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Utilization of Palm Oil Mill Residue as Sustainable Pavement Materials: A Review

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Abstract: The advances in industrial technology have led to a major rise in the amount and forms of residue, especially during the processing of agricultural products. With the paradigm shift towards renewable energy and sustainability, there is much emphasis on biomass energy around the world which generates an immense volume of residues yearly. These residues are burgeoning issues because they are not effectively managed and utilized. Hence, one solution is utilizing them in the pavement industry. This article focuses on palm oil mill residues that are abundantly available and discarded in Malaysia. This study evaluates published works of literature relating to the utilization of these residues like the Palm Oil Fiber (POF), Palm Oil Fuel Ash (POFA), and Palm Oil Clinker (POC) and Palm Kernel Shell (PKS) in the pavement industry. The outcome of the review acknowledges the greater sustainability potential of these residues with affirmative and satisfactory performance via the result of numerous research work. Also, with a reduction in CO_2-emission, low radioactivity, and heavy metal leaching level. Therefore, the review suggests more exploration and utilization of the residue in the pavement industry since it promotes safety and harness sustainability.

Keywords: Pavement industry, palm oil mill residues, CO_2-emission, sustainability, heavy metal leaching level

1. Introduction

Recently, with the paradigm shift towards renewable energy and sustainability, a more significant deal of emphasis is put on biomass from agricultural residue around the world. Also, to mitigate unsuitable residue management, while at the same time exploring eco-friendly low-cost resources as substitutes to the exploitation of natural materials [1], [2]. Rapid population growth and industrialization have emanated to the accumulation of substantial volumes of residue materials, the majority from activities from the agricultural, industrial, quarry, and domestic [3]. The rapid growth in the populace combined with the rise in consumption rate impending into a desperate state of residue management as a landfill is the primary form of disposal. As the accessible land to be utilized as landfill is becoming scarce, unlawful disposal or incineration solutions are introduced given the predominance of eco-friendly materials from the residue composition [4], [5]. The amount of residue, especially agro-waste, is increasing at an exponential rate annually around the globe [3], hence devising a way to reuse or reduce them is of utmost importance. Fig. 1 indicates generated residue

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after processing biomass; Malaysia has a high oil palm shell which is used as biomass fuel to produce palm kernel shell ash (PKSA), POFA, and POC and theses residues are underutilized.

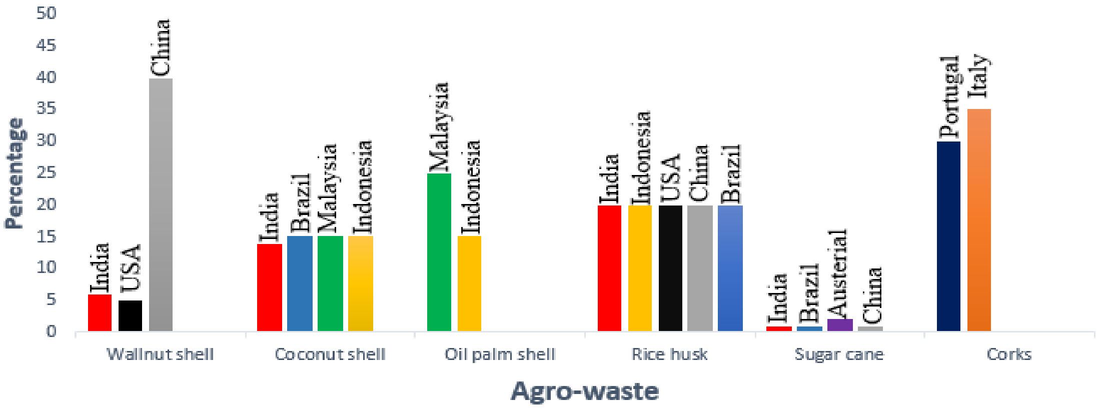

Fig. 1 - Annual agro-residue balance for some selected countries [6]

Consequently, if this massive amount of residue produced is not adequately utilized or recycled, it would constitute ecological risks and alter the ecosystem's balance. In tackling this menace, there is essential to resolve the current issue without jeopardizing the right of future generations to available resources [7], [8]. To foster a balanced environment, waste reduction, recycling, and reuse (3R's) strategy has been widely accepted around the world [5], [9], [10]. By this approach, local agriculture can be processed and implemented effectively to be used as a modifier or as a substitute for natural resources as the aims of Malaysia's national Green policy promote a sustainable economy while at the same time sustaining the climate [11]-[13]. Using residue as a substitute construction material production is becoming increasingly demanding in the academic world. As a major manufacturer of oil palm in the world, a large percentage is produced in Malaysia [14], which has more than 442 mills for fresh fruit bunch (FFB) processing as of October 2015, as stated by the Malaysian Palm Oil Board (MPOB), that generates around 82.74 million tons of FFB [15]. Additionally, mass processing of oil palm related products produces an almost equal amount of biomass residue that must be treated properly. Fig. 2 displays how the procedure of producing biomass residue in the oil mill.

Fig. 2 - Schematic diagram of producing biomass residue in the palm oil mill

In the palm oil mill, the pyrolysis of PKS and POF at an elevated temperature of about 850°C inside the boiler generates POC and POFA [15]. The quantity of POFA and POC generated per annum is about 4 million tons as unwanted residue [16]. The pyrolysis practice includes mixing POF and PKS to produce electricity at an average ratio of 30:70, respectively [17]. This process of pyrolysis ended up creating POC a porous, bulky solid which are dumped near the palm oil mills. POFA is the major ash by-product material produced in the mill [18], [19]. The quantity of this residual waste is growing, as the production of palm oil in Malaysia also increases [20]; the POFA production is over 10 million tons/year [21], [22]. POFA is an environmentally friendly and geopolymer material [23], [24]. In current practice, this residue is usually neglected on landfill that causes contamination of the environment [25], [26] and has now become an environmental problem [27]. These residues are just deposited in Malaysia's landfills with minimal utilization in other industries or completely harnessing their usability [28]. POFA and POC are one of Malaysia's most crucial biomass residues that can be used in the construction industry [25].

2. Properties of the Palm Oil Mill Residues

2.1 Physical properties of POF, POCP, and POFA

Physical properties of the residue material help identify the practicability of utilizing it because the physical properties of biomass residue can be very complicated. In Table 1, the physical properties of the palm oil residue were presented. It was observed that the palm oil waste has less specific gravity compared to Ordinary Portland cement (OPC) same as the particle's sizes were within the limits of the standard of pozzolan materials. Also, the particle size distribution is presented in Fig. 3 of some palm oil residue material compared to (OPC), which characterize the ability to be used as an alternative material. The Palm oil clinker powder (POCP)'s physical appearance, and chemical properties largely rely on the boiler's heating temperature [36]. Fig. 4 presents the process of generating various sizes of POC using mechanical milling for various periods.

Table 1 - Physical properties of palm oil residues compared to OPC

Physical property parameters	POF [29], [38], [30]	POFA [33], [34], [32]	POCP [30], [35], [31]	OPC
Specific gravity	< 1	1.81-2.60	2.53	3.14
Density (g/cm³)	0.7-1.55	-	-	13.62
Retained on 45 μm	-	11.62	29.0	-
Diameter μm	150 -500	-	-	-
Tensile Strength Mpa	50-400	-	-	-
Median Particle size μm	-	17.62	37.97	22.47
Colour	Light yellow	Dark grey	Blackish	Grey

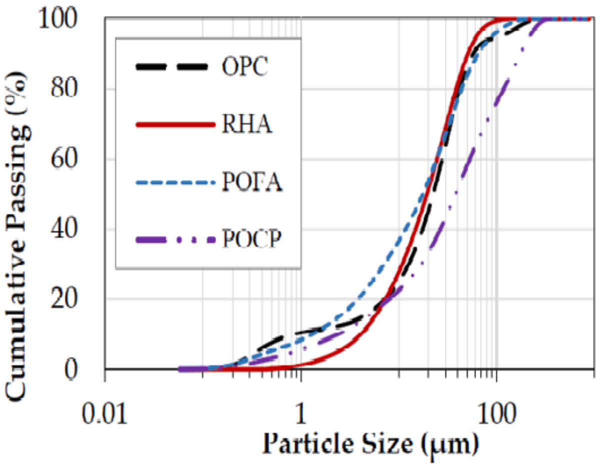

Fig. 3 - Pozzolans particle size distribution [37]

Fig. 4 - Various sizes of POC after milling

2.2 Chemical composition of POFA, PKSA, and POC

The chemical properties and constituent have a significant influence on the performance of the residue material. Waste with high silica content shows they can be used as a replacement for cement, as they have a portion of pozzolan which forms a secondary C-S-H gel when it reacts with the calcium hydroxide. PKSA, another POFA type, is a residue from the pyrolysis of PKS at 600 and 1000C [39]. Comparative studies on POFA and PKSA [18], [21], [40], [41] indicated that they both have a large silica and alumina content, making them a strong pozzolanic material. POFA, PKSA, and POC's chemical composition are indicated in Table 2 from studies based on variations. The sum of SiO_3 + Al_2O_3 + FE_2O_3 which determines the pozzolanic properties of a material for the palm oil mill waste are in accordance with ASTM C618 [50] specification; therefore, the palm oil waste be graded as pozzolan between classes C and F. The composition of chemicals depends on the types of species of palm oil tree, pyrolysis temperature [42], the percentage of PKS, POF, and grinding time [42], [43], and the type of soil where palm trees are planted [44].

The lower calcium content relative to OPC will help avoid thermal cracking. The largest volume of ash materials used in the pavement industry is extracted from well-designed incinerators [51] or treatment and milling of the waste materials.

Table 2 - The chemical compositions (weight %) of POFA, PKSA, POCP, and OPC

Chemical Composition	POFA			PKSA			POCP			OPC
	[45]	[46]	[23]	[18]	[47]	[48]	[42]	[49]	[23]	
SiO_3	59.62	53.50	64.20	57.10	34.72	54.80	74.29	59.90	64.20	21.00
Al_2O_3	2.54	1.90	3.70	4.56	3.48	11.40	3.11	3.89	3.70	5.90
Fe_2O_3	5.02	1.10	6.30	3.30	1.82	0.36	2.09	6.93	6.30	3.40
$SiO_3 + Al_2O_3 + Fe_2O_3$	**67.18**	**56.5**	**74.2**	**64.96**	**40.02**	**68.29**	**79.49**	**70.72**	**74.20**	**30.30**
K_2O	7.52	6.48	3.50	8.27	2.10	6.52	6.22	5.82	5.18	0.5
M_gO	4.52	4.10	4.58	4.23	1.48	6.11	1.72	3.30	4.80	2.50
P_2O_5	3.58	-	-	-	-	0.25	2.79	3.47	-	0.28
Na_2O	0.76	-	-	-	0.52	-	< 0.1	-	0.18	0.75
SO_3	1.28	-	0.87	-	-	1.14	0.15	0.39	0.72	2.40
CaO	4.92	8.30	5.80	6.55	8.76	-	5.10	6.37	5.80	64.70

3. Various Utilization of Palm Oil Mill Residue in the Pavement Industry

3.1 POFA and PKSA as Subgrade, Base, and Sub-Base Soil Treatment and Stabilization

Pavement structure both bounded and unbounded layer durability and performance are based not only on effective mix design but rather also on the subgrade mechanical performances**.** Thus, Soil stabilization helps to improve the bearing capacity and engineering properties of weak soil before laying the pavement. Hence residue materials are used as a stabilizer to improve soft soil properties and strength by chemical additive incorporation or mechanical compaction [1], [3]. However, due to the detrimental impact of conventional stabilizers like lime and OPC and the release of large quantities of CO2 into the environment. Thus, researchers have embarked on the feasibility of utilizing this residue from agro-biomass as soil modifiers [3]. Researchers such as Rahmat et al. [52], Pourakbar et al. [53] and Fauzi et al. [55] examine the potential of incorporating POFA as a renewable additive material as a substantial supplement of conventional lime and OPC. They observed its effect for each increase in POFA content through chemical composition, compaction properties, California bearing ratio (CBR), Optimum moisture content (OMC), Maximum dry density (MDD), unconfined compressive strength (UCS), and plasticity index (PI) for curing time of 28 days. Also, according to Pourakbar et al. [53] indicated POFA feasibility to enhance both the physical and chemical properties of subgrade soils because of its amorphous nature and silica content.

The feasibility of utilizing PKS-cement and PKSA as a mixture to improve soil engineering properties was investigated by researchers such as Nnochiri et al. [39], found that the addition of 4% PKSA+ 6% lime, the addition of 4% PKSA + 4% lime, and the addition of 4% PKSA + 6% lime raised the OMC, UCS, and CER by 8.20% while reducing the MDD about 10%. Also, Onyelowe et al. [47], Ekeocha & Agwuncha [57]. Their analysis indicates that PI increased to 19.1% with the addition of 25 % PKS to the natural soil and then decreased to 17.7% with 4 % asphalt stabilization. The incorporation of 4 % asphalt increased maximum Dry Density (MDD) and Optimum Moisture Content (OMC) to 75% laterite and 25% PKS to 1560 kg m^{-3} and 23.0%, respectively, with a decrease in average CBR to 1.15 % (unsoaked) and 0.55% (soaked). Generally, the outcome of their investigation indicates a decrease in the PI and MDD, with improved CBR, and UCS. Similar research was done by [58], [59] also observed increases in the engineering performance properties of the PKSA modified soil. Because of the high quantity of silica in POFA, calcium silicate hydrates (CSH), and calcium alumina hydrates (CAH) are created in the hydration reaction process [40], [54]. This reaction is responsible for the enhancement of the engineering properties of the soil over time. Table 3 highlights the performance of agro-biomass residue as a subgrade soil stabilizer.

Generally, from the literature, the application of POFA and PKSA as stabilizer dramatically enhances the mechanical properties and plasticity of the subgrade soil [3]. However, to use more residue from biomass as soil stabilizer or as pavement construction interlayer material, other conventional stabilizers need to be integrated. The results of the research show the feasibility and effectiveness, of using biomass residue from palm mill as a substitute for cement as a soil stabilizer, for sustainable road construction which complies with the standard.

3.2. POF as Bitumen and Asphalt Concrete Modifier

Nowadays, a lot of research has shown keen interest in utilizing natural residue fibers to improve the engineering properties of the mixture like Kenaf fiber [60], POF is also one of these natural fibers. The fiber is not only limited to use in concrete as it has been utilized by few kinds of research such as Aziz et al. [61] to evaluate the viscoelastic behavior of both pen 60/70 and 80/100 bitumen. The POF was blended by the weight of asphalt binder, in 0.2 to 1.0 percent. The rheological test indicates that asphalt bitumen modified by the POF shows a high ability to withstand fatigue and rutting deformation than the control sample [62]. It has also been investigated from other studies that the rheological properties of the PG 58 can be combined by the use of natural palm fibers extracted from date tree or o palm oil EFB [63]-[65]. Using 0.375 percent content of fiber by the total mixture weight for date palm fiber it has enhanced the mixture to PG 76 while for the POF; 0.3 percent dosage of fiber-enhanced the blend to PG 70. Also, Tayh et al. [66] utilizes POF at (0.15 to 0.75 %) with an increase of 0.15 and carbon fiber (0.75 to 2.75) with 0.5 increase by weight of asphalt to investigate the rheological and physical properties of various bitumen grades (PEN 60/70, 80/100 and PG-76 grade) improvement by the two types of fibers. The findings showed an enhancement of the modified bitumen's physical performance in terms of reducing penetration values, as well as an improvement in softening point and viscosity values.

Table 3 - Effect of POFA and PKSA as a stabilizer on engineering properties of soil

Material	Ref.	Type of soil	Properties of waste stabilized soil				
			OMC	MDD	CBR	UCS	PI
PKSA	[47]	Clay	Increased	Reduced	Improved	Improved	Increased
POFA+OPC	[52]	Laterite	-	-	-	Improved	-
POFA	[55]	Clay	Increased	Reduced	Improved	-	-
POFA+OPC	[53]	Clay	Reduced	Improved	Improved	-	Reduced
PKSA+ Asphalt	[57]	Laterite	Increased	Reduced	Improved	Improved	Reduced
PKSA +Lime	[39]	Laterite	Increased	Reduced	Improved	Improved	Reduced

As the resistance of the mixture to damage from moisture and severe rutting may affect the longevity of the asphalt pavement. Using unmodified or weak bitumen [67], high bitumen performance cannot be achieved adequately, bitumen age during transportation and laying as well as drain-down. Some stone mastic asphalt mixture, therefore, utilizes fiber as additives in the mixture with bitumen to maintain its uniformity [68]. The cellulose POF is utilizing as a bitumen modifier to enhance flexible pavement performance. By incorporating cellulose POF to the conventional asphalt enhanced asphalt bitumen recovery capability. Fauzi et al. [69] utilizes the high tensile resistance cellulose fiber to resolve major SMA problem. Marshall Stability, and Cantabro Loss and resilient modulus are among the studies concerned. Results indicate that cellulose fiber improved asphalt binder recovery capability. Adding 0.2% cellulose fiber from each experiment leads to the lowest abrasion value, while 0.3 % provides the best resilient module. Therefore, cellulose fiber incorporation is capable of improving SMA's properties. Syammaun & Rani [30] investigated a study to test the porous asphalt resilient modulus using POF, the weight of bitumen used five different amounts of fiber (1 to 5 %) laboratory tests were investigated out to relate and measure the OPF-modified porous asphalt mechanical performance. The results have shown enhanced rheological characteristics and can improve asphalt grade depending on the type of base asphalt [30].

3.3 POFA as Bitumen and Asphalt Concrete Modifier

Modification is a process that can be utilized to enhance the mechanical performance of asphalt pavement [70]. Usually, anti-stripping agents are integrated during bitumen processing to avoid moisture damage from asphalt concrete. OPC and hydrated lime, are the most widely used anti-stripping additives. However, the cost of hydrated lime and OPC is reasonably high as compared to residue materials like POFA. Previous studies have revealed that bitumen modified with POFA offers greater resistance to mineral aggregate coating and failure due to adhesion compared to conventional ones. This also reduces mixing temperature [71]-[73] that is prone to bitumen, rutting, fatigue, and thermal cracking. Researches on the performance of POFA in bitumen and asphalt concrete can be found in table 4. The modification method of using POFA involves two types the dry method and the wet method. The dry method involves using a modifier (waste) as a filler substitute added to aggregate (by weight of the mixture) before mixing with bitumen. Like research conducted by Borhan et al. [74] he examines the mechanical performance of POFA as a filler with several percentages of (0, 1, 3, 5, and 7 %). The study shows that resilient modulus and Marshall Stability were typically higher than typical mixture values. The mix's elastic modulus and strength were also enhanced; this is due to POFA's pozzolanic cementing ability. Similarly, the mixture fatigue life was substantially improved compared to the conventional. Also, Rusbintardjo et al. [73] published similar findings, as POFA is utilized as a bitumen modifier.

Results indicate that the performance of the mix is enhanced regardless of the POFA addition approach utilized. In related research by Ahmad et al. [75] POFA was utilized as filler in asphaltic concrete, where POFA passing 75μm by (0,3,5,7, and 10 % of mixture) was incorporated into the asphalt concrete. The outcome of the Marshall Tests demonstrated that the incorporation of POFA increases asphalt mixture stability and resilient modulus at certain dosage. Although at the optimum resilient modulus was achieved as 3%. Hence the findings further indicate that for asphalt mixture mineral filler POFA can be utilized. Likewise, Maleka et al. [72] used indirect tensile and Marshall to evaluate the performance of asphalt mixtures modified by POFA. It was observed that as compared to conventional samples, the modified asphalt concrete show enhanced flow and stability values. Also, with 5% POFA filler improved indirect tensile strength (ITS) was recorded POFA, suggesting that asphalt concrete is more resistant to fatigue, rutting, and moisture sensitivity than the conventional mixtures [72].

The wet method usually involves blending the modifier (waste) by a certain percentage of the weight of the asphalt bitumen using a mixer before mixing it with the aggregate. Rusbintardjo et al. [73] evaluated the physicochemical and rheological behaviour of POFA modified to determine its feasibility as a modifier. He suggested that POFA could change bitumen grade to a stiffer type and also the POFA quantity to be incorporated into bitumen should be between ranges of 5-7% by bitumen weight. Rheological studies indicate that 5% POFA with fine size can withstand rutting at 70°C, 20°C fatigue cracking, and thermal cracking at -15°C, as well as the findings of boiling water, static immersion tests, and drain-down test. Finally, its implementation in SMA-14 shows improve values of Marshall Stability. The research concluded that the use of POFA as a bitumen additive is feasible.

Similarly, Hainin et al. [76] researched POFA's effect on enhancing bitumen aging resistance because bitumen aging affects the structural network of bitumen, thus reduces the modifiers and influences the bitumen properties [77]. The research reported incorporating POFA decreases binders' temperature sensitivity as its effect improves bitumen's rutting resistance, as tests reveal that bitumen modified with POFA has a greater coating with aggregate and adhesive failure resistance than unmodified bitumen. On the dissimilar, the analysis by Akbar [78] considered POFA ineffective in the modification of bitumen. It is because adding POFA by 5% to PEN 40-50 bitumen makes the modified bitumen more rigid by increasing the value of penetration and not improving softening temperature. Also, the results of short- and long-term aging indicated that the modified bitumen is vulnerable to aging. Furthermore, the influence of POFA's fineness, on bitumen performance was investigated by Zulkefli et al. [79] and the findings revealed that POFA's fineness significantly affects bitumen properties with decrease penetration and increase softening temperature value than conventional bitumen and 7% fine size POFA modified bitumen provides better performance. The overview performances of POFA as a modifier in both bitumen and asphalt concrete is presented in Table 4, which has been explained in the sub-topics.

Table 4 - Shows review research on the utilization of POFA as a modifier

Modifier Performances effect on	Wet Modification (Blend with bitumen)				Dry Modification (Blend with the aggregates)				
	*[73][a]	*[76][b]	*[79][c]	*[81][d]	**[82][e]	**[80][f]	**[75][g]	**[74][h]	**[72][i]
Softening point	↑	↑	↓	NE	-	-	-	-	-
Penetration	↓	↓	↓	NE	-	-	-	-	-
Viscosity	↑	↓	-	-	-	-	-	-	-
$G^*/\sin\delta$	↑	-	-	-	-	-	-	-	-
$G^* \sin\delta$	↑	-	-	-	-	-	-		-
Penetration index	↑	↑	↑	↑	-	-	-	-	-
Temperature susceptibility	↑	↑	- -	- -	-	-	-	-	-
Marshall stability	↑	-	-	-	↓	↑	↑	↑	↑
Flow	-	-	-	-	↓	↑	↑	↑	↑
Stiffness	-	-	-	-	-	↑		-	↑
Moisture damage	-	-	-	-	↑	-	-	-	-
Cantabro Test	-	-	-	-	-	↑		-	-
Rutting	-	-	-	-	↑	-	-	↑	-
Resilient modulus	-	-	-	-	↑	-	- ↑	↑	-
ITS	-	-	-	-	-	↑	-	-	↑

*****To investigate by weight of bitumen performance of POFA modifier bitumen at

a Different percent and size by sizes using DSR; **b** Different aging time.

c Different micro sizes of POFA.

d Different grinding time on physical properties

******Evaluate the performance of POFA modified asphaltic concrete at different percentages of asphalt mix. [e, f, g, h, and I]

↑ ↓

= Increase =Decrease and NE =No effect

Maleka et al. [80] investigated the performance of dense-graded asphaltic concrete modified with POFA using Cantabro test using 1% OPC with 5 % POFA as filler. The findings show that the values of flow, stiffness Marshall Stability, stiffness, and Cantabro loss indicate overall enhancement. Sukaimi studied the impact of POFA grinding time and varying percentage of POFA on changed bitumen physical properties [81]. Field Emission Scanning Electron Microscope (FESEM) was also used to examine microstructural characteristics of POFA. Similarly, Marshall and indirect tensile tests were utilized to check the POFA modified bitumen performance. From the analysis, the percentage of POFA and period of grinding do not affect the bitumen's physical properties. While Maleka et al. [72] assesses the influence of POFA as a filler on the AC 14 wearing course. The findings indicate that the values of flow, Stability, stiffness, and indirect tensile strength of modified POFA mixture generally are enhanced in comparison with the unmodified. While using POFA for warm mix asphalt modification, Abdulrahman et al. [82] investigates the WMA performance of bitumen modified with POFA. He incorporated 0.75 % Evotherm and 5% POFA and blended with PEN 60/70 bitumen. Findings of the bitumen test indicate values of penetration and ductility were decreased substantially; however, the viscosity increased by 40%. The test from asphalt pavement analyzer test and dynamic creep indicate that WMA POFA mixtures have enhanced resistance to rutting by 30% compared to traditional HMA. Generally, from the works of literature, the penetration grade of bitumen for HMA is the PEN 80/100 which when POFA was added stiffen the bitumen to PEN 60/70 only Abdulrahman et al. [82] utilizes POFA on WMA and PEN 60/70 was used, the results show a decrease in penetration valued by 55% and for the bitumen. Also, the palm oil clinker fine powder found was also utilized as bitumen modifier and positive results were obtained for the Marshall mixes [83]. The overall summary of Table 4 is that when POFA is blended with bitumen it tends to enhance its physical properties by decreasing penetration (stiffen the bitumen) and improving the softening point, penetration index and rheological properties of the bitumen while when it used as additives (blend with the aggregates) it's generally improves the Marshall properties and mechanical performances properties of the mixture. From, the researched findings indicate the compatibility of using POFA and the experimental value conforms to the Department of Public Works and Asphalt Concrete Mix Specification. This indicates its feasibility to be used as a modifier on a larger scale to produce asphaltic concrete.

3.4. POC and PKS as Aggregate replacement.

With much pressure on natural resources like aggregate, a major by-product discarded in Malaysia from the palm oil mills is POC and PKS which be utilized a substitute for aggregate material in concrete [42], [49], [84], [85] and for cement substitute by [36], [86], [87], the results of the studies have shown concrete properties enhancement. In highway pavement, there are limited studies on the use of POC as aggregate replacements, and the studies are presented in Table 5. POC is ideal in the concrete mixture to replace standard gravel aggregate also to match pavement design [88]. Babalghaith et al. [89] investigated the impact of POC as a fine aggregate substitute on stone mastic asphalt (SMA) mixture properties. Resilient modulus, drain-down, and the indirect tensile strength performance of the SMA asphalt concrete were improved as the fracture life was also improved by 3.4 times with 100% replacement.

Table 5 - Studies on the use of POC and PKS as aggregate in pavement industries

Material	% Replacement and Type of mix	Marshall stability	Flow	Resilient Modulus	Fatigue Test
POC [89]	SMA (100 %)	Enhanced	Improved	Enhanced	Enhanced
PKS [90]	HMA (10-70%)	Decreased	Improved	-	-
PKS [91]	HMA (10-100)	Decreased	Improved	-	-

Thus, the use of POC as a substitute for aggregates in both concrete and SMA mixture suggests its strong prospect for commercialization in the asphalt industry. Another aggregate substitute is the PKS Ndoke [90] and Samuel [91] considered the capacity using PKS as coarse aggregates replacement in HMA with an emphasis on asphalt concrete strength. The study recommended that PKS up to 10 % should be used for replacement for heavily trafficked roads. In comparison, 100 % replacement in rural settings is possible for lightly trafficked roads even though all the Marshall stability was reduced and flow increase but still the values are within the standard specification.

4. Reduction of Carbon Footprint

The use of palm oil residue can help in mitigating of carbon-footprint, which had become a significant issue with the use of conventional materials. A study conducted by Kanadasan & Razak [92] stated that POC samples collected in Malaysia have a carbon emission of 9.6 percent lower on average than in the conventional mix [92]. A similar investigation by Islam et al. [93] and Alnahhal et al. [94] to examined CO_2 (CO_2-e) emissions of agricultural residue that around 52-61% of CO_2-e reduction by substituting cement with industrial POFA by-product. Furthermore, the substitution of granite in concrete by PKS lowered CO_2-e by 42-52 percent relative to concrete granite [86]. McLellan et al. [95] observed similar research result that geo-polymer like POFA and POCP technology in concrete would minimize 44-64% of CO_2-e [94]. By using these industrial by-products in concrete, more than 50 percent of CO_2-e can be reduced [37]. Table 6 indicates that the CO_2-e emission of palm oil residue material compared to conventional OPC is much lower. Note, the total CO_2-e was estimated by taking into account the resources used in the treatment and recycling process and the transport of materials within 100 km [87]. The total CO_2-e was estimated, taking into account the resources used in the treatment and recycling process and the transport of materials within 100 km [87].

Table 6 - CO_2 emission factor (kg CO_2 / kg of material)

Materials	POFA	PKSA	POCP	OPC
References	[87], [88]	[87], [86]	[87], [88]	[87]
CO_2 emission factor	0.1102	0.1102	0.1292	0.820

5. Safety in Terms of Radiological Activity and Heavy Metals Leaching Assessment

The possible radiological health risks assessment of using palm oil residue as construction material should also be investigated. Recently study conducted by Karim et al. [96] in the research, numerous radiological parameters and indices such as equivalent to radium activity, absorbed dose rate, and annual effective dose, etc. were estimated for possible radiological hazard assessments. Radioactivity level for POC, POFA, and other construction materials is shown in Table 7. The concentration activity level indicated POC and POFA are non-hazardous and can be used in the construction industry since the activity levels for radiological hazards were significantly lower compared to other construction materials from corresponding literature [96]-[98].

Table 7 - Radiological risk assessment for POC and POFA compared to other construction materials

Material	Ref.	Mean concentration activity (Bq kg^{-1})		Equivalent radium activity (Bq kg^{-1})
		^{226}Ra	^{232}Th	
POC	[96]	**6.40**	**4.50**	**57.74**
POFA	[96]	**8.10**	**7.02**	**52.49**
Coal fire ash	[97]	67.6	74.3	225.3
OPC	[98]	34.7	32.9	96.2
Sand	[98]	43.2	39.8	140.1
Standard **safe limit** should be		**< 50 Bq kg^{-1}**		**< 370 Bq kg^{-1}**.

Furthermore, the heavy metal characterization and toxicity evaluation are important concerns for ensuring the protection of the environment and health before the integration of residue material POC [99] for use on a larger industrial scale. Research conducted in Malaysia by Karim et al. [99] to investigate the POC's heavy metal leaching activity as well as the environmental and health risk related to it. The level of toxicity of leaching and heavy metals in POC was evaluated using the risk assessment code (RAC). The assessment indicates the safety of using Palm oil-related by-products as the values were far below the standard risk limit of materials, as shown in Fig. 3.

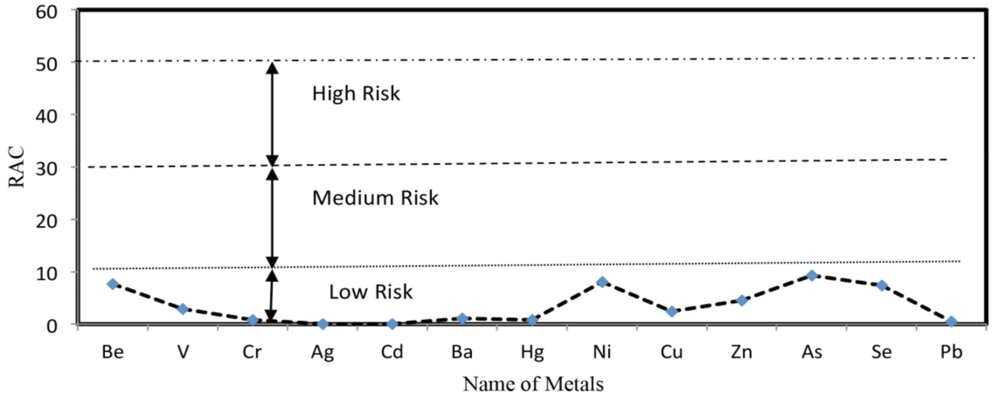

Fig. 3 - Heavy metals leaching level potential of POC [99]

6. Overview Utilization of Palm Oil Mill Residue in The Pavement Industry

From the review, it can be deduced that different palm oil residues can be utilized in the various field of the pavement industry as it has shown encouraging results, as shown in Table 8.

Table 8 - Researched synopsis of the utilization of palm oil mill residue in the pavement industry

Material utilization in the pavement industry	POF [30], [61], [69]	POC [36], [86], [88], [89]	POFA [55], [72], [73], [76]	PKSA [57], [90], [91]
Soil stabilization	-	-	Yes	Yes
Replacement of cement	-	Yes	Yes	-
Coarse aggregate	-	Yes	-	Yes
Fine aggregate	-	Yes	-	Yes
Bitumen modifier	Yes	-	Yes	-
Mineral filler	Yes	Yes	Yes	-

7. Conclusions

This review suggests more exploration and implementation of palm oil mill residue as a modifier and as a substitute material in the pavement industry because literature has demonstrated the competence of using such environmentally friendly materials. However, the previous researcher focused exclusively on residue consumption from single sources. Hence, there is a need to harness two or more residues as modifiers. The utilization of residue in the pavement industry could contribute to a decrease in the emissions involved with the disposal of residue and further contributes to the cost reduction of wasteland and pavement construction as reuse of such materials will minimize pressure on conventional materials. Also, more than 50 percent of CO_2-e can be reduced, and they have minimal radioactivity levels. Thus, as in the years to come, the Malaysian pavements industry could become a self-sustainable industry. Furthermore, there is a need for a comprehensive budget, equipment, timeframe, and overall details of implementing in the pavement industry for large scale production because most researched investigations and evaluations are laboratory-based.

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