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Review

Utilization of solid waste materials as alternative fillers in asphalt mixes: A review

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HIGHLIGHTS

- This study reviews 20 different widely produced wastes as alternative fillers in asphalt concrete mixes.
- Influence of physical and chemical properties of wastes over performance of asphalt mixes was analyzed.
- Suitable wastes when added to an optimum concentration could produce superior asphalt mixes.
- Critical gaps in existing literatures are identified and future scope of research is proposed.

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ABSTRACT

The amendment of producing asphalt mixes with waste materials serves as an avenue to limit the enormous volume of wastes produced from various sources. This also reduce the consumption of naturally mined materials, therefore, minimizing the carbon footprint and pavement industry impact on the environment. This manuscript reviews the wide spectrum of more than 20 well known but under-utilized wastes produced from various sectors (industrial, agricultural, municipal, mining, construction and demolition) which could be utilized as fillers in asphalt mixes. Emphasis was given to the physical and chemical properties of the wastes and their influence on the performance of mixes against primary distresses. This manuscript is likely to motivate researchers and serve as a guideline for adopting non-traditional fillers by highlighting areas likely requiring further research and refinement. Several studies in the recent times have suggested that the use of waste materials in optimum proportion as fillers would lead to production of sustainable asphalt mixes.

Contents

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1. Introduction

The global road network consists of more than 36 million km of the unpaved and paved road network [33]. Majority of paved road network consists of asphalt pavements whose maintenance and further expansion depends upon continual and frequent availability of natural resources like aggregates and carbon-based asphalt/asphalt binders. Filler can be considered as the finest portion of aggregate which passes through a particular sieve (0.075 mm in United State, India and 0.063 mm in Europe) and occupies up to 12% by weight in asphalt mixes [43,71]. Despite of being used in limited concentration, inclusion of filler in asphalt mix has significant influences over properties of mixes such as (i) filler satisfies the aggregate gradation specification and influence the strength and volumetric requirements of the mix [5,117]. (ii) filler extend the bitumen to increase the bitumen volume in the mixture and reduce optimum bitumen content and material cost of mix [29,40]; (iii) filler stiffen the bitumen to improve the mechanical properties of the mixture, and not only influences the ability of mixes to resist permanent deformation at high temperatures but also cracking resistance at low temperature and fatigue life at intermediate temperatures [109,118]; (iv) influence "bond" in the aggregate-bitumen system which further effects moisture sensitivity of mix [72,85], (v) fillers also influences aging process of asphalt mixes by either catalyzing oxidation or by hindering the diffusion of oxygen in mastic [10,44,91]; (vii) influence thermal performance of asphalt mixes [26]; (vii) influence constructability of mix by influencing its mixing and compaction temperature [119]. All these effects are ultimately linked to physical and chemical characteristics of chosen filler, its interaction with bitumen and its volumetric concentration in the mix. Hence the choice of suitable filler is a primary concern amongst field engineers. Conventionally, materials such as stone dust, hydrated lime, and cement are being utilized in asphalt mix composition as fillers since they deliver satisfactory performances in the mix [60]. These fillers are directly obtained by mining earth's crust and their incessant use in asphalt mixes has led to their scarcity in various regions. Exhaustive mining for conventional fillers also leads to problems like as vegetation loss, loss of water retaining strata, lowering of the groundwater table and disturbance in the existing ecosystem. This lead to the imposition of restrictions on mining in several regions and reduced the availability of good aggregates at shorter haul distances. The collection of aggregates from longer distances increased their transportation cost to the construction sites which consequently increased the overall cost of pavement construction [102,94]. In addition to this, various agencies has introduced environmental rating systems such as Leadership in Energy & Environmental Design (LEED) and Life Cycle Assessment (LCA) to promote sustainable design and construction practices for attaining a reasonable equilibrium between the structural, health, environmental and socioeconomic objectives without sacrificing quality of life [42,120]. Utilization of waste materials as fillers in place of conventional fillers will definitely enhance the sustainability practices in pavement construction. Hence there is an immediate need to find affordable and eco-friendly alternatives for conventional fillers in asphalt mixes.

Today, developing economy such as India alone contributes 960 million tons of solid waste generated from industrial, agricultural, municipal and mining sectors annually, which consists of both hazardous and non-hazardous wastes [83]. The disposal of these wastes is usually done by landfilling, incineration and by recycling. However, the limited capacity of landfills, air pollution associated with incinerators and limited alternatives for recycling limits the safe disposal of wastes. Legislation such as directive 2008/98/EC

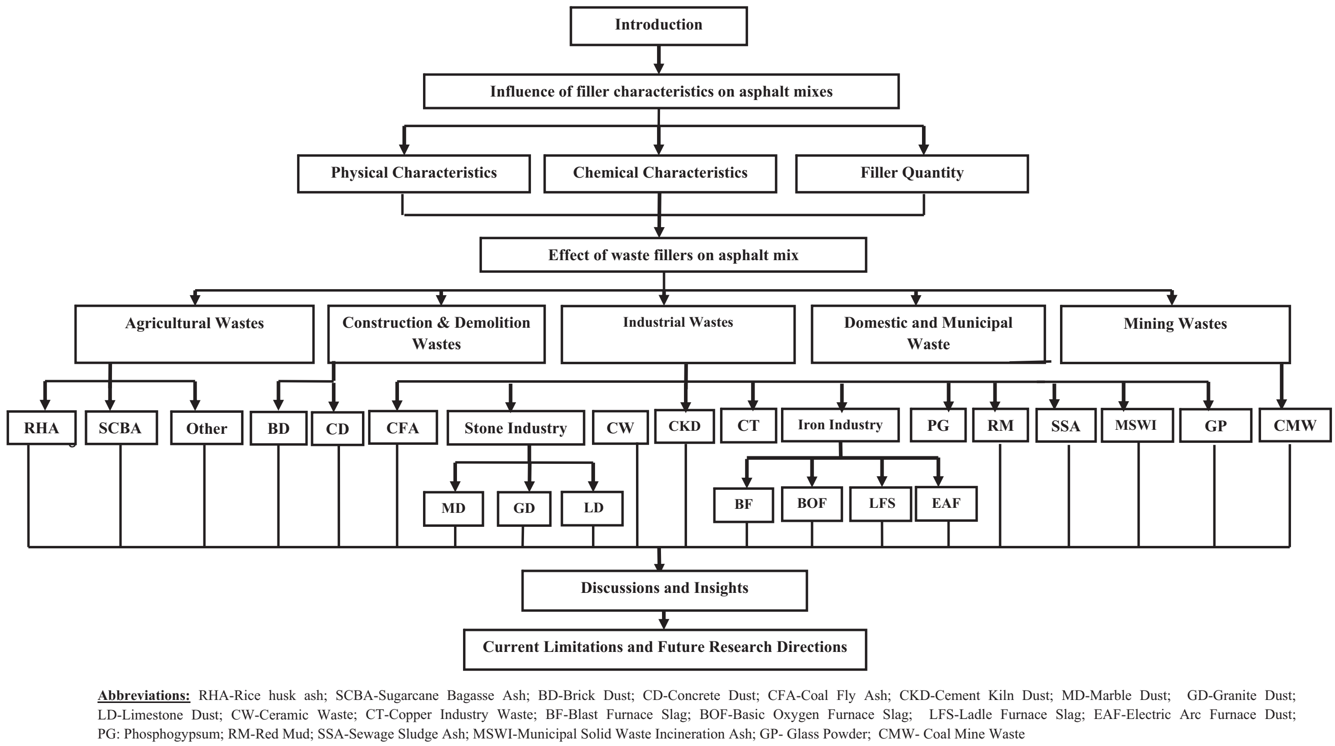


Fig. 1. Schematic illustration of this state of the art study.

has been enacted by governments to mandate the recycling of these wastes in various applications. However, in countries like India, industries just manage to recycle 15–20% of solid wastes in various building components [83]. Hence utilization of these wastes as components of asphalt mixes not only can ensure their safe disposal but also move the pavement industry to the path of sustainable construction.

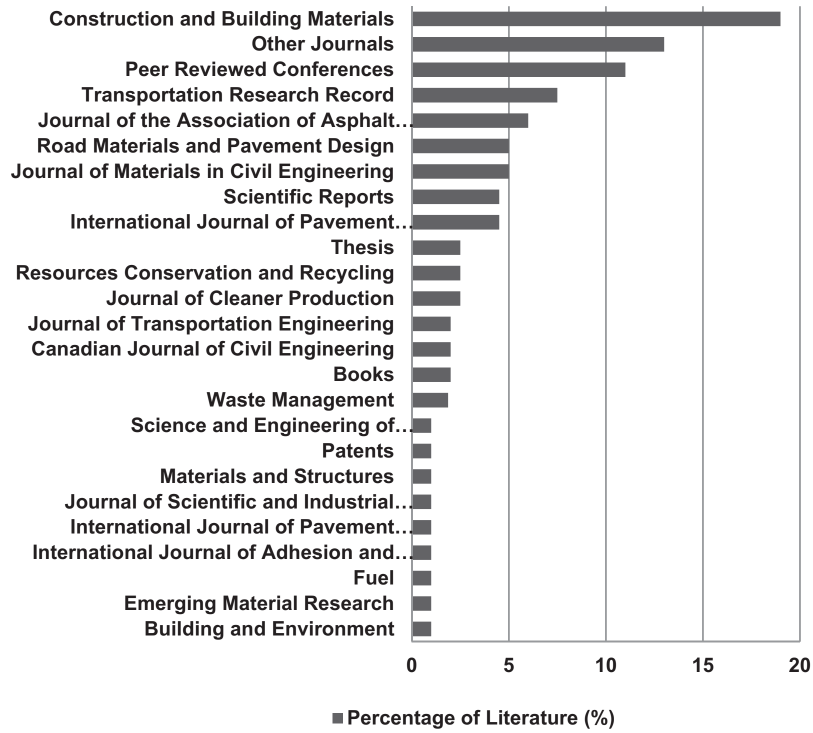
Since the year 1900, several studies have been focusing on finding alternatives which could be used in place of conventional fillers. Waste materials obtained from industries sources suggested that, numerous waste materials such as biomass ash [69], borogypsum [121], coal fly ash [99], electric arc furnace dust [122], glass powder [14], marble dust [25] and other similar byproducts from various processes when added to their optimum proportion have displayed promising results in various aspects of asphalt mix performances. Similarly, mixes consisting of wastes such as green liquor dreg [84] phosphogypsum [53], and waste bleaching clay [115] doesn't deliver as superior performance as required. Performance of waste such as oil fly ash was also found to be improved when a suitable surface treatment with acids was given to it [125]. The above studies have suggested that the performance of the asphalt mix is dependent upon the choice of optimum waste as filler. However, recent regulations on filler for asphalt mixtures [1,15,38,71] has established limits for only primary characteristics such as particle size distribution, plasticity index, water content and organic content [69]. Also the quantity of filler in the mixture is limited by filler/binder ratio, which should be in the range of 0.6–1.2 by weight. These parameters may be used primarily for quality control, but are not sufficient to obtain expected performance of asphalt mixtures. This problem is more pronounced for alternative fillers, which often exhibit unique traits. There is a clear lack of comprehensive literature which helps the researcher to choose proper filler as per its intended requirements. The choice of any unknown waste materials in any individual design as well as in any pavement design guidelines invited various legitimate engineering, environmental and economic concerns, and this review will be focusing on addressing these issues for various types of wastes.

2. Scope of the study

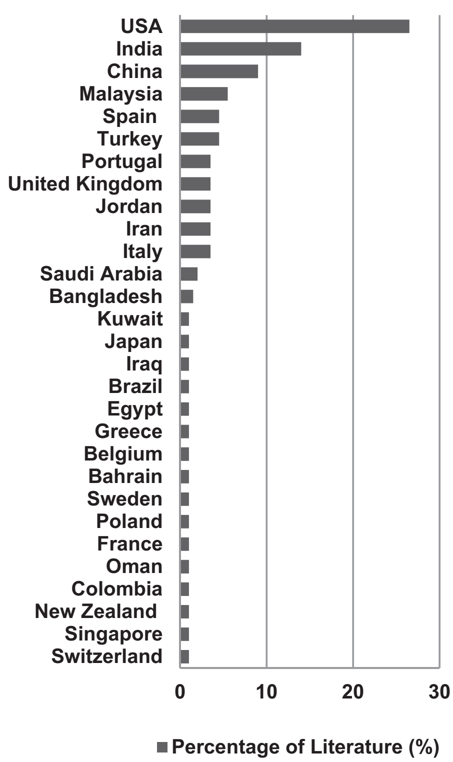
This study focuses on investigation of the performance of more than 20 different types of wastes obtained from various sources in 30 major countries. All wastes included in the study are obtained in substantial quantities in their respective study area as specified by respective researchers. Influence of various characterization properties on the performance of asphalt mastics and mixes are discussed. Emphasis is given in identification of effects on structural and environmental performances of asphalt mixes after the inclusion of waste materials. This study also discusses the effect of physical and chemical modification of various wastes and how it influences the performance of waste in mastics and mixes. Additionally, the potential of various to fulfill the current and future structural and environmental requirements of paving projects are discussed. Finally, critical gaps in existing works of literatures are identified and future scope of research is suggested. Flow chart specifies the schematic outline of the study (Fig. 1)

3. Strategy for literature survey

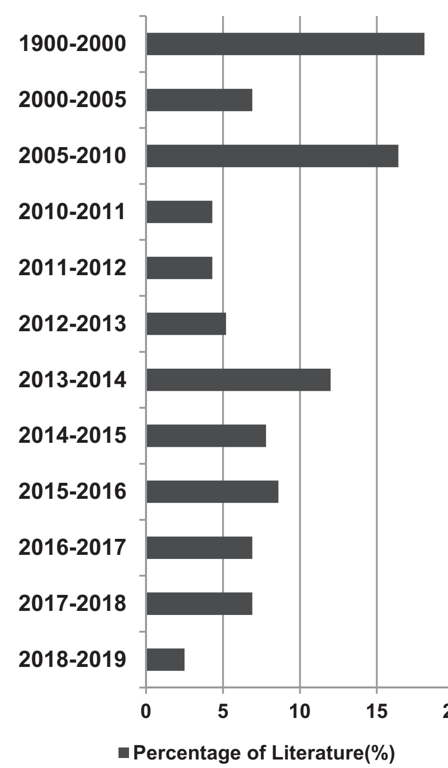
An organized state-of-the-art literature review was done to address the research objectives stated in previous sections. Relevant works of literatures were identified used keyword-based searches in various electronic databases and library services [120]. Two most famous indexed databases: Web of Science database (http://www.webofknowledge.com) and the Google Scholar database (http://www.scholar.google.com) were primarily explored. Oldest study on filler was found in the year 1905, so the study period of 113 years (1905–2018) was considered for analysis. The primary focus is given to the literature published



(a) Various Sources of Literature



(b) Study Area of Various Literatures



(c) Year of Study of Various Literature

Fig. 2. Details of Literature included in the Study.

after the year 2000, however, any relevant older literature is also included in analysis. Initially, the authors tried a brainstorming procedure and then adopted a snowballing processing technique to add additional keywords to the search. The resulting search terms were combined using the Boolean operators (“AND” and “OR”) in the investigation of keywords, titles, abstracts, and full article text. Any unpublished or non-English literature was excluded from the analysis. Furthermore, some relevant articles

Table 1
Influence of filler characteristics and quantity on performance of asphalt mixes.

Filler Parameter	Inferences	Reference
Rigden Voids (RV)/Porosity	Fillers with high Rigden voids (RV) can convert free bitumen into structural bitumen (bitumen that fills the voids among filler particles), thus creating a stiffer structure of bitumen filler mastic and increasing rutting resistance of mix.	Rigden [110], Faheem et al. [39], Kandhal et al. [50] Wang et al. [109]
	Fillers having excessively high RV have a detrimental effect over workability and compaction properties of various asphalt mixes.	Brown and Cooley [23], Melotti et al. [69]
	Rigden voids of fillers failed to correlates with rutting potential of asphalt mixes	Mogawer and Stuart [75]
Particle Shape	The particle shape of filler significantly affects permanent deformation of asphalt mix.	Tayebali et al. [105]
	Filler shape had a little influence over rut depth of asphalt mixes	Huang et al. [45]
	Fillers having large particle size and regular shape acts as friction lubricant agent by acting as tiny rollers during the compaction process, thus resulting in lowering of compaction resistance of asphalt mix.	Zulkati et al. [117]
	Sphericity/roundness of filler particles has significant influence over the viscosity of asphalt mastic.	Grabowski and Wilanowicz [43]
	Non-spherical filler particles increase shear strength and stiffness of bitumen which in turn increases resistance to plastic flow of asphalt mix and improves its Marshall stability.	Al-Hdabi [6]
	Fillers having irregular shape may negatively affect workability and fluidity of asphalt mix	Melotti et al. [69]
	Geometrical irregularity of filler could lead to a decrease in effective bitumen which may cause detrimental effect over stripping resistance of asphalt mix.	Sobolev et al. [100]
Particle Size	Finer filler particles can act as bitumen extender which may lead to the production of over-rich mixes which can cause problems such as loss of stability, bleeding, and high rutting and flushing.	Kandhal et al. [50]
	Filler having low D60 values stiffens the bitumen more and thus increases rutting resistance of asphalt mix.	Kandhal et al. [50]
	Asphalt mixes prepared with fillers with low D10 values have higher stiffening which also enhances the resistance of mixes against stripping	Kandhal et al. [50]
	At a similar filler bitumen ratio, fillers with medium and coarse sized particles improve rutting and fatigue resistance of asphalt mix.	Muniandy et al. [78]
Particle Size Distribution (Gradation)	The particle size distribution of filler influences the stiffening level of asphalt mastic.	Brown et al. [22]
	Fillers having homogenous particle size distribution increases mastic viscosity and rutting resistance of asphalt mixes.	Antunes et al. [11], Clopotel and Bahia [34]
Particle Texture	Fillers with rough surface texture leads to higher bitumen adsorption at the surface which increases stiffness of the asphalt mastic and forms high strength mixes.	Craus et al. [36]
	Mixes prepared with the filler having a rough texture and high surface area have high OBC.	Zulkati et al. [117]
Surface Area	The larger surface area of filler absorbs a higher quantity of bitumen which influences the performance of asphalt mix.	Antunes et al. [12], Clopotel and Bahia [34], Taylor [106]
	Interaction between bitumen and filler due to its higher specific area influence compaction properties and void content of the asphalt mix.	Zulkati et al. [117]
Specific Gravity	Fillers with lower specific gravity occupy greater volume in the compacted mix and leave lesser space for bitumen to be accommodated, thus reducing OBC of the mix.	West and James [110]
Chemical and Mineralogical Composition	Hydrated lime and some other basic fillers improved the moisture resistance of asphalt mix by interacting with carboxylic acid present in bitumen and forms water-insoluble calcium salts. These salts absorb at aggregate surface and releases aggregate molecules (eg. SiOH) which combines with nitrogen groups of bitumen and forming strong bonds.	Little and Jones [64], Read and Whiteoak [90]
	Hydrated lime slows down bitumen ageing due to the acid-base reaction caused between polar molecules of bitumen and lime surface.	Petersen et al. [87]
	Fillers with the presence of strong bases like $Ca(OH)_2$, CaO and $Mg(OH)_2.Ca(OH)_2$ reduces ageing of bitumen. On the other hand, fillers having a weak base like $Mg(OH)_2$ doesn't reduce ageing.	Lesueur et al. [61]
	Siliceous fillers form weak mechanical (Vanderwall force) bond with bitumen, while basic fillers like lime form a strong chemical bond with bitumen.	Antunes et al. [11]
	Basic fillers (hydrated lime and limestone) improved the tensile bond strength of mastic in comparison to acidic filler (gritstone).	Jakarni [48]
	CaO content in filler displayed good correlation with the rutting potential of asphalt mixes.	Wang et al. [109]
	Chemical composition of filler doesn't have any direct influence over stiffening of asphalt mastic.	Antunes et al. [11]
	Filler mineralogy doesn't have any correlation with rutting potential of asphalt mix.	Huang et al. [45], Mogawer and Stuart [75]
	Good physiochemical interaction between bitumen and filler can improve fatigue life of mix by providing better resistance to micro cracking by lowering the rate of damage evolution and damage accumulation.	Kim et al. [55]
	Mineralogy of mineral fillers has significant influence over active and passive adhesion between aggregate and bitumen.	Pasandin and Parez [85]
	Presence of minerals such as mica, chlorite and hydrated iron oxides in filler may significantly lower the performance of asphalt mix against moisture sensitivity and freeze-thaw action.	Loorentz and Said [66]
	Chemical composition of fly ash and other coal combustion products as the filler has a significant influence on stiffening potential of bitumen filler mastic. Higher quantities of CaO, SO_3, and LOI (loss in ignition) increased the stiffening rate and formed stiffer mastics. Increase in Al_2O_3 and SiO_2 decreases the stiffening of mastic.	Bautista et al. [17]
Filler Quantity	A higher concentration of filler may result in stronger asphalt mixes due to improvement in mix's cohesivity and internal stability caused by good packing.	Brown et al. [22], Tunnicliff [108], Tayebali et al. [105]
	An excessive amount of filler may require a higher amount of bitumen to coat aggregates completely, which may weaken the asphalt mix.	Kandhal et al. [50]

(*continued on next page*)

Table 1 (*continued*)

Filler Parameter	Inferences	Reference
	OBC of asphalt mixes decreases with increase in filler content. Higher filler content in mix requires less amount of bitumen to form the same amount of mastic to lubricate the aggregates.	Brown and Cooley [23], Chandra and Choudhary [28], Huang et al. [45], Kandhal et al. [50], Tayebali et al. [105]
	Excessive filler content in asphalt mix may negatively affect fracture behavior of pavement by causing brittle failure and by promoting oxidation and hardening of bitumen.	Kandhal et al. [50]
	Quantity of filler influences viscoelastic properties of bitumen and affect the stiffness of asphalt mixes.	Zulkati et al. [117]
	Increase in viscosity due to the inclusion of filler decreases the severity of short term aging of bitumen	Lesueur et al. [61]
	Filler type and filler content have a significant influence on the moisture sensitivity of the asphalt mixes.	Aljassar et al. [5]
	Cracking resistance of mixes increases with the increase in the filler content due to improvement in strength of mastic by increasing concentration of filler.	Huang et al. [45]
	Fatigue resistance of asphalt mixes decreases with the increase in the filler content in mix. This is due to increase in the brittle nature of mastic by the inclusion of a larger amount of filler.	Huang et al. [45]
	Moisture susceptibility of asphalt mixes decreases with the increase in filler content due to subsequent lowering of their OBC.	Chandra and Choudhary [28], Huang et al. [45]
	Increase in filler binder ratio increases the viscosity of mastic which requires more compaction energy to produce uniformly compacted asphalt mixes.	Anani et al. [8]
	Rheological behavior of asphalt mastic at low and high temperatures is significantly influenced by the volumetric composition of filler.	Lackner and Spiegl [59]
	Optimum filler binder ratio of mix is dependent upon surface mineralogy of aggregate and surrounding temperature.	Zejiao et al. [115]

were not listed in the above method. Therefore, the table of contents of high-quality journals, books, reports, and proceedings of peer-reviewed conferences was also manually investigated to carry out the bibliographic research. Major papers were mainly found in Science Direct, American Society of Civil Engineering, Transportation Research Record, Taylor and Francis, Springer, Digital Library. All selected papers were critically analyzed to ensure that their content was in harmony with the primary objectives of this study.

A recording form in MS-EXCEL was then developed to document and categorize specific details from the chosen literature. The recording form categorizes literature characteristics in terms of document type (Journal article, book, patent, etc.), type of asphalt component analyzed (asphalt mix, mastic etc.), publishing year, study area, source of waste, authorship, article title and affiliation of the first author. Analyses were made to address the issues that are put forward in previous sections. Finally, around 130 literature items were selected for analysis which covers studies of more than 20 different wastes from 30 countries distributed over 113 years (1905–2018) (Fig. 2). To simplify the analysis, selected wastes are further categorized into 5 different categories based on their sources and process of production.

4. Influence of fillers over the performance of asphalt mixes

As per [16], the mineral filler should consist of "finely divided mineral matter", which should dry enough to flow and should be free from agglomerations. As per current Indian asphalt mix design practices [71], the filler is restricted to that material, which is fine enough as measured by 75-μm sieve. It should be free from organic impurities and should have plasticity index (an indirect indicator of clay content) not greater than 4 (except for cement and hydrated lime). Fillers can either have natural origin when obtained from crushing of rocks (stone dust) or can be manufactured in industries like cement, lime, ash, and slag.

The role of filler in asphalt mixes is very complex. Intentional use of filler in asphalt mix was traced back to DeSmedt in the 1870s. However, until 1893, clear intention for the addition of filler in asphalt mix was not understood by researchers and it was simply utilized to fill the interstices between aggregates in the mix to improve density and impermeability of asphalt mix [92]. Early studies such as by [92] postulated that, unlike other aggregates, the function of filler in asphalt mixes was not just void-filling. Richardson also implied the existence of some sort of physico-chemical phenomenon in the filler-asphalt system (asphalt mastic). In 1911, Einstein in his study hypothesized that inclusion of filler in mastic linearly increases its stiffness with a rate specified as Einstein coefficient [37]. Later it was verified that filler plays dual roles in mixes, not only they primarily act as inert material which fill interstices between larger aggregates in mixes but also finer particles of filler along with asphalt binder form asphalt mastic which is a thermorheologically simple linear viscoelastic material playing key roles in asphalt mixes by holding the mix together and influencing its performance against various distresses [11,45]. The inclusion of finer filler particles in asphalt mixes stiffen mastic and improve mechanical properties such as asphalt mix density and strength. Finer particles of fillers having size smaller than thickness of bitumen film also act as bitumen extender in mastic and make mix behave such as if there is additional binder present [25]. This behavior resulted in problems such as stability loss, binder bleeding, and fat spots. The stiffness of asphalt mastic not only influences the ability of mixes to resist permanent deformation at high temperatures but also cracking resistance at low temperature and fatigue life at intermediate temperatures [109,118]. Some fillers also act as an anti-stripping agent preventing moisture damage due to its interaction with bitumen and aggregates [29,60]. Furthermore, some fillers also influences aging process of asphalt mixes by either catalyzing oxidation or by hindering the diffusion of oxygen in mastic [10,44,91].

In existing Indian asphalt mix design and highway construction practices [71], asphalt mixes are designed by taking their physical properties (Marshall stability and flow values), volumetric properties (air voids, voids in mineral aggregate, voids filled with bitumen), rutting resistance (Marshall quotient) and moisture susceptibility (minimum tensile strength ratio) in consideration [71]. Although the influence of fillers on the overall parameters mentioned above is well understood, most worldwide regulations on filler for HMA [85,15,1,38] established limits for only a few characteristics such as grading, plasticity nature, organic content,

Table 2
Characterization properties of wastes materials.

Category of Waste	Material Type	Characterization Property								
		Specific Gravity (gm/cm^3)	Water Absorption (%)	MBV (g/kg)	Particle Shape	Specific surface area (m^2/kg)	Primary mineralogical composition	SiO_2 content (% by weight)	CaO content (% by weight)	References
Agricultural Waste	Rice Husk Ash (RHA)	2.05	1.0	NA	H	231	Quartz; Crystobalit; Anorthite	86.67	1.88	Melotti et al. [69], Farooque et al. [41]
	Sugarcane Bagasse Ash (SCBA)	2.52	NA	NA	Fs and G	514	Quartz; Calcite; Corundum; Halite	62.43	11.80	Zainudin et al. [114]
	Palm Oil Fuel Ash (POFA)	2.22	NA	NA	I	492	NA	43.6	8.4	Borhan et al. [20],Hamada et al. [131]
	Bio Mass Ash	2.18–3.13	0.2–32	0.7–5.3	I	NA	NA	5–95	3–65	Melotti et al. [69]
Industrial Waste	Coal Fly Ash (CFA)	1.97–2.23	0.13	1.24	R	300–600	Quartz; Mullite; Dolomite; Montmorillonite; Rutile	37.05–59.70	1.71–2.3	Chandra and Choudhary [28]; CPCB [35]
	Marble Dust (MD)	2.69	0.97	4.5	SA	1140	Dolomite; Quartz; Calcite; Chlorite; Tremolite	15–30	20–40	Chandra and Choudhary [28], Kumar et al. [130]
	Granite Dust (GD)	2.79	0.92	2.25	SA-SR	131	Quartz; Kyanite; Sphene; Albite	37.49	7.84	Barra et al. [16], Chandra and Choudhary [28]
	Limestone Dust (LD)	2.65	NA	3.75	G	NA	Calcite; Quartz; Enstatite	23.50	37.85	Choudhary et al. [30]
	Phosphogypsum (PG)	2.3–2.6	NA	NA	Fs	NA	Calcite; Quartz; Gypsum	3.70	35.7	CPCB [35], Katamine [53]
	Cement Kiln Dust (CKD)	2.75	NA	NA	A	460	Portlandite; Lamite; Hartrurite,	15–18	45–52	Modarres et al. [74], Ramadan and Ashteyat [88].
	Ceramic Waste (CW)	2.07	0.97	2.0	R	588	Quartz; Mullite; Zircon; Hematite; Orthoclase.	76.41	7.1	Medina et al. [68], Munaindy et al. [79]
	Electric Arc Furnace Dust (EAFD)	NA	NA	NA	SR	NA	NA	4.0	1.4	Alsheyab and Khedaywi, [122], Loaiza et al. [65]
	Steel Slag (SS)	3.4	0.2	0.3	A	238	NA	41.41	4.25	Muniandy et al. [79]
	Red Mud (RM)	3.12	NA	2.875	G	NA	Hematite; Quartz; Rutile; Sillimanite; Calcite.	9.60	15.44	CPCB [35], Choudhary et al. [30]
	Copper Tailings (CT)	2.72	NA	1.5	A	NA	Quartz	NA	NA	Choudhary et al. [30]
Construction & Demolition Waste	Brick Dust (BD)	2.68	1.0	1.67	A.	256	Quartz; Chromite.	68.1	2.05	Chen et al. [26], Kuity et al. [57]
	Concrete Dust (CD)	2.637	0.9	1.10	A	372	Quartz; Calcite; Gobbinsite.	35.59	29.20	Chen et al. [26], Kuity et al. [57]
Domestic and Municipal Waste	Sewage Sludge Ash (SSA)	2.78	NA	NA	I	630	Quartz; Hematite; Whitlockite; Thernardite.	17.21	29.88	Aburkaba and Munaindy [2], Tenza-Abril et al. [107]
	Municipal Solid Waste Ash (MSWI)	2.18	NA	NA	I	NA	Quartz; Calcite; Portlandite.	18.81	38.92	Tasneem [104], Xue et al. [113]
	Glass Powder (GP)	2.62	NA	1.25	A	NA	Quartz	71.42	7.462	Arabani et al. [14], Choudhary et al. [30]
Mining Waste	Coal Mine Waste (CMW)	2.324	NA	NA	NA	NA	Quartz; Kaolinite; Pyrite; Calcite; Gypsum.	34.8	0.51	Modarres and Rahmanzadeh, [129]

Abbreviations A- Angular; SA- Subangular; R- Rounded; SR-Sub rounded; G-Granulous; Fs: Fibrous; Fy-Flaky; H- Honeycombed; I-Irregular, C- Cubicle; NA: Not available.

and water content. These aforesaid characteristics are necessary for quality control but are not sufficient enough to assess the expected field performance of asphalt mixes and there is a need to include more characterizing properties to serve the purpose. The influence of various characterizing properties of filler over the performance of the mixes is stated in Table 1.

5. Fillers derived from waste materials

There are numerous waste materials generated from different industrial, construction, domestic and agriculture sectors. They can mainly be classified under following heads (a) Agricultural waste like biomass wastes (b) Industrial wastes such as fly ash, slag, cellulose waste; (c) Municipal/household/domestic wastes such as incinerator residue, waste glass, and scrap rubber; (d) mining wastes such as coal mine refuse and (e) construction and demolition (C&D) wastes such as recycled fine concrete aggregates and recycled brick dust. This section discussed various widely generated waste materials from different origin which were utilized as filler in asphalt mixes. Comparison between various physical and chemical properties of wastes materials utilized as filler in previous studies is stated in Table 2. This will help researchers to choose optimum filler while taking techno-economic considerations and ensuring the paramount performance of asphalt mixes.

5.1. Agricultural wastes

The agriculture sector is one of the primary waste producing industries and generates large amounts of biomass. Countries like India which has agro-economy alone produces residues to the order of at least 840 million tons [89]. Other than the residues that are generated during the harvest, the processing of agricultural products (milling, oil extraction, etc.) also create substantial by-products that become waste when left unutilized. Many biomass wastes with high fuel value, such as rice husk, sugarcane bagasse, waste wood, etc., can be recycled as fuel for electricity generation. Studies have suggested that ashes produced after uncontrolled and controlled burning of agricultural biomass could be readily utilized as filler [6,124].

5.1.1. Rice Husk Ash (RHA)

Rice husk is natural sheaths formed over rice grains during their growth, and is a highly prevalent solid waste in South East Asia. RHA is a byproduct produced by incinerating rice husks as a fuel source for a boiler at 600°-800 °C to produce energy and power a manufacturing facility. The former method is costly and produces ash with amorphous silica, a high surface area having smaller non-spherical and non-agglomerated particles [6]. In some areas, RHA is also generated by uncontrolled open burning which is relatively cheaper but causes environmental pollution. In most of the studies, partial and complete replacement of RHA has produced superior mixes than conventional fillers. RHA at replacement rate of 50% with limestone filler, produced asphalt concrete mixes with improved Marshall stability and volumetric properties [98]. RHA particles reinforce the binder and improve its stiffness and cohesion which in turn improve the Marshall property of asphalt mixes [6,70]. RHA modified asphalt concrete mixes also had superior resistance against moisture damage, permanent deformation, cracking and long term aging as compared to mixes prepared with OPC and hydrated lime as fillers [6,70]. In contrary, another study by [14] has observed that the porous nature of RHA can also negatively affect the performance of asphalt concrete mixes prepared with it in terms of stability, moisture susceptibility, rutting resistance and fatigue cracking than conventional stone dust mixes.

5.1.2. Sugarcane Bagasse Ash (SCBA)

Sugarcane bagasse is obtained after crushing the sugarcane stalks to produce cane juice. This bagasse is used as boiler fuel for energy generation by the processing factories which after incineration produce SCBA. India alone annually produce 90 million tonnes of bagasse which after burning produces 8–10% of SCBA by its total weight [58]. SCBA in comparison to RHA has lighter weight, higher surface area, low amorphous silica as well as low carbon content. Due to their low specific gravity, they occupy greater volumes, thus require special attention especially before utilizing in gap graded mixes like SMA. The asphalt concrete mixes prepared with SCBA as filler had slightly improved Marshall parameters with an appreciable improvement in resilient modulus values as compared to conventional mix [114].

5.1.3. Other Agricultural Wastes

Palm oil fuel ash (POFA) is produced after combustion of palm husk, fiber, and oil palm shell during the production of crude palm oil. POFA is majorly generated in Thailand and Malaysia at a rate of over 100,000 tons per year [125]. POFA displays high pozzolanic properties due to the relatively high silica content (55–65%). Due to its pozzolanic action, POFA modified asphalt mixes displayed similar stability and higher resistances against rutting, fatigue, cracking, and moisture susceptibility than conventional limestone filler mixes [23,67].

Melotti et al. [69] examined the suitability of 27 different types of biomass ashes as fillers and considered most of them as a potential replacement of good filler. Although the majority of ashes displayed positive traits such as low methylene blue value, low water solubility, and CaO as the primary component, some of them also have coarser particle sizes as well as high Rigden voids and needed additional milling before being utilized in the field.

5.2. Industrial wastes

Various manufacturing industries produce unwanted by-products, some of which are recycled for the industry's production, but a considerable part of the material ends up as waste. This section subjects major waste producing from industries to closer examination for identifying reusable materials for fillers.

5.2.1. Coal Fly Ash (CFA)

CFA is a mineral by-product obtained after combustion of pulverized coal in thermal power projects for electricity generation. It is a non-plastic material, which is obtained in small, predominantly spherical hollow particles whose density is lower than conventional fillers. The particle size of CFA varies between 1 and 60 μm and their fineness lies between 300–600 m^2/kg [35]. It has hydrophobic nature and free lime content, which may improve bitumen aggregate adhesion and durability of asphalt mix against moisture.

The small particle size of CFA has a significant effect on viscosity and rheological properties of asphalt mastic and mixes, which in turn influence mechanical and durability properties of asphalt mixes [40]. Utilization of CFA in asphalt mixes also reduce mixing effort, placement temperature and improve workability of asphalt mixes without causing any detrimental effects over its performance. These effects were attributed to its fine particle size, spherical shape and its tendency to act as bitumen extender and enhancer [27,40]. A recent study by [40] has observed no change in workability of asphalt mix when 10% volume of bitumen in the mix was replaced with CFA. This behavior was attributed to the inter-aggregate lubrication effect caused by CFA particles, which lead to lesser energy consumption as well as an additional reduction in mix's cost and greenhouse gases emission.

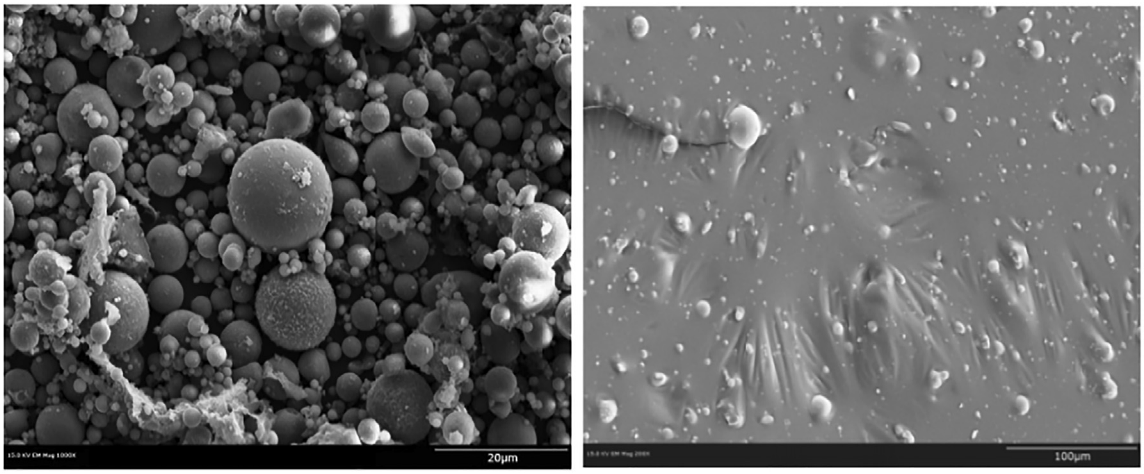


Fig. 3. (a) SEM image of CFA particles (Left image). (b) SEM image displayed cracking pinning by the introduction of 60% CFA in asphalt mastic (Right image) [100].

The small particle size of CFA and their even distribution within asphalt mastic also displayed crack arresting behavior by pinning and deflection of brittle cracks as observed from microstructural investigations (Fig. 3) [100]. CFA also improved asphalt binder thickness coating of aggregates which improved ravelling, stripping and aging resistance of asphalt mix [40].

Swaminathan and Nair [102] constructed a stretch of asphalt concrete road in India with fly ash as filler which satisfactorily withstood the traffic of 5,000 vehicles per day for the study period of 2 years. Asphalt concrete mixes prepared with CFA of different sources added at different filler percentages showed improved fatigue life, low temperature cracking, low moisture sensitivity and high rutting resistance than conventional stone dust mixes, due to high porosity and calcium oxide content of CFA [29,99,70].

Recent studies are largely focused on the enhancement of properties of CFA and asphalt mixes by modifying it with some other wastes to form binary or even ternary fillers [80,126]. Apart from conventional asphalt concrete mixes, CFA has now been utilized in unconventional mixes such as stone matrix asphalt (SMA), foamed bitumen stabilized mixes and cold emulsion mixes [80,126,95], SMA mix prepared with composite filler (CFA + 8% Plastic waste) displayed superior rutting resistance, resilient modulus, higher allowable number of vehicles, reduced drain down and improved moisture sensitivity as compared to conventional mixes prepared with hydrated lime as a filler [126]. Nassar et al. [80] have used binary and ternary fillers prepared with CFA in combination with Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) in cold asphalt emulsion mixes. Cold emulsion mixes prepared with both binary filler (CFA + GGBS) and ternary filler (CFA + GGBS + SF) displayed significantly higher creep stiffness moduli which were suitable to be used in heavy trafficked roads.

Despite numerous advantages, CFA utilization also demands extreme caution. Kavussi and Hicks [54] have stated that mastic containing CFA is susceptible to brittle failure due to their high porosity. It must be noted that CFA in higher concentration may lead to excessive stiffening of mixes leading to several problems related to mixing, compaction, and cracking. In India, CFA is prohibited in gap graded mixes such as stone matrix asphalt (SMA) due to its larger specific surface area and spherical grains [47].

5.2.2. Ceramic Waste (CW)

It has been expected that about 30% of the annual production in the ceramic industry is converted to waste during cutting, grinding, dressing and polishing operations [79]. This waste ceramic could be easily crushed to the desired size and form ceramic dust which could be utilized as filler. Most ceramic materials such as fire ware scrap are made from Kaolin clay (halloysite), which has low moisture sensitivity due to its water-insoluble nature and have no harmful decomposition products. Improvement in Marshall stability and rutting resistance at higher OBC were observed when CW was introduced in asphalt concrete and SMA as compared to conventional fillers [2,46]. This was due to high strength, porous nature and higher absorption of bitumen on surface of CW. SMA mixes prepared with CW filler having particle size in between 0.075 and 0.020 mm had better cohesive strength than that prepared with limestone filler in the same size range. This resulted in enhanced resistance to fatigue cracking and moisture-induced damage [2,78].

5.2.3. Cement kiln dust (CKD)

CKD is a by-product of cement industry which is generated in large volumes (15–20% of produced cement) and collected from electrostatic precipitators during the production of cement clinkers [56]. CKD meets gradation, plasticity, and organic impurities requirement for mineral filler and constitutes a high proportion of reactive CaO. The addition of CKD in bitumen produces low ductile asphalt mastic and ensures stripping resistance to asphalt mixes [19]. At optimum concentration, CKD can produce asphalt mixes with similar Marshall parameters and volumetric properties at similar OBC as that of conventional mixes containing hydrated lime and limestone filler [105,103]. Some asphalt mixes prepared with CKD also displayed improvements in specific gravity, Marshall stability, fatigue resistance, rutting resistance and low temperature cracking resistance at slightly higher OBC [3,74]. CKD also consist heavy metals in its composition, however, leaching analysis has suggested that bitumen present in asphalt mixes has a stabilizing effect over CKD particles which limits the leaching of heavy metal from the mix [73].

5.2.4. Copper Industry Wastes (CT)

Extraction of copper from its ore in copper industries produces two types of waste named as copper slag and copper tailings. The copper slag is produced during the process of smelting for sulphide ore and collected as the material that floats on the top of the molten copper in a furnace. This material ultimately turned into glassy solid after cooling and discarded as waste in dump yards. After suitable crushing, this waste can be utilized as filler in asphalt mixes. Copper slag has a finer gradation and higher specific gravity than limestone filler due to relative higher oxides of iron [72]. It consists of CaO and SiO_2 in its composition and can display pozzolanic properties which could improve the performance of its mixes against moisture [81]. It also has a relatively higher CaO content than granite and silica aggregate and is expected to display superior performance in saturated and freezing-thawing conditions [72]. Despite this, there are very few studies that explore the potential of copper slag as filler in asphalt mixes. It was observed that replacement of conventional limestone filler with copper slag can produce asphalt mixes with superior fatigue and cracking resistance [72]. This was attributed to finer gradation of copper slag, which can produce stiffer mix at same filler content. Although copper slag had trace amounts of heavy metals like As, Cd, Cu, Cr, Pb and Zn in its composition, they were found to be stabilized due to their encapsulation by the bitumen present in asphalt mix [72].

Copper tailing is the waste rock remaining after ore has been processed to remove the copper. It is usually pulverized to the size of fine sand. It has relatively high specific gravity and primarily consists of silica in its composition. Due to presence of silica, asphalt mixes prepared with it displayed relatively lower yet satisfactory moisture resistance and adhesion than that of conventional OPC modified mixes [30]. It is relatively less porous, due to which it can produce economical mixes with lower OBC [30]. However, a recent study has suggested that asphalt mixes produced with copper tailings have marginally lower yet satisfactory Marshall stability and rutting resistance [30]. Unlike copper slag, copper tailings doesn't found to have any heavy metals in its composition.

5.2.5. Dimensional Stone Waste

Dimension stone is a popular construction material which is widely used in flooring, cladding, and paving of buildings and monuments. During the processing and polishing of these stones, a large quantity of waste slurry is obtained which is dumped to open spaces, where its water gets evaporated leaving behind huge quantities of fine dust which could be utilized as filler. There is a wide spectrum of dimensional stones such as granite, marble, limestone, sandstone, quartzite, and slate. Marble is a metamorphic rock which has calcium-based calcite and dolomite minerals in its composition. These water-insoluble minerals form stronger bonds with bitumen which resulted in highly moisture-resistant mixes [25]. Mixes prepared with marble dust (MD) were found to have similar or improved Marshall properties and could be optimally utilized up to 7% of the total weight of mix [29,51]. Fatigue lives of asphalt concrete mixes prepared with marble dust were also found to be improved up to 20% compared to that of stone dust due to improvement in mastic stiffness [25]. Limestone is the most widely used calcium-based dimension stone. Choudhary et al. [31] has observed that utilization of Indian limestone (Kota stone) in asphalt mixes can produce mixes with higher stability, rutting resistance and cracking resistance at lower OBC, due to its finer nature and lower porosity. Other than that Kota stone mixes also displayed satisfactory adhesion as well as resistances against moisture and raveling due to the presence of calcite in its composition.

In comparison to marble and limestone, granite has a lesser amount of calcium in its composition, however, it doesn't have any significant negative effect on moisture susceptibility of its mixes [25]. Granite has angular particles with rougher grain texture which although increase the OBC of mixes at higher concentration but also forms highly rut resistant mixes [25]. Akbulut et al. [4] have stated that granite dust at higher concentrations fills the microvoids in the asphalt mixes ensuring mixes with higher stability and superior resistance to moisture damage and permanent deformation.

5.2.6. Phosphogypsum (PG)

India produces 6 million tons of phosphogypsum annually during the production of phosphoric acid from rock phosphate in the fertilizer industry [35]. It is a fine material which is majorly constituted of calcium sulphate. Katamine [53] has determined that asphalt mixes having phosphogypsum as the filler has higher Marshall stability and OBC than limestone mix. This was attributed to the microcrystalline structure of phosphogypsum. Although phosphogypsum modified mixes have higher rutting resistance than limestone mixes in the dry state, they collapsed when sample been tested with immersion wheel tracking test. This behavior was attributed to loosening of mechanical interlock between phosphogypsum particles by softening of its microcrystalline structure in the presence of water.

5.2.7. Iron and Steel Industry Wastes

Iron and steel making industries generate millions of tons of byproduct during the separation of the molten metal, iron, and steel, from oxides. These by-products can be identified in four types: the blast furnace (BF) iron slag, the basic oxygen furnace (BOF) steel slag, the ladle furnace slag (LFS), the electric arc furnace (EAF) dust [18]. Blast furnace slag is a by-product obtained when iron ore, coke, and limestone are superheated in the blast furnace to produce pig iron. It has high specific gravity, alkaline, and non-plastic in nature [79]. SMA mixes prepared with blast furnace slag were found to have higher stability and rutting resistance at slightly higher OBC than limestone mixes [78]. However, they also had lower resilient modulus and fatigue lives than limestone mixes [77].

BOF slag is also known as steel slag is non-hydraulic, porous, alkaline and crystalline in nature and contains a certain amount of Fe_2O_3 and P_2O_5 [40,62]. For every ton of steel production, 200 kg of BOF is produced. Li et al. [63] had observed that steel slag powder modified asphalt mixes had higher cracking resistance than limestone modified asphalt mix due to efficient bonding between bitumen and filler caused by alkaline nature of steel slag. Asphalt mastic containing steel slag also displayed superior rheological properties than limestone mastic at high temperature due to higher stiffening of slag as well as higher chemical action between alkaline slag and acidic bitumen.

The ladle furnace slag (LFS) is produced in the secondary metallurgy process, during the final stages of steelmaking. It has high specific gravity and relatively higher porosity. It composed of following oxides: quicklime CaO (50%), silica SiO_2(20%), magnesium oxide MgO (15%), alumina Al_2O_3 (9%) and Iron oxide FeO less than 2%. Asphalt mastic and mixes prepared with LFS displayed higher strength, stiffness and fatigue resistance than conventional counterparts. However mixes prepared with it also had low compactability and higher OBC [18]. Hence its maximum limit should be specified to avoid brittle failure, especially at low temperatures. Electric arc furnace (EAF) dust is a complex hazardous waste generated from electric arc furnace operated at 1600 °C. It is considered hazardous by EPA since it consist of heavy metals such as Zn, Pb, and Cd. However recent study by Loaiza et al. [65] have stated that interaction between filler and bitumen at various compositions form composite materials in which bitumen can act as a stabilizer and inhibits leaching of heavy metals from the EAF (Fig. 4). Mastics prepared with EAF at various compositions displayed satisfactory rheological properties at various temperatures and can be considered as an environment-friendly way to dispose of this hazardous EAF.

5.2.8. Red mud

Red mud or bauxite residue is a high volume solid waste produced by aluminium industries after digestion of bauxite ore with caustic soda in Bayer's process. Global production of red mud is more than 145 million tons annually, out of which, 4 million tons alone is produced in India [127] Red mud constitutes of fine particles (more than 80% of red mud passes through 0.075 mm sieve),

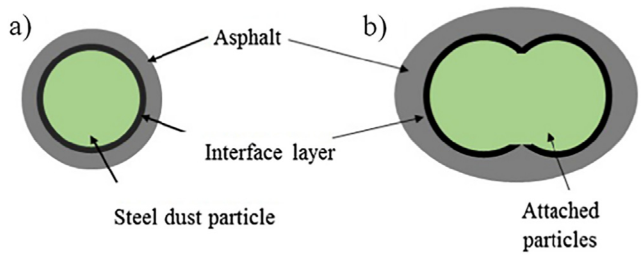


Fig. 4. EAF dust particle surrounded by the interface layer and bitumen: a) less than 10 wt% of EAF dust, b) more than 10 wt% of particles.

which has relatively higher specific gravity, and highly alkaline nature [30]. In contrary to other wastes which primarily consists of silica and calcium-based minerals, red mud is primarily composed of oxides of aluminium and iron oxides in large quantities. This slight unusual chemical composition was found to be responsible for the better high-temperature performance of its mortar as well as higher Marshall stability of its modified asphalt concrete mix [30,116]. Open graded asphalt mixes prepared with red mud displayed better performance in terms of rutting and ravelling resistance, which was attributed to the improvement in adhesion in its mortar due to increase in its stiffening upon the addition of red mud [116]. However, another study has observed a slight decrease in adhesion in mixes due to the incorporation of red mud in comparison to dolomite stone dust filler [30]. This was attributed to the mineralogical composition of red mud which lacks the calcium-based compounds like calcite and dolomite that improved aggregate bitumen adhesion. Red mud was also found to be relatively porous in nature due to which it absorbs higher amount of bitumen which increased the OBC of its mixes [31,35]. Finer nature of red mud was considered as a responsible factor for higher cracking resistance of its asphalt concrete mixes [30]. A primary concern regarding the use of red mud as filler is its mineralogical composition which constitutes of oxides of heavy metals in trace quantities that could leach into ground water. However, based on previous studies on other materials, it is believed that the stabilizing action of bitumen can inhibit the leaching of these metals. However, detailed leaching analysis of red mud mixes is needed to be done using TCLP tests in future studies.

5.3. Construction and demolition wastes

Construction and demolition wastes consist of the debris generated during construction, demolition and renovation of buildings, roads, and bridges. Although it consists of numerous types of wastes such as bricks, concrete, fiberboard, plastic, timber, metal, paper, glass, etc. This study is focused on two major wastes i.e. brick dust and concrete.

5.3.1. Recycled Brick Dust (RBD)

RBD is produced after the efficient crushing of broken brick pieces. RBD has rough particles, high silica and also possibility of high clay content. Asphalt mixes produced with it were found to deliver very variable performances. [26] have found that RBD has rougher particle surface and homogenous particle size distribution than conventional limestone, due to which it had higher bitumen adsorption, resulted in higher OBC of prepared mix. Asphalt concrete mixes prepared with RBD had better moisture susceptibility and fatigue life than respective control mixes [14,26]. RBD also produced stiffer mastics with higher viscosity at high temperature as compared to limestone filler. Although it was beneficial in terms of rutting resistance, mixes with stiff mastic required higher temperature for mixing and compaction which required additional energy. This will not only increases the cost of construction but also causes damaging effects to the environment due to greater emission of greenhouse gases. Stiffer mastics prepared with brick dust are also susceptible to cracking at a lower temperature [112]. On contrary of the above results, Kuity et al. [57] have observed lower rutting resistance and moisture susceptibility of asphalt concrete mixes incorporated with RBD. This behavior was attributed to its high moisture retention rate as well as on larger percentages of silica in the form of quartz.

5.3.2. Recycled Concrete Dust (RCD)

Recycled concrete waste is one of the primary demolition wastes, whose fine portion is mainly composed of cement mortar and fine aggregates. These wastes are difficult to be utilized as substitutive aggregates and could be adopted as alternative filler. Similar to brick dust, RCD also has a rough texture which resulted in higher OBC of asphalt mix [26]. However, unlike brick dust, it has calcite in its composition which resulted in the formation of superior moisture resistant asphalt mixes. Utilization of RCD in asphalt concrete mixes improved moisture sensitivity, fatigue life and rutting resistance at normal and higher temperatures [30,57]. However, it also displayed relatively poor performances in terms of low temperature cracking resistance as compared to conventional limestone mixes [26,128] in their study has observed an improvement in stability, rutting resistance, fatigue life and resilient modulus of asphalt mix when recycled concrete aggregates are utilized as fine aggregates and fillers.

5.4. Domestic and municipal wastes

Domestic and municipal waste constitutes waste produced by households, hospitals, institutions, small business, and commerce.

5.4.1. Municipal Solid Waste Incineration Ash (MSWIA)

It is solid by-product produced during efficient combustion of municipal solid waste in a well-maintained incineration facility. MSWIA has two major byproducts; about 80%–90% of the it is bottom ash (BA) and 10–20% is fly ash (FA) by weight. The former is coarse noncombustible material, relatively rich in metal scraps and relatively poor in heavy metals; the latter is particulate matter removed by the preliminary filter and rich in heavy metals and toxic compounds. MSWIA exhibited internal porosity and possessed angular to irregular morphology, which may exhibit reduced workability and increased leaching susceptibility of asphalt mixes [104]. However, bitumen is found to be an efficient agent who solidifies and stabilize the MSWI ash and inhibit the leaching of toxic materials and enables for safe application in the pavement as shown by toxicity characteristics leaching procedure (TCLP) tests [113]. MSWIA as filler in SMA mixes showed superior performance regarding Marshall stability, dynamic stability, and fatigue life as compared to limestone filler [113]. However, mixes prepared with MSWI were found to have higher moisture sensitivity which was attributed to its lower CaO and higher SiO_2 content, which reduced the adhesion between bitumen and aggregate fraction.

5.4.2. Sewage Sludge Ash (SSA)

Similar to MSWIA, SSA is produced by efficient combustion of dewatered sewage sludge from the wastewater treatment plant in a well-maintained incineration facility. SSA is non-plastic, silty-sandy material which has low moisture, organic content and has 90% particles having size less than 0.075 mm. It has a high amount of CaO content in their concentration and has alkaline nature due to utilization of lime in the treatment plant for sewage conditioning. SMA mixes prepared with SSA was found to have higher rutting resistance and lower moisture susceptibility as compared to mixes prepared with limestone and cement fillers [7,107] had concluded that asphalt concrete mixes prepared with SSA at same bitumen content have lower Marshall stability and quotient than of limestone mixes. SSA is superior to MSWIA regarding the concentration of leachable toxic compounds and has a concentration within limits specified by the Environmental Protection Agency (EPA). However, it is recommended to perform TCLP tests on ashes and asphalt mix before field utilization.

5.4.3. Waste Glass Powder (GWP)

Glass is an inorganic material made by sintering of selective raw materials, so it can neither be incinerated nor decomposed. Glass is one of the primarily used commodities which have numerous applications such as utensils, lighting, window shelves, flooring, appliances, solar panel, and fiber optic cables, etc. Nearly 10 million tons of glass waste is generated in metro cities annually, which is about 3–5% of the total domestic waste. Although, it can also be treated as demolition waste when it is produced from crushed window panes or can be treated as glass industry waste when produced during cutting and polishing operations. Since in most of the studies, it is obtained from crushing of bottles, it is here placed in category of domestic waste. Glass is brittle in nature having low absorption and primarily consists of silica in composition. Many studies have observed the improvement in Marshall stability after incorporation of glass as a filler [14,15,29,96]. in their study has observed significant improvement in stability, fatigue life, stiffness modulus, and rutting resistance when GWP as used in place of brick dust, stone dust and rice husk ash in asphalt concrete mixes. The reason behind this was improved physicochemical interaction between glass and bitumen as compared to other fillers. Recent studies have observed that glass powder modified mixes displayed superior resistance against rutting and cracking, however, glass powder displayed poor moisture resistance as well as poor active and passive than conventional OPC and stone dust mixes [32,35]. Poor moisture sensitivity and adhesion of glass modified asphalt mixes are attributed to poor bitumen asphalt bonding; due to the predominance of silica in the composition of glass. However, a recent study has observed that utilization of glass powder with the small amount of hydrated lime (2%) can significantly improve the moisture resistance as well as active and passive adhesion of asphalt mix [32]. This was attributed to the anti-stripping nature of hydrated lime caused by the presence of calcium-based water-insoluble minerals like calcite and portlandite in the composition of hydrated lime. Hence future studies on glass fillers shall be focused on improving the moisture resistance of glass mixes with the optimum amount of anti-stripping agents.

5.5. Mining wastes

5.5.1. Coal Mine Waste (CMW)

Coal after being mined undergoes various washing and preparation processes. Coal preparation comprises of physical processes like regulation, gradation, and reduction of mineral substances such as sulfur and ash to improve the coal quality. Coal wastes are generated during coal preparation processes which include operations such as screening, cleaning, crushing, and separation. These wastes after being reduced to suitable fineness can be used in asphalt mixes. Studies on the utilization of waste coal powder as filler in asphalt mixes are limited; however, it was utilized as aggregates in HMA and caused a decrease in mixture durability [49,74]. stated that CMW modified asphalt mixes had higher Marshall stability, fatigue lives, cracking resistance and resilient modulus than limestone modified mixes. TCLP test was performed on all mixes and heavy metal concentration in a mix containing CMW was found to be similar to that of control mix. However, traces of Chromium and Arsenic were found in leachates, but they were within the regulatory levels due to the stabilizing effect of bitumen. Some CWP also has higher moisture content than that was specified in specifications which cause negative effect over its performance in asphalt mixes. [129] had prepared asphalt concrete mixes with conventional limestone filler and CWP at different replacement rates. CMW and limestone had a predominance of SiO_2 and CaO in their composition respectively, which are usually, associated with high and low moisture susceptibility. Interestingly, asphalt mix prepared with a filler having an equal proportion of both materials displayed superior performances in terms of moisture sensitivity and cracking resistance than conventional limestone mix. This was attributed to combined pozzolanic action of silica in CMW and water-resistive properties of CaO in limestone which gave better performance than in case of utilization of both materials single-handedly. At all replacement percentages, mixes prepared with CMW satisfied minimum criteria required for moisture stability, and highest stability was displayed by mix having 100% CMW as filler.

6. Discussions and insights

This section summarizes the performances of various waste filler modified mixes in primary aspects (stability, rutting resistance, cracking resistance, fatigue resistance, moisture resistance, and OBC) to mixes prepared with conventional fillers (stone dust, OPC, hydrated lime, etc.). These results are summarized in Fig. 5, which suggest the variable performance range of waste modified mixes when compared with conventional filler mixes. Although, in some cases for wastes like phosphogypsum, sugarcane bagasse ash, red mud, and copper tailings etc., there are very limited studies existed. However, these charts will provide a general idea regarding the performance of various waste fillers in different aspects of asphalt mixes.

6.1. Effect on stability

Stability determines the ability of asphalt mixes to resist deformation caused by applied loads. It is dependent on the contact points develops within the aggregate skeleton and on the properties of binder film that enveloped those contact points. Coarser part of filler forms the contact points that wedged-in by the binder films, which hinder their displacement when stressed. On the other hand, the inclusion of the finer portion of filler particles in asphalt mixes stiffens mastic and improves asphalt mix density as well as stability. All waste modified mixes (Fig. 5(a)) provided satisfactory stability as demanded by their respective paving standards. It can be seen that out of 17 types of waste into consideration, 9 types of waste mixes always have higher stabilities than conventional mixes, whereas 5 types of wastes displayed mixed results. The improvement in Marshall stabilities in waste modified mixes were attributed to several factors such as improvement in stiffness and cohesion due to the reinforcing effect of non-spherical filler particles to the bitumen [6], good physico-chemical interaction of filler with bitumen due to fineness of filler [14,73], high pozzolanic properties of CWA [73], microcrystalline structure of filler [53] and angular shape of filler [14]. Since all waste modified mixes delivered satisfactory stability, there should be no concern regarding the low stability on the field.

6.2. Effect on rutting resistance

Rutting can be defined as permanent deformation in the transverse profile in wheel patch which occurs due to repeated heavy traffic loading, especially at high temperatures. Numerous filler characteristics such as Rigden Voids (RV), particle size, particle

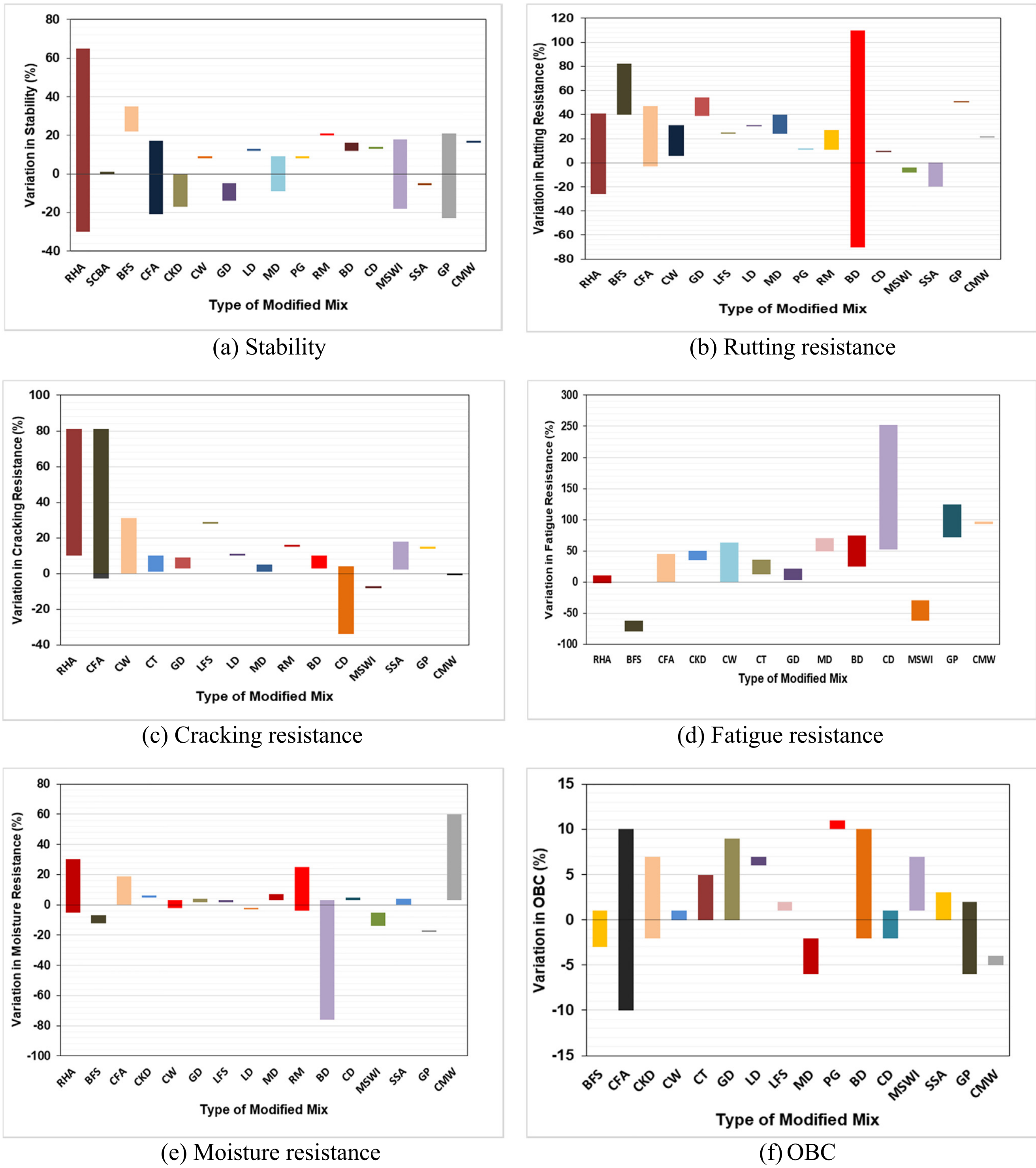


Fig. 5. Variations in various properties of waste filler modified mixes in comparison to conventional filler mixes. Aburkaba and Munaindy [2], Al-Hdabi [6], Al Sayed et al. [7], Arabani et al., [14], Bocci [18], Chandra and Choudhary [32,25], Chen et al., [26], Choudhary et al. [32–35], Katamine [53], Kuity et al. [57], Mistry et al. [70], Modarres and Bengar [72], Modarres et al. [87,74], Saltan et al. [96], Sargin et al. [98], Sharma et al. [99], Sutradhar et al. [101], Taha et al. [103], Tenza-Abril et al. [107], Xue et al. [113], Zainudin et al. [114].

shape, particle size distribution, surface area, CaO content, and clay content affect the performance of mixes against rutting resistance. There is no well-defined criterion specified for rutting resistance especially in Indian specifications [71]. Asphalt mix which possesses higher Marshall quotient value displays superior stiffness as well as better load distribution capability, which ultimately results in its improved resistance against creep or rutting. Marshall quotient has been used by various researchers to assess the rutting resistance of various types of asphalt mixes [14,21,76,111]. In Indian specification [71], an allowable range of Marshall quotient (2–5 kN/mm) is specified for dense graded asphalt mix to design rut resistant as well as to avoid excessive brittle mixes. Analysis of rutting resistance of mixes made from 16 different wastes is done in Fig. 5(b). Out of 16 wastes, 11 of them have given higher rutting resistance than conventional mixes, whereas, 3 of them has shown mixed results. The improvements in rutting resistance of waste modified mixes were attributed to factors such as higher stiffening of mastic due to the fine size of filler [14], high physico-chemical interaction between bitumen and filler due to angular shape and sharp particle edges [14,25], enhanced stiffness of mastic and mastic aggregate adhesion due to absorption of light components of bitumen by fillers, chemical composition of filler [116]; high bitumen absorption due to large porosity [27], and larger contact area of filler in mix due to its lower specific gravity [27]. MSWIA and SSA modified mixes have displayed lower rutting resistance (lower dynamic stability as per the dynamic creep analysis) than conventional mixes which may be attributed to their irregular particle shape and predominance of silica in their composition. It must be noted that phosphogypsum modified mixes displayed superior rutting resistance than conventional mixes in the absence of water as determined from Marshall quotient analysis. However, these mixes also found to be highly susceptible to water as they were collapsed under the water exposure in immersed wheel rut testing. This was attributed to the microcrystalline structure of phosphogypsum which loosens its mechanical interlock and softens in the presence of water. Brick dust mixes displayed the higher variability in results, they not only displayed superior rutting resistance due to their rough texture and angular particle shape [14] but also displayed poor rutting resistance (higher permanent deformation in static creep test) [57]. Hence these materials should be utilized judiciously on the field.

6.3. Effect on cracking resistance

Cracking is one of the primary types of pavement distresses caused due to the application of heavy traffic load as well as due to the harsh service environment. Since filler cause stiffening to the asphalt mixes, it directly influences the performance of mixes against cracking. However, there is no criterion specified in mix design specifications for designing of crack-resistant mixes. Out of 15 different wastes considered in the study (Fig. 5(c)), mixes prepared with 11 of them have higher cracking resistance than conventional mixes, whereas, 2 of them have shown mixed results. The primary causes for improved performances of waste filler modified mixes are: finer nature of filler which cause its even distribution in bitumen [72], fine particle size distribution of filler [72], improvement of cohesion in the mix [107] and hardening effect of minerals such as $Ca(OH)_2$ in the filler [18]. Although filler provides stiffening to mixes which increases its cracking resistance, selection of suitable filler type and its quantity should be made judiciously to avoid excessively brittle mixes.

6.4. Effect on fatigue resistance

In asphalt pavements, fatigue cracking is primary distress which predominately occurs at low and intermediate temperatures, due to successive tensile strain induced by repetitive traffic loading. It initiates with adhesive and/or cohesive micro-cracking at the bottom of the layer and propagates upwards as microcracks grow and coalesce. Some studies suggested that fatigue cracking primarily depends upon characteristics of binder and filler, physicochemical interaction between binder and filler and on other factors that affects micro crack development. Above stated physicochemical interaction is dependent upon fineness, mineralogical composition and surface characteristics of fillers [55]. However, few studies haven't found any correlation between fatigue cracking and various characterization properties such as Rigden voids, German filler test values, particle size distribution, methylene blue value and plasticity indices of filler types [62,82]. Hence the role of filler over fatigue life is not well defined amongst researchers and open for wide speculation.

There are no well-defined provisions specified in paving specifications to design fatigue-resistant mixes. Out of 13 different types of waste filler modified mixes, 11 were found to have fatigue resistance similar to or higher than conventional mixes. Only MSWIA and LFS formed relatively inferior fatigue-resistant mixes. The improvements in fatigue resistance for majority of waste modified mixes were attributed to factors such as: enhanced stiffness of mixes due to higher porosity of filler [25], stiffening of mixes due to fine gradation of filler [72], improvement in cohesive strength of mixes [77], hardening effect of $Ca(OH)_2$ present in composition of filler [18].

6.5. Effect on moisture susceptibility

Moisture is a primary cause of failure of asphalt mix because its presence could lead to its loss of structural strength and durability. It can be defined as breaking or weakening of the bond between aggregate and binder due to permeation of moisture. It is usually caused due to dislodgement of aggregates by the continued action of moisture-induced weakening and cyclic traffic loading. This failure can manifest in the form of distresses such as stripping, shoving, raveling, rutting, cracking, loss of strength and durability in asphalt mixes. Mineral filler can influence adhesion between binder and aggregate for two reasons. Firstly, the filler can fill voids in the asphalt mix and prevent the entry of water. Secondly, some fillers (hydrated lime and OPC) tend to show the higher chemical affinity towards binder which improves moisture resistance of mix. Asphalt concrete mixes having a minimum tensile strength ratio (TSR) of 0.8 as determined from Modified Lottmen test (AASHTO T283) is classified as moisture-resistant mix as per Indian specification [71]. A large number of countries follow this test method with a similar or altered requirement of TSR. Moisture resistances of 16 types of wastes modified mixes are stated in Fig. 5(e). Along with these 16 wastes, moisture resistance performance of phosphogypsum modified mix (not mentioned in the diagram) is also taken into consideration. Out of these 17 wastes, 8 types of mixes always had higher moisture resistance than conventional mixes whereas 4 of them has shown mixed results. Five types of materials (phosphogypsum, glass, MSWIA, blast furnace slag, and limestone dust) have shown relatively poor performance than conventional filler. The primary reasons behind this improved performance are: enhanced adhesion between aggregate and bitumen due to even distribution of fine filler particles [70], low clay content in filler [29,50,99], pozzolanic properties of filler [73], hydrophobic nature of filler [31,73], presence of adhesion promoters like calcite [25]or free calcium etc. Brick dust mixes have shown high variability in their performance, in some studies they have shown good performance which was attributed to the hydrophobic nature of brick dust [27]. Whereas, its poor performance was due to its high clay content and acidic nature [57]. Phosphogypsum and glass mixes has shown substantially poor performance in the presence of water. The poor performance of phosphogypsum mix is due to the microcrystalline structure of phosphogypsum which loosens its mechanical interlock and softens in the presence of water [53]. On the other hand, glass modified mixes have poor adhesion with bitumen due to high silica in its composition. High silica content was also the primary reason for the poor performance of MSWI and blast furnace slag mixes [113]. Interestingly, despite the presence of bitumen adhesion promoter like calcite in its composition, limestone dust mixes have shown satisfactory yet marginally lower moisture resistance than conventional mixes [30]. This was attributed to high clay content in its composition. However, the performance of limestone dust need further studies.

6.6. Effect on OBC

The initial cost of pavement is governed by the cost of materials and construction. Bitumen is amongst one of the costliest components of asphalt mix, and optimum binder content (OBC) (bitumen content to ensure optimum strength and durability of HMA) affects the cost of pavement the most. The binder in any asphalt mix can be classified into two parts, fixed binder (binder filling the voids amongst the compacted filler grains) and free binder (excess binder remaining after voids are being filled). Sufficient amount of free binder is necessary for the mix since it coats the aggregate structure and ensures the durability of the mix. Physical and chemical properties of fillers have direct influence over volumetric properties of asphalt mix and thus affect the OBC of the mix. Majority of wastes modified mixes were found to have higher OBC than conventional filler mixes. Out of 16 types of mixes in consideration, 8 had higher OBC than conventional mixes whereas 6 had shown mixed results. Higher OBC of waste modified mixes was due to higher bitumen absorption due to filler's: high porosity [14,25,70], high specific surface area [70,103], high surface roughness [21,26,27] and particle shape and homogenous particle size distribution [30,99]. Hence in general observation, it can be said that inclusion of waste as filler increases the initial material cost of the mix. However, in many cases waste fillers with particle sizes smaller than bitumen film thickness exhibited bitumen extender function by which they can provide partial substitution of asphalt binder which also can economize the mix [25,70,99,100].

7. Current limitations and future research directions

There has been extensive research since 1900 or earlier that emphasize on the utilization of waste materials as alternative fillers in asphalt mixes. The current knowledge base as it pertains to the utilization of waste fillers, would benefit from more extensive research in several areas. The following section enlists the current limitations as well as future research directions to increase the efficiency of current practices.

7.1. Reevaluation and updating of current design practices

It has been well established that type of filler and filler content has a significant influence over the performance of asphalt mastic and mixes. The performance of any waste material as a filler depends on numerous factors, and it is vital to take the synergistic effect of various factors (such as particle shape, particle size distribution, porosity, mineralogy, hydrophobic nature, etc.) into account to predict the field performance of its asphalt mixes. The existing asphalt mix design practices especially Indian paving specifications [71], has fallen short of meeting present needs. For example, unlike European standards [38] and Chinese specifications (JTG E42) which classify fillers much comprehensively, Indian specification classifies fillers based on the limited criteria of particle size and plasticity index alone. These two criteria are insufficient to predict field performance of asphalt mixes and there is need to establish limits for important characteristics like specific gravity, porosity (Rigden Voids) and bitumen affinity (hydrophilic coefficient). The viability of current plasticity index criteria is also questionable amongst researchers and need to be replaced with much viable methylene blue value test. Various agencies limit the amount of filler based on the established range of filler-binder ratio that usually varies in between 0.6 and 1.2. However, since waste fillers significantly vary in gradation, particle shape, surface area, mineralogical composition, and physicochemical properties, their maximum allowable limit should be different for different fillers. Finally, the provision of toxicity characteristic leaching procedure (TCLP) tests should be added in specifications to avoid hazardous wastes and limit health risks and environmental problems.

7.2. Development of inexpensive testing methods

Although the performance of HMA has been influenced by numerous filler characteristics. It is not easy and practically viable to include all criteria in design specifications. There is an immediate need to derive correlations amongst various characteristics. This will not only reduce the number of tests required to accurately predict the field performance but also can replace expensive tests with inexpensive ones. For example, in field conditions, tests such as Rigden void test can be attempted to replace with simple German filler value tests, since various researchers have found negative correlation amongst both [32,50]. Similarly, attempts can be made to find correlations between quantities of CaO and SiO_2 determined from expensive X-ray fluorescence (XRF) and simple pH value or hydrophilic coefficient test to eliminate the need to perform the XRF.

7.3. Detailed study of unexplored/seldom explored wastes

There is an appreciable amounts of literature available on the performance of wastes like coal fly ash, brick dust, and cement kiln dust etc. as filler in asphalt mixes. However, there is lack of detailed performance studies on a several types of wastes that could be a viable alternatives to the conventional fillers. Few of the wastes which expect to form mixes with superior performance and are needed to be explored in future are stated below.

(a) *Sugarcane bagasse ash:* It has finer size and non-spherical particles due to which it can form mixes with higher fracture resistance and stability. It also has lower specific gravity and higher specific surface area which may enable it to form mixes with lower optimum binder content and higher rutting resistance. However, the optimum quantity of ash needed for satisfactory performing mix is needed to be determined since its excessive quantity may form brittle and moisture susceptible mixes.

(b) *Bauxite residue:* It has fine nature, rough texture and oxides of iron and aluminium in composition which might enables it to form mixes with higher cracking resistance, rutting resistance and stability. It also has lower clay content, alkaline and hydrophobic nature that ensure its strong bonding with the bitumen which might result in the formation of moisture resistant mixes. However it also has a presence of heavy metal like Titanium in its composition and a detailed leaching analysis is needed to be done before its field application.

(c) *Dried lime sludge:* Lime sludge is a major solid waste generated from paper and acetylene industries. It primarily consists of calcium carbonate along with small amount of Al_2O_3 and SiO_2 [52]. Due to higher amount of $CaCO_3$ in its composition, it may form mixes with strong bitumen-filler bonding and higher moisture resistance. Its higher affinity towards bitumen may also results in higher rutting and fracture resistance.

(d) *Waste bleaching clay:* Bleaching clay is used in food industries to remove coloured impurities from vegetable, mineral and animal oils. It has lower specific gravity and relatively higher porosity than limestone filler, which form mixes with higher rutting resistance and resilient modulus. The main concern with these clay are their composition which consist of montmorillonite in large quantity, which is a mineral that expects to swell in presence of water and may form moisture susceptible mix. A recent study has investigated the suitability of waste bleaching clay as filler in porous asphalt mix and it is suggested that it doesn't significantly affect the moisture sensitivity of mix. [97]. Hence the use of bleaching clay in the various types of asphalt mixes is open for wide exploration.

(e) *Waste seashells:* Seashells are the marine waste found in the coastal areas which after washing and effective crushing can be used as filler. It consists of CaO in higher quantities which form stronger bond with bitumen and form moisture resistance mixes. However, seashell also has a rough surface texture which may also increase the optimum binder content of their mixes. There is one peer reviewed study existed on mixes containing seashell filler which suggested that, replacement of seashell forms mixes with superior rutting and fatigue resistance [13]. However, the efficient utilization of seashell requires the establishment of a proper collection channel.

Apart from these wastes, several other highly produced and unexplored wastes/byproducts such as Jarosite (Zinc industry), Kimberlite (Diamond mining), Phosphogypsum (fertilizer industry), ladle furnace slag (iron industry), copper tailing (copper industry), and Zeolite catalyst (Oil refineries), etc. should also need to be investigated.

7.4. Lack of in-depth analysis in various aspects of mix

The current studies on waste amended asphalt mixes is lacking in-depth analyses of the effects of alternative fillers on the properties such as long term durability, aging, permeability, thermal and electrical conductivity of asphalt mixes. While most of the studies analyzed the influences of waste fillers over mix's properties such as stability, cracking resistance, rutting resistance, fatigue resistance, and moisture sensitivity, analyses regarding their influences over long term aging, permeability, thermal and electrical conductivity are not well documented. This presents a potential avenue for future research of waste fillers to gain further acceptance in more harsh climates and special pavements like conductive asphalt pavements, porous pavements and cool pavements with low heat island effect. Influence of some characterization properties over the performance of asphalt is also not well established. For example, few researchers [109] found the influence of CaO over the moisture susceptibility of HMA, whereas some [12] didn't found any correlation amongst them. Similarly, the influence of quantity of filler over the OBC of the mix is also not clear. Some researchers stated that the mixes with higher quantities of filler have lower OBC, whereas other contradicts it. These discrepancies need to be addressed.

7.5. Design of composite fillers

In some studies, fillers prepared by mixing two different materials gave superior performance, than in a case when materials used alone [129]. However, recent studies are focusing on enhancement of properties of wastes like coal fly ash by modifying it with some other wastes to form binary or even ternary fillers [80,126]. But apart from fly ash there is no study on other waste which focuses on the development of inexpensive composite mineral filler that not only performs optimally against multiple pavement distresses but also prevents leaching of toxic materials. Future studies should be focused on developing composite fillers by mixing multiple local wastes in optimum proportions, or by providing effective physical and chemical modification to ensure techno-economic feasibility of asphalt mixes.

7.6. Study of unconventional mixes

Most of the studies on waste fillers are majorly focused on their utilization in hot mix asphalt, particularly in mixes like asphalt concrete and DBM mixes. Although some studies focused on gap graded mixes like SMA, and few studies on coal fly ash which focused on special mixes like cold asphalt emulsion mix foamed bitumen stabilized mixes. But overall there are very limited studies on utilization of fillers in unconventional mixes like warm mix asphalt, recycled asphalt mixes, cold asphalt mixes, foamed bitumen stabilized mixes, and this field requires further exploration.

7.7. Research and development of efficient material processing technologies

Most of the wastes required suitable pretreatment which majorly includes procedures like washing and milling to remove deleterious substances and to reduce waste to suitable fineness. Type and extent of pretreatment not only can increase the cost and energy consumption of the material but can also alter its property and affect the overall performance of mix. A significant analysis can be done to establish a correlation between the pretreatment done on various mixes and their overall influence over the performance of asphalt mixes. Some primary areas of analyses can be as follows,

(a) Research efforts can be made for the development of inexpensive material processing technology which can produce materials into more homogenous stockpiles, with minimum milling as well as least amount of toxic materials.

(b) Previous studies have suggested that burning temperature of biomass/agriculture waste affects the physical (porosity, particle shape, and size) as well as chemical composition (carbon and silica content) of its ash which can alter strength, durability, and workability of asphalt mixes [69]. An investigation into the analysis between the degree of calcination/incineration/burning and properties of mixes can be done in order to quantify energy consumption versus improvement value.

(c) Degree of milling of various wastes can affect its physical properties like porosity, particle shape, particle size, and particle size distribution which affect filler's interaction with binder and influence performance of mixes. Similar to the previous case, investigation into the analysis between the degree of milling and properties of mixes can be done to quantify energy consumption versus improvement value to ensure optimum performance at commercial stage.

(d) A detailed investigation into water removal from slurry wastes such as sewage sludge and red mud slurry in a cost and energy-efficient manner is needed.

7.8. Life Cycle Analysis (LCA)

Most of the wastes stated in the study have not had LCA performed; the primary obstacle to performing LCA is the inherent variability of these materials. An investigation of initial and maintenance of asphalt mixes over a long-term period need to be collected and documented to appreciate the benefits of waste modified mixes and to make recommendations for implementation.

7.9. Development of nation wide database

A national-level database can be developed based on the production of waste materials which include their total generation along with their physical and chemical properties. It will help to identify locally available wastes that could be utilized as filler beneficially at local levels without increasing any significant transportation cost. This will also eventually be beneficial to the entrepreneurs to set up industries for the development of new innovative fillers. The database will also help in designing a proper collection channel ensuring the beneficial use of domestic wastes as well as to generate suitable occupational opportunities for rag pickers. This scheme can be linked to existing government programs such as "Clean India Campaign" to ensure their optimum working.

8. Conclusions

The optimum utilization of waste materials as alternative fillers has the potential to be beneficial for the flexible pavement infrastructure as well as for the environment. The literature included in this study has verified the positive influences of studied wastes over various aspects of asphalt mastics and mixes. It becomes evident that there is an emerging need for alternative materials that can replace conventional fillers like stone dust, hydrated lime, and OPC. The global demand for fillers in the foreseeable future is going to be increased and as the movement towards more environmentally feasible pavement materials endures, it is necessary for pavement industry to consider alternative materials that previously would not have been considered for the purpose. Hence, the research community must immediately fill the existing knowledge gaps regarding the countless potential alternatives. Currently, there is a fundamental lack of scientific knowledge on the performance of these less frequently evaluated wastes fillers. Literature review suggested that various physical, mineralogical and chemical characteristics of filler as well as their quantity in asphalt mix influence performance of asphalt mix. However, existing specifications around the globe, including Indian paving standards [71], characterize fillers based on limited criteria (particle size distribution and plasticity index) which can only be used for quality control but are not sufficient enough to accurately predict the field performances of asphalt mix. This need is more pronounced in case of utilizing waste materials, whose performance/properties not only varies with their type but also varies along with their source and process of production. Hence firstly there is an immediate need to introduce additional characterization parameters/tests for filler, which could help in accurately predicting the field performance of asphalt mixes. It is found that the physical and chemical characteristics of waste fillers are responsible for delivering satisfactory performance of their mixes in comparison to conventional mixes. However to reduce variability in properties as well as to economize the initial cost of mixes, potential improvement is needed in preprocessing technologies especially in SSA, MSWIA, biomass ash, and in construction and demolition wastes. The benefits of utilizing waste fillers are not only constrained to the improvement in mechanical and durability performance of mixes but can be observed through a significant reduction in economic and environmental cost. The benefits are often multifaceted: firstly, by the diversion of significant materials from a landfill, secondly, through a decrease in cost related to conventional fillers, and finally, replacement of conventional fillers especially cement renders the overall asphalt mix more carbon conscious and environmentally friendly. However filler is a very fine material which require careful handling and safe exposure. Without the proper safety gear, the excessive fine dust exposure may cause serious respiratory (asthma, silicosis, chronic obstructive pulmonary disease, mesothelioma, and lung cancer), skin (dermatitis) and vision (eye itching and vision loss) problems to the construction workers. These problems become more acute while working with wastes like ashes, glass powder and red mud. Hence unlike aggregates which are usually stacked in open areas, these waste fillers are needed to be stored in closed rooms. Proper regulations should also be enforced by the government agencies, while workers themselves should comply with protection practices such as using respirator masks in need. In conclusion it can be said that, if more waste fillers can be refined to a greater degree than today's standards, the widespread acceptance of less frequently utilized alternative fillers will become the industry standard and help facilitate the global sustainable development goal of creating an economically sustainable circular economy.

Declaration of Competing Interest

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

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