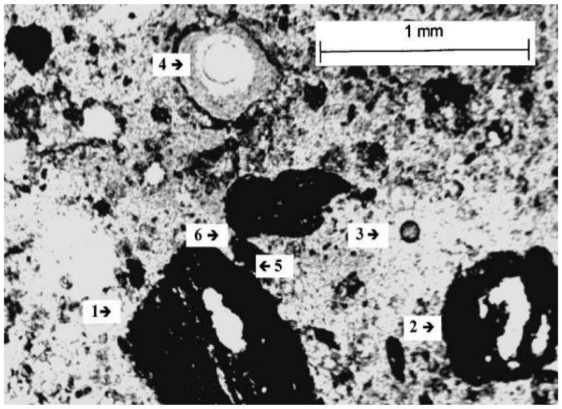
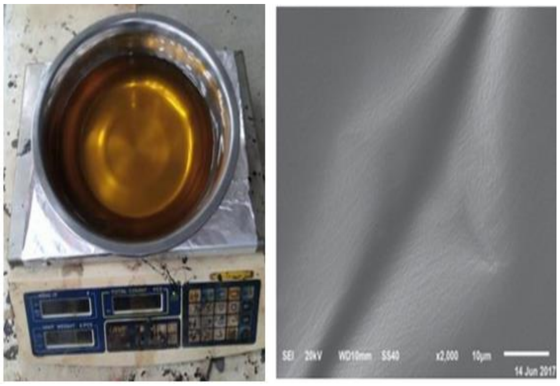


Figure 6 Microscopic morphology of CBA [85]

2.2 Qualities and utilization of WCO

When WCO is used in pavement, asphalt binder performs better at lower temperatures; but, as temperatures increase, this improves less [141]. Yel-shorbag [142] suggested using WCO as a binder modifier to enhance untreated asphalt roads and bring back their original qualities. Zargar *et al.* [143] also stated that a workable remedy for WCO environmental pollution is the incorporation of this substance into asphalt roads. However, despite its wide variety of anticipated environmental and functional benefits, its actual application is still restricted. There are two main categories for WCO-bio-oil waste. Fatty-free acids (FFAs) that are not greater than 15% are categorized as the first class, known as "yellow grease"; and FFAs that are greater than 15% are categorized as the second class, known as "brown grease" [144]. Following an open-air frying method, the oxidation reaction using different techniques modifies the structure of cooking oil [145].

A study conducted by Azahar *et al.* [146] demonstrated how WCO can enhance the bodily qualities of asphalt when blended with bitumen, leading to a significant reduction in fatigue cracking and the development of the binder's mechanical qualities. A study conducted by Yel-shorbag [142] recommended using WCO as a rejuvenator to improve raw pavement and restore its original qualities. Zargar *et al.* [143] also recommended that incorporating WCO into asphalt concrete is a practical way to reduce pollution in the environment. The surface microscopic morphology of WCO with various sizes and with some shapeless particles are displayed in Figure 7(b). The WCO was successfully applied as a modifier for aged binder, and it can be recycled as a cost-effective and environmentally friendly alternative [142].



(a) (b).

Figure 7 (a). Original-WCO; (b). Microscopic structure of WCO [142]

Asli *et al.* [147] and Chang [148] examined the possibility of using WCO as a viable green solvent and a modified asphalt binder, respectively. With an increase in WCO dose, the physical and rheological qualities of aged asphalt pavement may essentially restore it to its state-of-the-art condition, according to researchers' findings.

As Figure 8 illustrates, Chhetri *et al.* [149] discovered the highest value of Oleic acid (52.9 mm) when compared to Foroutan *et al*., [150] (41.04 mm) and Sharma *et al*., [151] (24.69 mm). Similarly, Sharma *et al*., [151] found the highest value of Linoleic acid (40.88 mm) when compared to Foroutan *et al*., [150] (17.98 mm) and Sharma *et al*., [151] (13.50 mm). The above Figure also shows the acid values of the other types of FFAs.

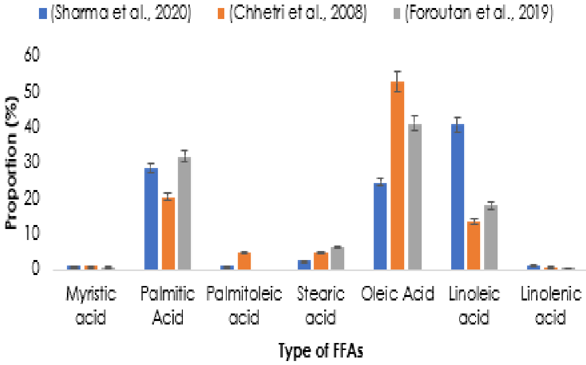


Figure 8 WCO's chemical compositions

The viscosity of WCO at 40 ^{0}C is higher (47.444 mm^2/sec) than at 100 ^{0}C (10.645 mm^2/sec) as shown in Figure 9. This suggested that viscosity increases with decreasing temperature and vice versa. Other physical qualities of WCO are also depicted in the same Figure.

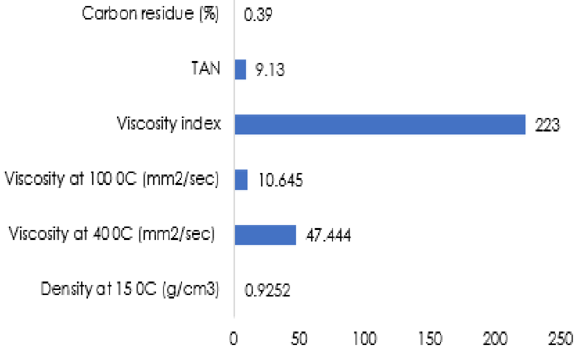


Figure 9 WCO's physical qualities

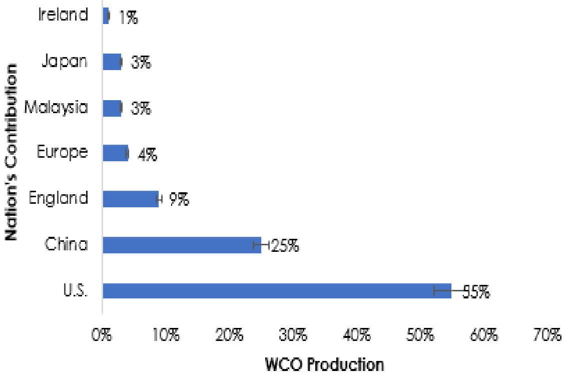


Figure 10 Nations' contribution to WCO annual worldwide production [158]

Asli *et al.* [147] stated that the lower WCO dosage can improve the physical qualities of revived aged bitumen. Sun *et al.* [152] observed distress in the pavement's resistivity as a result of the higher WCO dosage. In aged bitumen, small amounts of WCOs can react and volatilize without stress, and in modified polymer asphalt, polymerization might take place. When fuel asphalt is susceptible to excessive temperatures, WCO-based asphalt can be evaluated more quickly than fuel asphalt [153].

As shown in Figure 10, the US leads the world in WCO production, accounting for 55%, or 10x10^6 tons, of the total annual production [154]. The Republic of Ireland is the lowest producer at 1% of annual global production or 153x10^3 tons [155]. According to Azahar *et al.* [146], only 3% of the world's yearly production of WCO is produced in Malaysia because of the nation's abundance of palm oil disciplines and low-priced conservation. According to some researchers, the world produces roughly 15x10^6 tons of WCO annually [141, 142, 143]. But in the asphalt sector, very little of it has been appropriately collected and repurposed [159].

2.3 Qualities and Utilization of WEO

WEO is among the many categories of waste bio-oil that is frequently utilized to produce sustainable asphalt concrete pavement [142]. WEOs are petroleum byproducts that share many of the same fundamental qualities as bitumen [160]. The advancement of humankind's current standards and the development of automobiles have led to the massive production of WEOs in recent years [160]. The combustion process, which affects the operating temperature and the end pollutants such as rust, metal particles from engine wear, diluents, moisture, detergents, and soot, determines the physical and chemical qualities of WEO. [146, 147, 148]. It was observed by Jahanbakhsh, *et al.* [164] that the moisture susceptibility of mixtures made of Recycled Asphalt Pavement (RAP) increased when blended bitumen binders containing 60% RAP were added with increased WEO content.

Table 3 presents a review of the WEO's fundamental qualities from previous studies. Liu *et al.* [165] reported that the molecular weights of less than 200 grams/mol are the chemical qualities. Low molecular weights have been proposed as the primary components of WEO. A summary of their findings is given in Table 4 and Figure 11, which show that the principal ingredients are paraffin oil, aromatic solvents, and polyolefin oil.

Table 3 WEO's physical qualities review

Quality	**Unit**	**Reference**			
		[166]	[167]	[165]	[168]
Acid value	mg KOH/g	≤ 0.400%	-	-	5.600
Admixture	%	-	0.063	0.362	-
Color	-	Dark brown	-	-	Black
Density	g/cm^3	0.920 @ 25 ^{0}C	-	0.882	-
Flash point	^{0}C	-	214	220	159
Kinematic viscosity	mm^2/s	63.500 @ 60 ^{0}C	41.200 @ 40 ^{0}C	101.52 @ 40 ^{0}C	0.097
Oxidation stability	min	-	35	-	-

Table 4 WEO's chemical qualities [165]

Sample	Duration of Retention (min)	Wt. of Molecular (%)	CAS	Structure	Formula	Alternative Name
W1	4.929	120.192	620-14-4		C_9H_{12}	Benzene, 1-ethyl-3-methyl-
W2	5.329	120.192	108-67-8. 95-63-6		C_9H_{12}	Benzene, 1,3,5-trimethyl-; Benzene, 1,2,4-trimethyl-
W3	5.704	120.192	526-73-8. 108-67-8		C_9H_{12}	Benzene, 1,2,3-trimethyl Benzene, 1,3,5-trimethyl-
W4	6.118	152.233. 134.218	20053-58-1. 933-98-2		$C_{10}H_{16}O$ $C_{10}H_{16}O$	2,3-Epoxycarane, *(E)*-; Benzene, 1-ethyl-2,3-
W5	6.477	152.233. 134.218	20053-58-1. 99-87-6		$C_{10}H_{16}O$ $C_{10}H_{14}$	3-Epoxycarane, *(E)*-; 1-Methyl-4(1-methyl ethyl)
W6	6.932	134.218	95-93-2. 488-23-3		$C_{10}H_{14}$	Benzene, 1,2,4,5-tetramethyl-; Benzene, 1,2,3,4-tetramethyl-
W7	7.346	132.202	2234-20-0. 824-90-8		$C_{10}H_{12}$	2,4-Dimethylstryrene. 1-Phenyl-1-butene
W8	7.796	188.222. 185.222	132316-80-4-. 13131-19-6		$C_{12}H_{12}O_2$ $C_{12}H_{11}NO$	2-Naphthalenol, 1,2-dihydro-; acetate-; N-Methyl-9-aza-tricyclo [6.2.2.0(2,7)] dodec-2,4,6,11-tetraene-10-one-
W9	8.540	146.229	4489-84-3-. 6682-71-9		$C_{11}H_{14}$	Benzene, (3-methyl-2-butenyl)-; 1-H-Indene, 2,3-dihydro-4, 7-dimethyl-
W10	9.140	142.197	90-12-0-. 91-57-6		$C_{11}H_{10}$	Naphthalene, 1-methyl-; Naphthalene, 2-methyl-

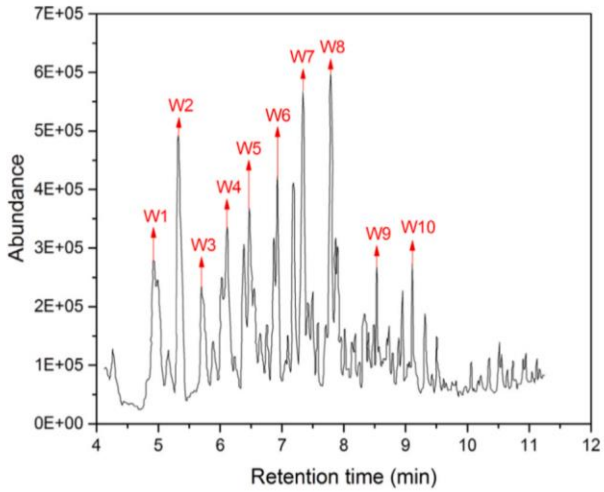
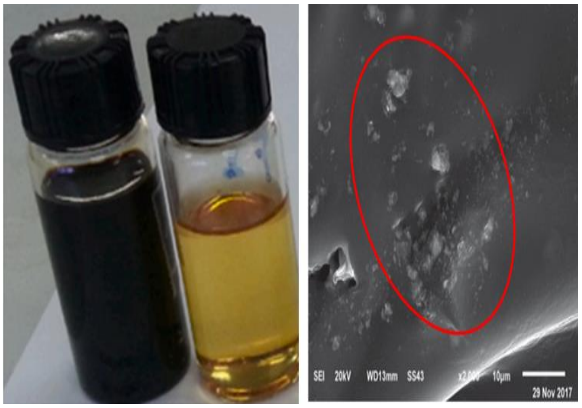


Figure 11 WEO's gas-chromatography mass-spectrometry chromatogram [165]

Additionally, as a common practice, vehicle workshops gather leftover WEO from various cars. These residues frequently contain contaminants during the engine wear, operation, and heating system [143]. High-quality transmission electron microscopic offers detailed data on the microstructure of elementary particles, including elementary particle size distribution, unconventional distance and torsion, and unconventional splitting length [169]. According to Liu *et al.* [170], the aging performance of WEO-modified asphalt depends on the microscopic, rheological, and conventional features. However, for the modified binder with WEO, some residues (Figure 12(c) are still observed proving that materials (WEO) did not appropriately improve the aged binder as needed [142]. This could be a result of the element components found in WEO, as earlier discussed, which raised the concentration of Al_2O_3 and impeded the modification.

Bitumen and WEO molecular structures are similar, suggesting that WEO may be used in asphalt pavement construction to lessen the toughening effect of recycled roadway materials [160]. Thus, if adequately mixed with reclaimed asphalt pavement, small amounts of WEO may help lower the stiffness and improve the toughening of aging bitumen. [142]. However, the use of WEO must be carefully addressed to encourage sustainable development, as it destroys water and land resources [162]. Furthermore, WEO is a material that has the potential to damage the environment if wrongly handled [162]. Its application in asphalt concrete pavement may reduce both the construction expenses and environmental effects [162].



(a). (b).

Figure 12 (a) Original-WEO [171]; (b) Microscopic structure of WEO [142]

The need for inexpensive and ecological waste management has increased demand, which has led to an increase in the focus on reprocessing wastewater effluent [74]. The inclusion of WEO improved the negligible temperature cracking resistance [74]. Shoukat and Yoo [172] showed that WEO improves asphalt's resilience to thermal cracking. Al-Saffar, *et al*. [173] found that WEO decreased the rutting behavior. This is because, especially at higher temperatures, the aggregate bitumen has a weaker adhesive and cohesive bond. However, it was also observed that this material (WEO) had an undesired influence on the aggregate-bitumen bond, indicating the use of antistripping agents. Al-Saffar [173] evaluated the rheological and chemical qualities of four distinct asphalt binders utilizing WEO and maltene (MLT) rejuvenators. The results of the Fourier transform infrared spectra of the four distinct types of asphalt binders, as performed by the researcher, are shown in Figure 13.

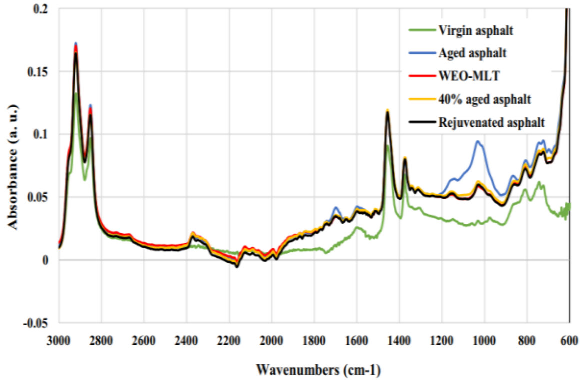
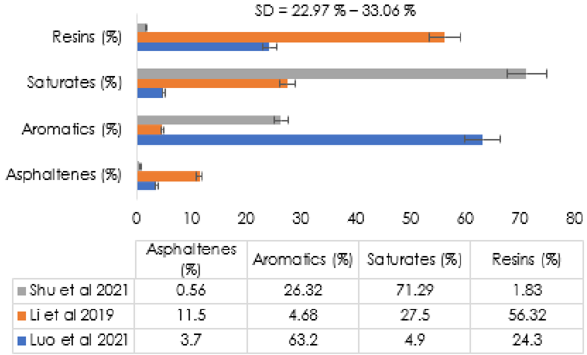


Figure 13 WEO's infrared analysis [173]

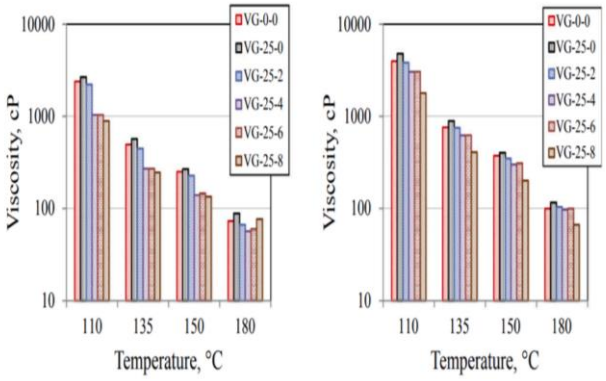
According to Jwaida *et al*. [162], the metal content of WEO ranges from 3.9% to 5.7% as ash, which needs years of wear and tear from machinery to be recognized naturally. The sources and experimental procedures have an impact on the different qualities of the WEOs. These qualities include asphaltenes, aromatics, saturates, and resins [162]. Furthermore, earlier researchers discovered the qualities of WEO's maximum contents. As illustrated in Figure 14, Luo *et al*. [166], Li *et al*. [174], and Shu *et al*. [175] have reported the maximum contents of aromatics, resins, and saturates at 63.2%; 56.32%; and 71.29%, respectively. The qualities of the resins may affect the WEO stability and modified asphalt binders [162].



	Asphaltenes (%)	Aromatics (%)	Saturates (%)	Resins (%)
Shu et al 2021	0.56	26.32	71.29	1.83
Li et al 2019	11.5	4.68	27.5	56.32
Luo et al 2021	3.7	63.2	4.9	24.3

Figure 14 Qualities of WEO

The viscoelastic qualities of aged and virgin binders improved with WEO at various temperatures and were examined by Qurashi and Swamy [176]. Figure 15 illustrates the results, which showed that the viscosity decreased as the temperature increased. When compared to binders with a virgin binder, the binder improved with WEO and exhibited lower viscosity below a particular temperature. Furthermore, at all temperatures, the modified-WEO binders showed larger phase angles but negligible softening points and complex modulus. Substantially, it was found that a WEO content range of 2% to 4% produced the best results [176]. Using WEO as a partial substitution in the asphalt binder system can successfully minimize the increased stiffness caused by Using aged asphalt binders [162]. This type of substitution, even in part, will contribute to ecologically friendly construction practices, resource conservation, energy savings, and higher recyclable dosage [162].



(a). (b).

Figure 15 Temperature's effect on blend viscosity with varying WEO contents for (a). unaged mixtures; (b). short-term aged mixtures [176]

Furthermore, Liu *et al.* [165] assessed WEO's impact on the improved asphalt. Nine slices were grouped from the chromatographic profiles of the used asphalt specimens. As shown in Figure 16, the slices with labels ranging from 1 to 4 were determined to be “large molecular size”, the slices with labels ranging from 5 to 7 to be “medium molecular size”, and the slices with labels ranging from 8 to 9 to be “small molecular size” [165]. The researchers also found that adding 4% and 8% WEO, respectively, increased the asphalt specimens' high-temperature classification from 5 to 9.

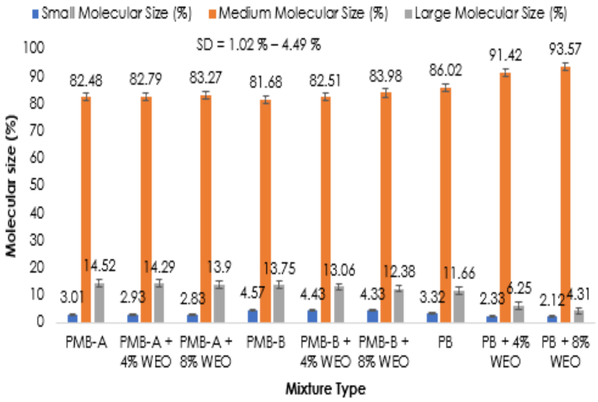


Figure 16 WEO asphalt mixture’s molecular sizes

2.4 Qualities and utilization of RHA

To improve the compressive and flexural strengths of cement-mortar specimens, RHA can be used as a cement additive. It has been demonstrated that the RHA alternate, which accounts for 10% of binder weight, has the most positive effect on cement resistance [177]. The husk is reclaimed as petroleum to make steam [178, 179]. But, because of its high silica contents, RHA is utilized as a partial substitute in bituminous concrete [179].

According to Carmago-Perez [180], the Agriculture and Food Organization of the United Nations states that rice husk is a byproduct of the agro-industrial development technique of rice, which plays a major part in the rudimentary food basket. RHA is an extensive, yearly global production [178]. Depending on the technologies available, both controlled and uncontrolled burning procedures can yield RHA [181]. According to Khassaf [178], the global production of rice paddy is approximately 500x10^6 tons annually. If RHA is disposed of in a landfill, it may cause ecological problems that contaminate the air and water [178]. The notable mass of 22% of the pulverized paddy is produced as husk because nearly 78% of the mass is produced as rice, bran, and broken grains [161, 163,]. The husk is reused as fuel to produce steam [161, 163]. About 75% of the husk's bulk is made up of unstable carbon-based compounds, with the remaining 25% being made up of inorganic minerals [161, 163]. In addition, 25% of this husk's mass gets burned and converted into ash [161, 163].

The physical qualities of RHA affect the durability and mechanical qualities of concrete, such as mean particle size, SSA, specific gravity, and fineness modulus. These qualities may affect how RHA is utilized for physical concrete. With a density of roughly 180 - 200 kg/m^3, RHA is discovered to be very porous and light in weight [182]. Table 5 presents the RHA’s physical qualities. Generally, about 85% of RHA is made up of amorphous SiO_2 (Table 6). Trace amounts of CaO are present in RHA along with other chemical oxides [182]. Furthermore, the loss of RHA's ignition is mostly caused by the processes used to process, burn, and grind RHA [182]. According to Antiochus *et al.* [183] and Djamaluddin *et al.* [184], RHA's amorphous nature is very beneficial for giving concrete extraordinary strength.

Table 5 RHA’s physical qualities

Quality	**Unit**	**Reference**		
		Safiuddin [185]	**Habeeb** [186]	**Ganesan** [187]
Grinding time	mm	-	90 180	-
Mean particle size	(µm)	6	63.80 31.30	3.80
SSA	m^2/g	2.33	- -	36.47
Specific gravity	g/cm^3	2.10	- 2.11	2.06
Fineness modulus (passing 45 µm)	%	-	- -	99

Table 6 Review of the RHA's chemical oxides from the previous studies

No.	Reference	Chemical oxide (%)						
		CaO	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**Na_2O**	**K_2O**
1	[181]	1.13	86.29	0.57	0.57	0.62	0.12	2.30
2	[187]	0.48	87.32	0.22	0.28	0.28	1.02	3.14
3	[188]	1.84	86.68	1.66	1.06	0.98	-	0.42
4	[189]	0.97	89.74	1.29	0.97	-	-	0.19
5	[190]	0.74	88.59	0.31	0.29	0.66	0.26	2.46
6	[191]	1.04	87.80	0.12	-	0.81	1.15	2.61
7	[192]	0.60	87.00	0.80	1.20	0.40	2.63	3.70
8	[193]	0.58	96.23	0.28	1.36	0.27	0.05	0.45
9	[194]	1.50	93.10	0.30	0.20	0.60	0.06	2.30
10	[195]	2.42	81.40	0.26	0.93	1.02	0.18	6.79
11	[196]	0.73	87.89	93.20	0.28	0.47	0.66	3.43
12	[197]	0.90	82.6	0.40	0.50	-	0.10	1.80
13	[198]	0.76	93.44	0.21	0.18	0.43	0.05	1.98
14	[199]	1.04	86.81	0.50	0.87	0.85	0.69	3.61
15	[200]	2.88	77.19	6.19	3.65	1.45	0.00	1.81
16	[201]	1.10	93.20	0.40	0.10	0.10	0.10	1.30
17	[202]	0.41	91.15	0.41	0.21	0.45	0.05	6.25
18	[203]	0.97	92.00	0.31	0.38	0.47	0.20	0.20
19	[204]	0.41	91.15	0.41	0.21	0.45	0.05	6.25
20	[205]	1.96	87.10	0.13	0.28	0.77	0.03	1.87
21	[206]	1.27	90.21	2.12	0.80	0.67	0.14	0.76
22	[207]	1.03	91.42	0.14	0.20	0.82	1.12	2.59
23	[208]	1.07	91.56	0.19	0.17	0.65	0.16	3.76
24	[209]	0.39	86.73	0.04	0.61	0.08	9.76	0.01
25	[210]	0.49	94.10	0.03	0.04	0.27	0.05	1.79
26	[211]	0.41	91.15	0.41	0.21	0.45	0.05	6.25
27	[212]	0.69	83.05	1.80	0.58	3.59	0.13	5.65
28	[213]	1.03	87.55	0.39	0.20	0.67	0.05	2.85
29	[214]	2.42	81.40	0.26	0.93	1.02	0.18	6.79
30	[215]	0.55	87.20	0.15	0.16	0.35	1.12	3.60
31	[216]	0.39	94.38	0.27	0.10	0.48	0.21	1.60
32	[217]	0.90	87.40	0.40	0.30	0.60	0.04	3.39
33	[218]	1.12	86.02	0.36	0.16	0.39	1.15	-
34	[219]	0.87	90.75	0.75	0.28	0.63	0.02	3.77
35	[220]	1.25	90.89	0.93	0.47	0.81	-	2.34
36	[221]	1.49	89.59	-	0.75	-	-	7.05
37	[222]	-	94.40	0.20	0.20	-	-	-
38	[223]	0.99	78.21	4.43	-	4.89	-	-
39	[224]	1.27	90.21	2.12	0.80	0.67	0.14	0.76
40	[225]	1.27	89.90	0.46	0.47	0.79	-	4.50

Several published studies have reported that one of the main contributing factors to RHA's durability is its high silica content [187, 208, 209, 210, 211]. Silica is an excellent material for utilization in construction and other industries where durability is essential since it is robust and resilient to corrosive and chemical attacks. The ideal RHA percentage for robust concrete is found to be between 15% and 20% of cement substitution. Some of the qualities of concrete incorporated RHA are provided in Table 7. By measuring the amount that harmful compounds can permeate the pavement's structural layers, capillary water absorption gives information on how durable concrete materials are [230]. According to Alaneme [231], Yuzer *et al.* [232], and Hwang [233], the maximum concentrations of amorphous silica with the largest potential SSA of 150 m^2/gram of RHA elements are generated by total burning temperatures between 500 ^{0}C and 700 ^{0}C as indicated in Table 8.

Table 7 Review of the RHA's durability qualities

No.	Reference	Quality	Unit	RHA Substitution (%)				
				0	5	10	15	20
1	[187]	Sorptivity ($x10^{-6}$)	$m/s^{1/2}$	11.05	10.60	9.16	7.37	6.00
2	[234]	Coefficient of carbonation	$cm/day^{1/2}$	0.15	0.14	0.13	0.09	0.07
3	[235]	Chloride diffusivity	coulombs	1161	1108	653	309	265
	[228]			1486	439	389	306	877
	[236]			2830	1970	980	1173	-
4	[236]	Porosity	%	11.00	-	10.00	9.00	11.50
	[236]			12.40	10.80	10.00	11.10	-
	[237]			-	11.30	11.30	13.40	-
5	[237]	Slump flow	mm	789	721	715	703	-
	[228]			740	700	670	610	580
	[185]			690	700	710	720	710
6	[196]	Water absorption	%	4.50	4.50	4.10	3.90	3.90
	[237]			-	4.70	4.90	6.10	-
	[187]			4.71	4.83	5.02	5.58	5.81
7	[235]	Water absorption Coefficient (x 10^{-10})	m^2/s	3.56	6.76	1.03	1.06	1.21
	[187]			1.62	1.42	1.03	0.99	0.92

Table 8 Influences of burning temperature on the RHA structure and its SSA [214, 215]

SSA (m^2/g)	Burning Temperature (^0C)	Structure
0.50 - 2.10	Up to 500	Elements are permeable like spheres.
76 - 122	500 - 600	Fine porous granules and partial crystallinity characterize the elements.
100 - 150	600 - 700	The amorphous elements have the largest pore diameter.
6 - 10	700 - 800	Coral-shaped crystals partly form moderately crystalline particles.
<5	800 - 900	Crystalline

Significantly, RHA is utilized as a partial substitute in asphalt concrete because of its high silica concentration [179]. Typically, it is made up of Fe_2O_3, SiO_2, and Al_2O_3, with trace amounts of CaO and MgO [161, 163]. The temperature at which rice husk burns and the length of time it takes to burn define the chemical composition of RHA [161, 163]. The pozzolanic quality of RHA is good due to its high content of SiO_2, Al_2O_3, and Fe_2O_3 [178]. The distribution particle size and appearance of RHA are depicted in Figures 17 and 18, respectively. The microstructural morphology of the final stage of RHA elements was detected by Ma *et al.* [229]. The researchers found that the RHA particles' uneven geometrical shape is visible when seen under a scanning electron microscope. In addition, the shear strength characteristics and the microstructural morphology employing energy diffusive spectrometry and scanning electron microscopic (Figure 19) show that RHA modification is a potential substitute for silica in the advancement of an automatically energetic and highly dependable pelletize multiple solder technique that will be used as interrelate products in reasonable temperature soldering activities [238]. The RHA modification has the strongest shear strength (14.60 MPa) when compared to pelletize multiple solder techniques, demonstrating its reinforcement influence [238]. In several cases, adding more RHA content did not improve the microstructural morphology or resilient of the concrete [229].

The RHA's chemical qualities are displayed in Figure 20. Ma *et al.* [229] discovered that the principal RHA's chemical quality is SiO_2, of which 83.93% is accounted for.

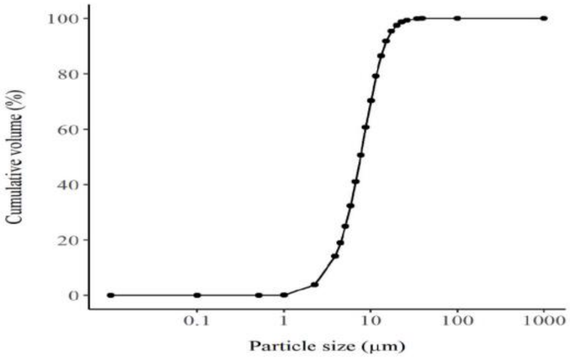


Figure 17 RHA's particle size distribution curve [229]

(a). (b).

Figure 18 RHA's appearance: (a). initial stage; (b) final stage [229]

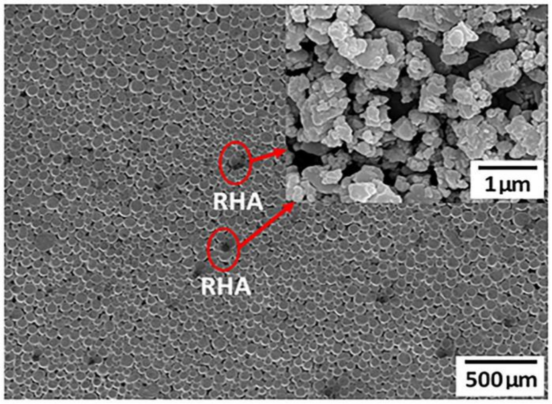


Figure 19 Microstructural morphology of RHA elements (inset) and pelletized multiple solder system [238]

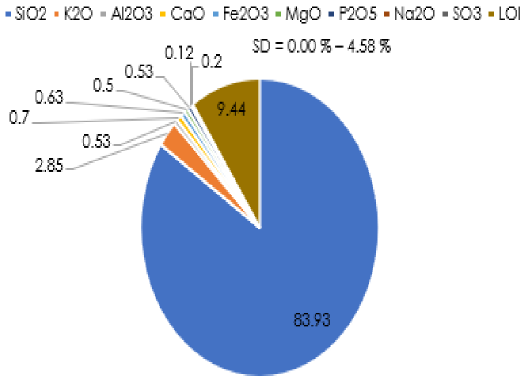


Figure 20 RHA's chemical qualities

3.0 APPLICATION OF WMA TECHNOLOGIES

WMA technology can be used to eliminate the environmental issues related to high production and compaction temperatures when using RAP [24, 220]. To reduce the mixing and compaction temperatures of asphalt pavements, several WMA technologies use foamed asphalt binders or warm mix additives [24, 220]. Therefore, using a WMA mixture is a useful method of integrating waste materials into asphalt pavement, producing, more often than not, a surface that is prospective for sustainable asphalt construction [24]. Because of its advantages in both the economy and the environment, WMA technology is seen as a viable and justified method of constructing pavements [41].

Compared to conventional HMA, WMA refers to the technique that can reduce the manufacturing temperature of asphalt mixes [240]. The consensus is that WMA technologies can lower the WMA production temperature between 35 ^{0}C and 55 ^{0}C (63 ^{0}F to 95 ^{0}F) compared to conventional HMA concrete, while the precise amount of decreased temperature varies from one introduction to the other [240]. Lower production temperatures result in lower power usage and a decrease in the amount of greenhouse gases and other harmful substances released into the atmosphere [241].

Zhao *et al*. [242] found that when WMA mixtures are made with less aging limitation than HMA mixtures, they have less resistance to rutting. Behnood [8] revealed that by controlling the different qualities of the WMA mixes and binders, the WMA production technique lowers the production and compaction temperatures. Depending on the time and temperature, the renewal of the binder qualities in a WMA mix, such as viscosity, can be either temporary or permanent[224, 225, 226].

The WMA technologies primarily decrease the binders' viscosity during the production and compaction of asphalt mixes [227, 228]. These technologies can also have various effects on the rheological qualities of binders and the physical and durability qualities of WMA mixtures [8, 229]. Substantially, WMA technology can generally be divided into three categories (Figure 21): (i) chemical technologies for example; zycotherm, evotherm, rediset, iterlow, etc.; (ii) organic technologies for example; sasobit, licomont 100, asphaltan B, etc.; and (iii) foaming technologies for example; water-bearing process and water-based process [227, 228]. Among these categories of WMA technologies, chemical technologies typically don't have a huge impact on the rheological qualities of binders [227, 228].

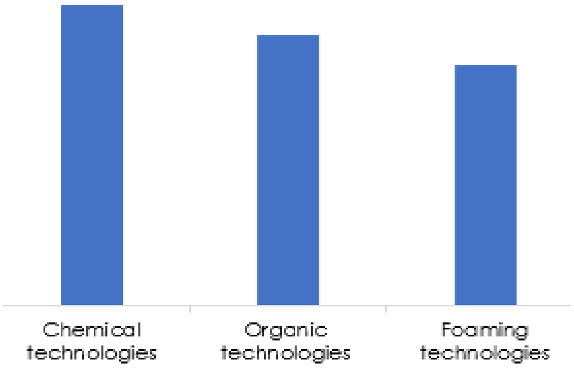


Figure 21 Categories of WMA technology

In addition, over the last ten years, the global community economy's rapid development has been greatly aided by the pavement substructure [249]. Modern theories, methods, techniques, abilities, and materials relevant to roadway engineering are evolving [249]. Many WMA technologies enable the construction of ecologically friendly pavement while also enabling reduced heat-engrossing and enhanced anti/de-icing features. These technologies also guarantee porous, self-luminous, noise-reduction, and exhaust-disintegrating qualities [250].

Sustainable asphalt pavements promise significant reductions in power and natural resource consumption as well as a decrease in harmful vapor emissions during pavement construction, which will affect the financial sector and ecosystem [232, 233].

Cheraghian et al [253] revealed that about 39% of asphalt mixtures were prepared as WMA mixtures, which reduce air voids, improve compaction efforts, and use less energy at lower temperatures. Studies that have been published on the use of industrial byproducts in asphalt pavements have reported that WMA mixture enhances pavement performance while reducing construction costs [235, 236]. Unfortunately, some drivers cause several distresses on the asphalt pavement as seen in Figure 22.

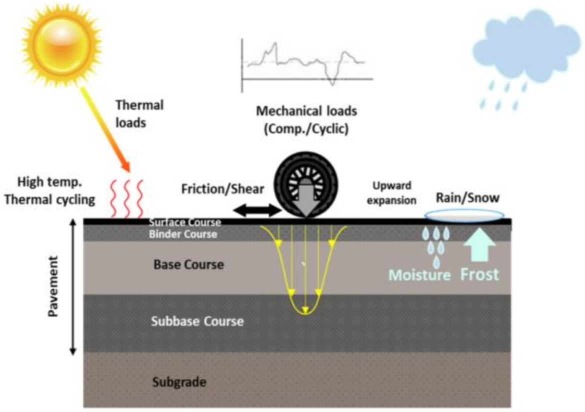


Figure 22 Some drivers responsible for asphalt pavement distress [256]

4.0 POTENTIAL BENEFITS AND DRAWBACKS OF WMA TECHNOLOGIES

According to Ali & Abdul [41], the decreased output temperature provides less WMA aging, increasing the lifespan of the asphalt road. Petrol savings and the WMA's reduced output temperature are directly correlated. The savings might be attributed to WMA technology, the petrol type, and the expense of petrol [257]. The decrease in Greenhouse Gas (GHG) production is another key benefit of utilizing WMA technology. The decrease in GHG production by WMA technology happens in two steps. The first step comprises a decrease in GHG production due to the consumption of less petrol. The decrease in GHG production resulting from heated asphalt mixtures the second step [246].

Using WMA technology has several functional, economic, and environmental benefits [258]. The key to the profitability of WMA technologies is the type of skill, which can be influenced by additional elements such as the characteristics of supplementary contents in WMA mixtures and the performance of warm mix compounds [8, 259]. In terms of environmental benefits, WMA technologies perform better than traditional HMA in terms of lower output, compaction temperatures, and energy usage [239, 258, 259]. Anti-stripping additives can be employed as a substitute to lessen moisture experience; though, this procedure could raise construction expenses and discourage the utilization of WMA [260].

Doyle & Howard, [261] stated that two of WMA technology's drawbacks are the superior vulnerability to moisture and the premature rutting of the asphalt road surface. Also, WMA can have two price-associated drawbacks [262]. The initial drawback is that the WMA blend was made early and needs several supplementary equipment. The utilization of warm mix compounds, which enhances production effectiveness and might be slightly offset by lower energy utilization, is the second drawback. As for the functional drawbacks, some WMAs have been discovered to demonstrate coating problems and unfortunate resistance to the vulnerability of moisture than HMAs [263, 264, 265]. One of the primary elements propagating these problems is the WMA blend's lower maximum binder content than the HMA blend's [8]. Additionally, variability of asphalt road distresses such as raveling, bleeding, and rutting may influence the WMA because of its reduced oxidative aging and air-void content, still, these qualities may benefit the WMA blends to recover their resilience [8].

5.0 PERFORMANCE CHARACTERISTICS OF WMA-INCORPORATED WASTE MATERIALS

Performance characteristics include Marshall stability and flow, Marshall density, Marshall air void, indirect tensile strength, tensile strength ratio, resilient modulus, and dynamic creep. Also, conventional characteristics such as storage stability, softening point, penetration, ductility, elastic recovery, flash point, fire point, and dynamic shear rheometer play vital roles in the performance characteristics of WMA-incorporated waste materials. The viable bituminous pavements promise an extensive decrease in the ingesting of natural products, and energy ingesting, and a decrease in contaminated particles during asphalt road construction, thereby producing an effect on the environment and monetary sector [251, 252].

The utilization of WMA is a beneficial instrument for integrating waste materials in bituminous pavement determining mostly, a pavement surface that has promise with the target of viable pavement construction [24]. According to previous investigations, waste materials can be reused into sustainable waste for asphalt pavements [2, 3, 4]. Investigators from all over the globe have focused on the problem, cost, and inactive pace of various remediation methods, as well as the potential utilization of waste materials in the pavement construction sector [7].

The WCO-integrated asphalt mixture also showed skilled performance in temperature cracking than the standard specimen that fulfilled creep standards and, to some point, less than the tensile strength [266]. However, the utilization of WCO in bitumen mixture has exhibited room for modification in terms of the softening point, penetration, and viscosity assessments [47]. A high penetration is possible when the WCO has a minimum viscosity value. Moreover, in some examples, the penetration has been as superior as a standard binder [24, 38] with superb fatigue resistance in the subsequent asphalt blend [146]. Zargar *et al* [143] stated that 4% WCO integrated into aged asphalt of grade 40/50 was capable of getting comparable viscosity value with a standard binder.

The incorporation of WEO enhanced the insignificant resistance to temperature cracking [74]. According to Shoukat and Yoo [172], WEO improves the resistance to thermal cracking of bitumen binders. Al-Saffar, *et al*. [173] found that WEO decreased the rutting performance; this is because of the decreased adhesive and cohesive bonding of the aggregate–binder, specifically at higher temperatures. The investigation was performed to assess the potential of WEO as a rejuvenator and suggested that this substance be used to restore the conventional characteristics of aged asphalt; however, it was also observed that this substance had an objectionable effect on the aggregate–binder bonding, representing the use of antistripping managers [268]. Yel-Shorbag [142] stated that the incorporation of WEO into aging asphalt, the creep stiffness, and the content of rejuvenated asphalt have fulfilled the super-pave requirements, which demonstrates that WEO improved the insignificant temperature thermal cracking of aging asphalt with a gradation of PG 64/28. Several characteristics of WEO are subject to the burning progression, output and compaction temperatures, and bases of toxins for example dilutants, corrosion, dust, moisture, cleaning products, and steam engine wear metallic particles [142].

6.0 ENVIRONMENTAL EFFECTS OF WASTE MATERIALS

Two of the most major problems facing people are universal warming and environmental problems [41]. Suspicions regarding climate variation and the application of non-renewable and renewable sources are influential problems that show the necessity for modern variation that will encourage society towards a competent environmental expectation for everyone [269]. Since cement producers use and produce a variety of emissions that are excessive in carbon discharges, they damage the natural environment [46]. These have various influences on the natural environment, for instance, climate variation and universal warming [270]. As can be seen, coal releases more CO_2 than other wastes. Consequently, coal is an environmentally benign source that is viable. There is a grave consequence to the natural environment and public health associated with the vulnerable dumping of CBA from a range of enterprises and thermal power installations [41, 271].

When utilizing RAP, the WMA technologies can be used to lessen the ecological problems related to high output and compaction temperatures [24, 239]. Compounds or foamed technologies are employed in numerous WMA technologies to reduce the mixing and compaction temperatures of asphalt pavements, which destroy the natural environment [24, 239]. The waste disposal problems and benefits of utilizing these substances in the pavement construction sector are shown in Figure 23.

(a). Disposal issues of waste materials

(b). Benefits of using waste materials

Figure 23 Disposal and benefits of waste materials [42]

According to Al *et al*., [71], the public disposal of CBA from different sectors and thermal energy stations has resulted in considerable ecological pollution and a host of health problems. Furthermore, the way the elements of CBA waste are disposed of may lead to surface or groundwater contaminations, threatening life as we know it (Figure 24) [71]. Spills are still a possibility, which might pollute surrounding areas because of the open disposal of CBA [272]. CBA causes contaminated substantial metals to dissolve and seep into the ground as leachate [71]. This could be the source of groundwater contamination.

Figure 24 Effects of coal wastes on the environment [273]

7.0 BIBLIOMETRIC ANALYSIS

The Scopus database was used since it is a major, well-known, and globally recognized peer-reviewed database [274]. Titles and abstracts were searched using the following keywords: "Waste Materials" OR "Asphalt Mixtures" OR "Asphalt Pavements" OR "Asphalt Binders" OR "Warm Mix Asphalt Technologies" OR "Warm Mix Additives". The analysis from the Scopus database found 3,914 published documents between 2009 and 2023. Only 32 of these documents were published by Scopus. The analysis also found that 89.4% (29 documents) of Scopus publications were technical articles and only 10.6% (3 documents) were review articles as shown in Figure 25. Furthermore, between 2009 and 2012, just 10% of all documents worldwide were published in Scopus journals. Surprisingly, 90% and 80%, respectively, of all documents worldwide between 2012 and 2016 and between 2019 and 2023 were published in Scopus journals.

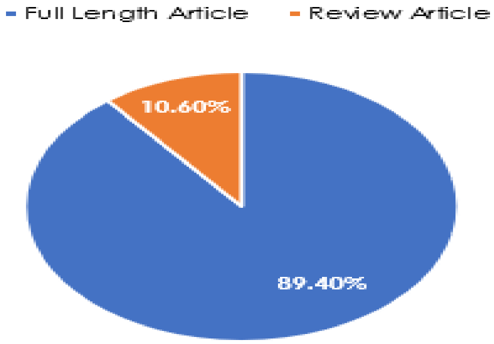


Figure 25 Scopus articles published by type

Figures 26 and 27 depict the correlation between co-occurring keywords and the relationship between authors, respectively. It was observed that both statistics showed a strong relationship. Figure 28 illustrates that one document was published in 2009, 2011, and 2013. However, no document was published in 2010 and 2012. Two and three documents were published in 2014 and 2015, respectively. Scopus published a maximum of 40.63% (thirteen documents) in 2016. Still, the number of publications decreased in 2023. Although the analysis was done in December 2023 there may have been an increase in Scopus publications in 2024.

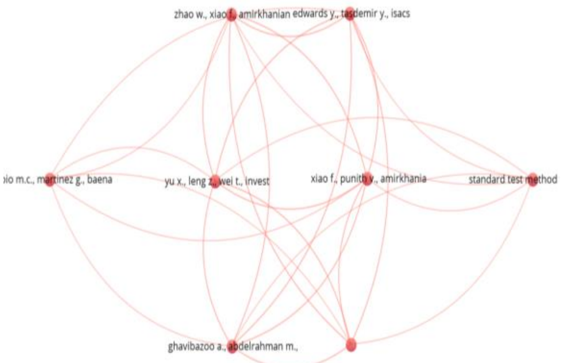


Figure 26 Relationship between authors from 2009 until 2023

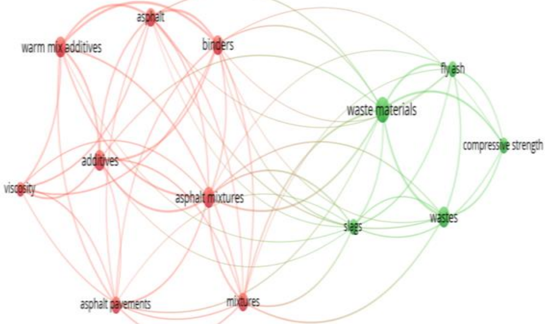


Figure 27 Correlation between co-occurring keywords from 2009 to 2023

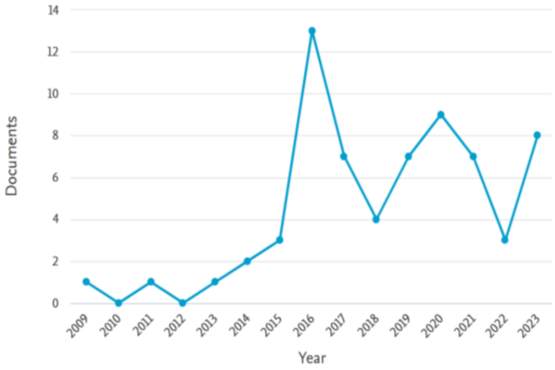


Figure 28 Scopus annual publication

Different nations also made significant contributions to Scopus' publication as shown in Figure 29. Out of all the nations that contributed to Scopus publications, the United Kingdom contributed 50% (sixteen documents), Italy contributed 25% (eight publications), China contributed 22% (seven publications), and Denmark contributed 19% (six documents). Moreover, Australia, France, and Hong Kong contributed 13% each (four publications), Malaysia, the Netherlands, and the United States contributed 16% each (five publications), and Hong

Kong, Australia, and the United States contributed 13% each (four publications). This indicated that the United Kingdom contributed the highest number of Scopus publications between 2009 and 2023.

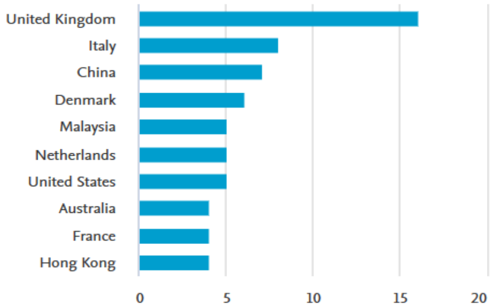


Figure 29 Nations' contribution to Scopus publication

Based on the contribution of subject areas (Figure 30), engineering, materials science, environmental sciences, and other subjects have contributed 37%, 29%, 19%, and 15% of all Scopus publications, according to an analysis of the Scopus database. This showed that engineering, materials science, environmental sciences, and other subjects had published 12, 9, 6, and 5 publications (32 documents as reported earlier), respectively. Figures 31 and 32 provide the overviews of all the Scopus researchers together with their citations and year of publication.

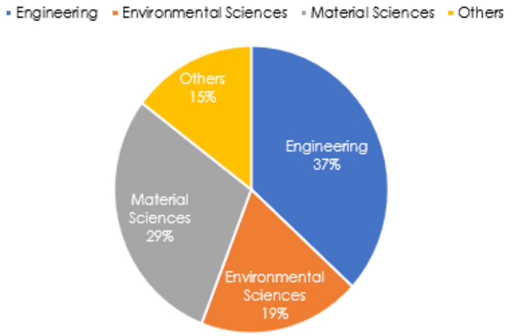


Figure 30 Contribution of subject areas to Scopus publication

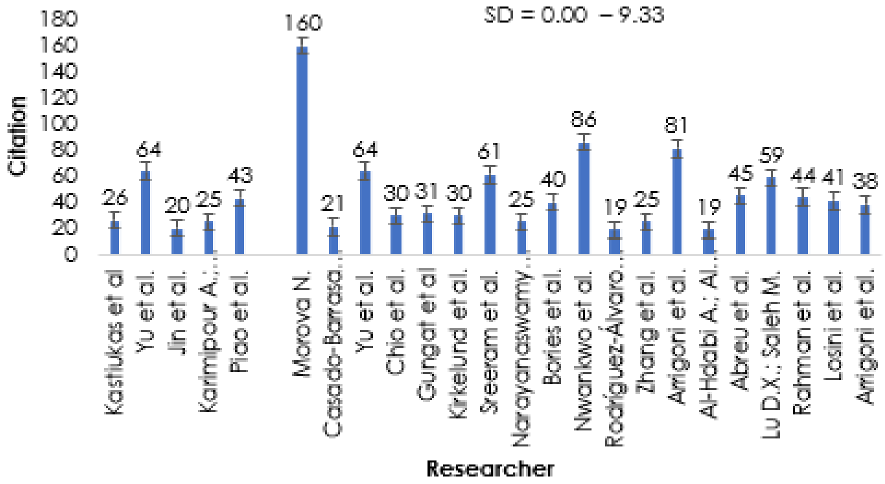


Figure 31 An overview of Scopus researchers with

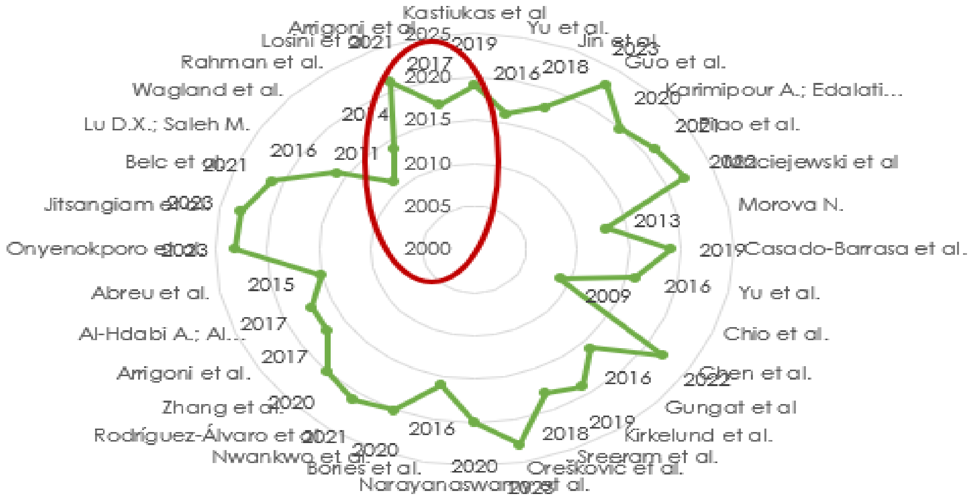


Figure 32 An overview of Scopus researchers together with their publication year

8.0 FUTURE DIRECTION

The study's extensive review led to the identification of the following research gaps:

- Many scholars have conducted in-depth investigations on waste materials. Unfortunately, most investigations focus only on the performance of HMA concrete. Therefore, further studies on the utilization of different wastes require stern consideration.
- There is insufficient evaluation of the optimization of the several physical and chemical processes used to treat waste materials, such as grinding, the use of superplasticizers, the addition of cementitious materials, etc.
- Because there is no control over the waste's content and quality, several studies using the same replacement ratio revealed significantly varying performance levels. There is a need for additional studies to confirm their real-world scenario.
- There are limited studies on WMA technology available on the Scopus database. Three categories of WMA technologies (chemical, organic, and foaming) require detailed exploration.
- Since there hasn't been may research done on the effects of incorporating waste materials into WMA mixture on the environment, careful consideration is needed.
- To guarantee that wastes are improved as sustainable materials in the construction sector, a cost-benefit analysis of these wastes should be carried out.
- This study reported an extensive review of different qualities and utilization of four types of waste materials (CBA, WCO, WEO, and RHA). Thus, immediate attention is needed to ensure the long-term performance of the WMA mixture with the appropriate contents of waste materials.

9.0 CONCLUSION

This study reported different qualities and utilization of waste materials in WMA concrete. The utilization of waste materials can save a substantial quantity of waste products and pave the way to acceptable advancement by converting waste into wealth and pollution into solutions. Waste materials under investigation enhanced the different qualities of asphalt mixtures. It is a helpful technology to add these wastes to asphalt mixtures, which typically results in durable concrete that can be used to construct sustainable roads. It has been demonstrated that waste materials can improve the durability and strength of WMA concrete. WMA concrete made from waste materials has contributed to a reduction in carbon emissions, which in turn has helped to reduce global warming. As a result, the economy, environment, and construction sector all benefit in various ways from these wastes. The WMA mixtures are less resistant to rutting when made with less aging limitation compared to HMA mixtures. WMA technology lowers the production and compaction temperatures by controlling the different qualities of the asphalt binders and WMA mixtures. It also decreases the viscosity of the asphalt binders mainly to produce and compact asphalt concrete. Hence, it can be categorized into three groups: foaming organic, and chemical technologies. The disciplines of engineering, materials science, environmental sciences, and others have contributed 37% (12 publications), 29% (9 publications), 19% (6 publications), and 15% (5 publications), respectively. The United Kingdom made a significant contribution

(50%) compared to all the nations that contributed to Scopus publication. The analysis from the Scopus database discovered 3,914 published documents between 2009 and 2023. Only 32 of these documents were published by Scopus. Furthermore, the analysis also found that 89.4% (29 publications) were technical articles and only 10.6% (3 publications) were review articles. The rheological and microscopic properties of the four wastes require additional review.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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