RESEARCH ARTICLE OPEN ACCESS

Recent progress in the utilization of waste materials for road construction

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ABSTRACT
The construction of roads and highways is one of the central socio-economic parameters in a country.The construction industry is expanding at a much larger scale and consumes highly costly materials such as cement, limestone, stone aggregates, concretes, and bitumen. Due to the non-renewability, unsustainability, and environment degrading nature of these materials, the researchers are looking for alternate materials to be explored in road construction and maintenance. The scarcity of conventional raw materials in road construction has further stressed the incorporation of unconventional ingredients including recycled waste materials. The possible utilization of wastes materials from the plastic industry, construction and demolition wastes, bottom ash wastes, municipal solid wastes, and other wastes can provide a better alternative for the construction of roads in a sustainable and environmentally friendly way. These materials provide several advantages such as renewable nature, inexpensive, eco-friendly, easy availability less energyconsumption, and improvement in the life cycles and performance of roads. This review provides an insight into the generation and applications of wastes generated from different sources that have been investigated and explored for the construction of roads, pavements, and highways. This work also describes the advantages and limitations of waste materials as compared to traditional materials in road engineering.
Keywords: Waste materials; Road and highway construction; Recycling; Plastic wastes; Construction & Demolition wastes.

Date of Submission: 20-07-2021 Date of Acceptance: 04-08-2021

Graphical abstract

I. INTRODUCTION

There is a continuous increase in the construction activities related to infrastructure development, construction of commercial structures, residential societies, buildings, and others. Along with these, the construction and maintenance of roads and highwaysaresome of the most important parameters in determining the socio-economic development of a country. Roads are one of the important lifelines of a nation's economy and form the backbone of the transportation industry. The construction and maintenance of roads is verytactical and signify various sources of income and expenditure. Construction of roads, pavements, and highways requires huge volumes of aggregated materials and mass haulage(Horvath, 2004; Zapata & Gambatese, 2005). In the year 2018, it was estimated that over 257 million tonnes of sand and gravel weregenerated by the leading countries(Hasan et al., 2020). Moreover, concerns related to increasing demands for bituminous materials, high costs of petroleum-derived asphalts, depletion of natural materials, and increased prices and taxes of materials have further worsened the situation. The current production costs and the processes do not go by the sustainable development goals set up by United Nations and therefore focus on the need for environment-friendly practices and materials/aggregates for road construction has increased(Dunmininu, 2020; Jia et al., 2020). Since it has become a necessity to consider the sustainability criteria in road construction, there is a need to utilize unconventional materials as compared to the use of standard materials in road construction.

The rapid upsurge in transport vehicles can result in failures of road sections. These failures are related to the stripping of topsoil, and at bottom of the surface layer and subgrade layer (Li et al., 2019). This has stressed the importance of materials that fulfill the basic need of toughness, good performance, and less maintenance and construction expenditure onroads. Different types of industrial wastes, by-products, municipal wastes, etc. can be exploited in road and highway construction replacing traditional construction materials(Abukhettala, 2016; del Río Merino et al., 2018). These materials can advance the efficiency of the construction process in terms of processing costs,economics, engineering aspects, viability, and maintenance. These materials must fulfill certain engineering properties and be eco-friendlier and more sustainable in use(Dunmininu, 2020). In this regard, the reuse of waste materials from the plastic industry, construction & demolition sites, rubber wastes, glass wastes, incineration bottom ash and fly ash, tire shreds, landfills and mining wastes, biological wastes, recycled concrete, etc. can be applied for road construction. These waste materials have been investigated and explored when used alone or in combination with other wastes or with other raw materials as a complete substitute for road construction materials.These materials are generally used as stabilizing agents (in replacement for cement, asphalt, concrete, etc.) with soil to improve the mechanical properties of soil(Dunmininu, 2020). However, the use of wastes and its application in road development is quite limited due to less knowledge and awareness. However, researchers and scientists are highly optimistic about the development and use of such materials, in near future, for the inclusion of these materials in the road industry. The research on laboratory and field-scale on better usage of these materials is still ongoing and flourishing.

The present work sets recent state of the art on the applications of waste materials as the alternative for conventional materials in road construction. The generation and utilization of different types of wastes produced on the physio-mechanical properties of different aggregates used in soil construction have been discussed. Further, the economic aspects of recycling wastes are discussed fromthe perspective of road construction.

II. SEARCH STRATEGY AND PROTOCOL OF THE STUDY

2.1Literature sources and search Strategy

To collect relevant articles applications on different categories of wastes produced and utilized for road construction, a comprehensive search was performed on 23 July 2021 on different sources such as Google Scholar, ScienceDirect, Springer Nature, Web of Science, and Scopus. All the research articles published from the year 2016 to 2021 were selected and further reviewed. The keywords used for the search were "waste material" AND "road construction" OR "highway" OR "pavements". Based on the inclusion and exclusion criteria as described further, the most suitable studies were collected. The articles were identified first based on title, abstract, and then full-text evaluation.

2.2 Inclusion and exclusion criteria

In this work, the following norms were considered for inclusion of studies for writing the review (a) Articles published in peer-reviewed journals in English language were chosen. (b) Only those articles were selected which include application of different wastes either used alone with combination with other materials for road construction (c) Availability of full text of article (d) Articles published in English language only. The exclusion criteria were (a) books, book chapters, letters to the editor, review articles were excluded from the study. (b) Articles published in languages other than English (b) Articles available on the internet without undergoing a peer-review process. However, the references of the related articles were extracted from thesepapers to access more articles. All the articles chosen were then sorted according to the category of the waste material and were investigated further for writing the review.

III. GENERATION AND UTILIZATION OF WASTES FOR ROAD CONSTRUCTION

Rapid industrialization has resulted in the production of huge quantities of wastes, both solid and liquid wastes, from the plastic industry, construction sector, metal, and metallurgy industry, rubber and glass industry, municipal corporations, landfill and mining wastes, etc. The complexity and heterogeneity of waste materials produced in large volumes can pose a hazardous danger to the environment as well as public health. According to United Nations, approx. 11.2 billion tonnes of solid wastes are generated that can endanger the water, soil, and air quality. It has become a collective responsibility of governments, industries, and the public to utilize these wastes and by-products for beneficial applications including the road construction sector. The motivation of using waste materials in road developments is mainly due to two main reasons, either to enhance properties of existing materials or to save expensive resources. The improvement in properties of traditional materials can be done either by substituting conventional materials such as bitumen with polymer blends or using a mix of different recycled materials to achieve synergistic beneficial properties. Regarding resource conservation, re-use of old materials such as construction & demolition wastes has been demonstrated to produce good quality roads. This section has been devoted to the recent scientific literature on the application of these generated wastes in the road construction industry.

3.1 Plastic wastes

Plastic is present all over the space in our phones, clothes, household materials, vehicles, and eatables. The immense use of conventional plastic such as high-density polyethylene (HDPE), polyethylene terephthalate (PET), or polypropylene (PP) contaminates natural resources, and cause risk to ecosystems(Schwarz et al., 2019; Zhang et al., 2020). Moreover, only between 5 to 25 % of total plastic wastes is being recycled (Siddiqui & Pandey, 2013).Among all the plastics, PET packaging has become one of the important sources of water pollutants. Around 250 million tons of PET wastes are generated annually throughout the world and around 60 % of these wastes are dumped in landfills(Meys et al., 2020; Thiounn & Smith, 2020). Plastic wastes have shown huge capability in road construction as soil stabilizing agents, road aggregates, blends, lightweight materials, polymer concretes bricks, and asphalt binder(Ali et al., 2018; Jaishwal et al.; Nazari et al., 2020; Rokdey et al., 2015; Sutar et al., 2016). According to a report by Asian Developmental Bank, the use of waste plastics is the most used method (46 %) in the newer technologiesfor rural roads construction (Fig. 1) under Pradhan Mantri Gram SadhakYojana in India(Heriawan, 2020).

Plastic wastes can be used in enhancing the performance of conventional bitumen binders. Binder modification can be done by either preparing plastic-modified bituminous concrete blends through a dry process or by the simultaneous blending of bitumen and waste plastics by wet mixing (Sasidharan et al., 2019).A study evaluated the application of recycled PET bottle wastes in the production of bituminous asphaltic concretes(Sojobi et al., 2016). It was shown that the bitumen modified with PET possess more stability, stiffness, and softening point. An increase in PET content resulted in an increase in air void, void in mineral aggregate, and Marshall stability.A study tested the combinations of HDPE and PP thermoplastic wastes with conventional bitumen material in the production of polymer modified bitumen material (Appiah et al., 2017). The experimental tests showed that modified material can enhance binder properties by increasing viscosity, softening, penetration values, homogeneity, and compatibility both in the case of HDPE and PP blends.Apart from HDPE, low-density polyethylene (LDPE) mixed with asphalt was employed as the laying material for road construction in Faisalabad, Pakistan (Ali et al., 2017). The material provided better resistance against water and also increases road loading capacity. A similar study conducted in Algeria utilized LDPE plastic bags mixed with 40/50 graded bitumen in constructing road pavements (Nouali et al., 2020). The produced concrete mix possessed better performance and compaction ability. Also, pure water sachets wastes made of LDPE were tested as the binding material in asphalt mix in the construction of roads in Nigeria (Bolarinwa et al., 2018). The economics of the study showed a 50 % reduction in road maintenance cost per km using LDPE modified bitumen as compared to conventional mix.

A study evaluated the use of plastic wastes collected from the garbage in the production of material aggregates for road construction (Manju et al., 2017). The plastic mixed with hot bitumen reduced the total content of bitumen by 10 %. Similar research was conducted to synthesize plastic waste-coated blends with bitumen by improving the binding of bitumen owing to increased bonding and area of contact between polymers and bitumen (Bajpai et al., 2017). This material with better aggregate impact value and low crushing value was used forthe construction of rural roads. In another study, a dry process was used for mixing bituminous concrete with shredded plastic wastes including 8 % LDPE and HDPE (Tiwari & Rao, 2018). The mixed material improved the Marshall stability and volumetric properties of the bitumen. There exists a considerable body of literature onthe incorporation of different categories of plastic wastes into developing materials for road and pavements construction(Asare et al., 2019; Das et al., 2019; Meti, 2018; Shaikh et al., 2017).Recently, shredded plastic bags were mixed with asphalt mixtures to improve the performance of asphalt in dry mixing process(Radeef et al., 2021). The modified asphalt mixture was shown to have a 35 % increase in resistance to strain and improvement in adhesive and cohesive properties of the mixtures.

Several other studies have reported the combined use of plastic wastes with wastes from other sourcesto producebituminous concrete. For instance, a study developed bituminous mixes by using plastics wastes with rubbers as binders and fly ashas fillers in fabricating bitumen concrete(Azizi & Goel, 2018).In the case of these mixtures, a significant increase in stability and void filled with bitumen (VFB) was observed as compared to conventional mixes. Also, reports have established the applications of plastic wastes with recycled crushed aggregates, crushed bricks, and crump rubber as the coarse material for the development of road bases(Maharaj et al., 2019; Perera et al., 2019). Recently, anasphalt-steel-plastic pavement structure was designedin China. The asphalt mixtures formed the surface layer, while steel plate and plastic materials worked as the main load-bearing layers (Jiang et al., 2021). The structure as shown in Fig. 2exhibited better efficiency in terms of production costs, durability, and mechanical properties including rutting resistance performance and fatigue resistance performance. Similarly, a heterogeneous plastic waste (known as Plasmix) has been investigated in the modification of bitumen in both wet mixing and dry process (Celauro et al., 2021). The experimental tests on the mechanical stability of the material confirmed that the addition of Plasmixaided in achieving high stiffness and viscosity and higher resistance to permanent deformation at high temperatures.The use of waste plastic fibers in road construction projects is very economical and environment friendly. Waste PET fibers can be used as the binder modifier required for highly porous asphalt concrete and can be used for increasing the mechanical strength of sand(Majid et al., 2019).A summary of all studies concluded that the plastic wastes modified bitumen in road construction can be a successful technology if it is applied in optimum content with required standards. Moreover, further analysis showed that plastic roads have a shining future ahead in terms of performance, durability, mechanical strength, production costs, and environmental impacts. The researchers should continue to develop such plastic-based materials with all types of plastic wastes to advance road engineering and other construction aspects.

3.2Construction & Demolition wastes

Construction & Demolition (C&D) wastes include heavy and bulky materials such as cement concrete, bricks, asphalt, metals, ceramics, bricks, debris, etc. from construction, building, and demolition of infrastructures such as buildings, houses, pavements, and bridges. United States Environmental Protection Agency (USEPA) has estimated the generation of around 569 million tonnes of C&D wastes in the USA in the year 2017. A majority of these wastes (70 %) are composed of concrete cement wastes while the rest of the wastes include asphaltic concrete and other debris (Gautam et al., 2018; Sangiorgi et al., 2015). C&D wastes can act as the substitute for natural aggregates and can also be used for producing new asphalt. The C&D wastes have shown great potential in highway and pavement construction as coarse aggregates, bulk fill, subgrade, and sub-base applications in road construction(Ray et al., 2021). The studies on the use of C&D wastes in road construction are well documented. For instance, numerous studies have reported good mechanical properties and high strength of materials such as recycled concrete aggregates (RCA), cement treated granular materials, and waste ceramic tiles to be used in road construction (Cabalar et al., 2017; Del Rey et al., 2016; Hou et al., 2019). C&D wastes can be recycled in unbound layers of roads including sub-base and capping layers of roads(Roque et al., 2016). The batch and leaching testsconfirmed the possibility of expoliting therecycled aggregates in the development of road pavement layers. Another study used recycled C&D wastes in base and sub-base layers of pavements (Aboutalebi Esfahani, 2018). The wastes were characterized using compaction, California bearing ratio (CBR), and resilient modulus tests. The results proved that these wastes can serve as good materials in sub-base layers.

Another study examined the application of C&D wastes in designing road pavements (Delongui et al., 2018). These wastes showed good elastic strain, resilience modulus, and good shear strength parameters as compared to densely graded crushed basalt. The study concluded that the C&D wastes showed elastic behavior and provide safety against rutting in medium traffic volume roads. Similarly, C&D wastes showing good resilience modulus,lower permanent deformations, and high structural capacity were employed in the construction of highway embankments (Zhang et al., 2019).The recycled C&D wastes also displayed less sensitivity to moisture and can therefore be used in hot and humid areas. The analysis of all the studies shows that the C&D wastes are gaining much attention as an alternative to conventionalconstruction material in the road sector due to higher mechanical stability and good performance.

3.3Bottom ash wastes

Incineration of the solid wastes at high temperatures leads to the production of residues or ash. The ash can be categorized into fly ash and bottom ash that does not rise. Bottom ash is the major part of the wastes which represents the non-combustible remains in the power plants, incinerators, boilers, and furnaces, left after the combustion process(Muthusamy et al., 2020; Sutcu et al., 2019). A large quantity of bottom ash is produced by coal-fired combustion plants as well as the municipal solid waste incineration (MSWI) units. During the operation of MSWI units, a 90% and 70% reduction in the volume and mass, respectively, occurs during incineration(Cho et al., 2020). However, despite the reduction to such a huge extent, a gigantic load of residues is still left behind. MSWI ash represents the majority of the remains (80%), which is estimated to be around 800 million kg globally indicating that incineration is not the last step of waste disposal(Joseph et al., 2018). The majority of this MSWI ash (majorly the bottom ash) ends up dumping into landfills because of non-conformity to the environmental regulations. Further, the incorporation of MSWI ash in road construction can serve the purpose of recycling besides solving the disposal issue. This not only lessens the consumption of non-renewable resources but also prevents the landing up of waste into landfills. Owing to its comparable properties to natural sand, MSWI ash has been demonstrated as a partial or complete replacement to sand or fine aggregates that are used in the construction sectors such as geomaterials, asphalt pavements, and concrete products (Phale & Thakur, 2021). For instance, the reusability of stabilized bottom ash (SBA) obtained from municipal solid waste incinerators was investigated for their application as a road material (Toraldo & Saponaro, 2015). The performance and compatibility of the mixture of SBA (as granular foundation), cement-bound mixes, and asphalt concrete were investigated for road construction. The results of study suggested that the non-hazardous waste (SBA) can be used for construction of roads in conjunction with the existing procedures and equipment. In another study, the analysis of mechanical performance of varied bottom ashes concentrations of MSWI BA (10-40%) was carried out for its application in road construction materials (An et al., 2014). The stability of mixture increased when replacement ratio of virgin aggregate with BA increased from 0 % to 20%. However, the further increase in BA concentration to about 30% and 40% led to decrease in stability. The optimum concentration of BA and asphalt in total mixture was found to be 20% and 6.8 %, respectively. Also, the physical and chemical characteristics of municipal solid waste incineration (MSWI) bottom ash were studied to identify the limitations associated with its usage as replacement material in roads (Tang et al., 2015). It was observed that the BA possesses a detrimental effect on cement hydration and mortar strength. Further, the application of BA as a replacement of aggregate in Hot-Mix Asphalt (HMA) and Portland cement concrete (PCC) is also a topic of concern due to its potential leaching effects (Tasneem et al., 2017). The chemical analysis of BA revealed that such 2nd-cycle recycled materials leach out to release the major alkaline (e.g. Ca, Al, Si, and Na) and trace level heavy metals when mixed with HMA and PCC. However, the release of such leachants decreases after mixing 10–20% of BA owing to the binding properties of asphalt and cement mixtures. In addition, the recycling of BA for road constructions is associated with emission of lead which is taken as a crucial factor in risk assessment (Van Praagh et al., 2018). Later on, the coupled investigation of physicochemical aspects and hydromechanical resistance of BA was also conducted (Le et al., 2018). Firstly, physicochemical tests were performed to analyze the chemical content. Next, themechanical and hydromechanical tests were carried out to check its fragment ability and degradability. The results of the study showed that the major component affecting the characteristics of BA was silica (SiO_2) which provides resistance to water or other chemical reactions in the environment for road construction.In another work, the application of BA was also investigated as a recycled filler material in bituminous mixtures for road pavements (Topini et al., 2018). Various parameters such as compaction properties, volumetric characteristics, and mechanical performance of the bituminous mixtures made from BA and the calcareous filler (standard filler material) were analyzed which led to the conclusion that the recycled BA is quite suitable for bituminous mixtures. Further, the use of BA increases the performance of mixtures as compared to the standard fillers.

In an interesting study, the MSWI bottom ash was blended with natural aggregates and successfully checked as a partial material for road base (Schafer et al., 2019). Two different weathered BA were mixed with upto 85 % content of conventional aggregates to reduce leaching and risks to human health. The study efficiently controlled environmentally leached and total concentrations from the ash residues. Similar studies reported the leaching pattern of heavy metals from mixtures of MSWI bottom ash and permeable asphalt when utilized in road construction materials(Zhao & Zhu, 2019; Zhu et al., 2020). Most recently, a field-scale application on the use of MSWI bottom ash was found to be most suitable in road development(Spreadbury et al., 2021). The study suggested that the layer thickness, compaction effort, and moisture content can affect the base layer's resilient modulus and permanent deformation. Some authors have driven the further development of concrete mixtures based on bottom ash and cement (Gražulytė et al., 2020). It was found that in the case of concrete mixtures developed with MSWI bottom ash, approx. 30 kg/m^3 of cement was used to get the desired compression strength of 20 MPa.Apart from bottom ash, fly ash wastes can also be a cost-effective solution used particularly used for the stabilization of soils for road construction works (Barišić et al., 2019). In the light of reported studies, it is conceivable that the bottom ash and fly ash wastes can be utilized as an economical material for road works. However, the main drawbacks of using the bottom ash wastes are the unknown composition of the material as it depends upon the incinerated material.

3.4 Glass wastes

Glass forms one of the major wastes in municipal solid wastes, particularly in urban areas. The glass waste is completely recyclable without any loss in its properties. This process is less energy-intensive and employs no additional materials. The glass wastes are generally the canisters used for packaging food and drinks, pharmaceutical products; and the glass used in the automobile industry. USEPA estimated the production of 11.4 million tonnes of glass out of which 7 million tonnes are disposed of in landfills(Dunmininu, 2020). It was reported in the literature that crushed glass wastes can be used as construction material in road works as aggregates in asphaltic concrete mixtures, aggregates in unbound base and subbase layers,and cementitious materials(Mohajerani et al., 2017).For instance, a study investigated the performance of waste glass as fine glass aggregates (FGA) in the development of bituminous emulsion mixtures(Kadhim et al., 2019). These mixtures showed high stability, better resistance to rutting, resistance to water sensitivity, and high durability as compared with hot mix asphalt (HMA). It showed great potential in developing structural surface layers for heavily trafficked loading conditions. Later on, a study was conducted to examine the effect of crushed glass on the performance of crushed recycled materials with 1 % crump rubber for road pavement construction (Saberian et al., 2019). The experimental tests demonstrated that the glass addition to the aggregates resulted indecreased workability of the mix. Also, the addition of crushed glass increased the California bearing ratio (CBR), and unconfined compression strength (UCS) of the mixes. Recently, recycled glass waste was incorporated along with crushed stone dust into asphalt concrete development (Gedik, 2021).The crushed glass was shown to enhance the thermal sensitivity and fatigue performance of the material and therefore it was used as a mineral filler in bituminous mixtures. The crushed glass wastes can also fulfill the requirement for cement and cementitious materials. For instance, the granulated expanded glass aggregate (GEGA) mixed with cement grout was effectively used as a protection layer in the construction of sub-base layers of the road(Kurpińska et al., 2019). The material was used for the construction of the road pavements, with the required load-bearing capacity and durability parameters. Another study reported the synthesis of geopolymer cement based on waste glass powder and fly ash (Xiao et al., 2020). The material was characterized with California bearing ratio (CBR), unconfined compressive strength, failure strain and drying shrinkage of base samples under different curing conditions. It was later used for the construction of pavement base materials. Although recycled glass wastes can be a promising alternative as filler material in asphalt concrete, more research should be conducted to study mechanical stability and durability in road engineering.

3.5 Miscellaneous wastes

Rubber wastes mainly include the disposal of waste tires that are non-biodegradable and can cause pollution in air and land emissions. Rubber wastes are highly complex depending upon the composition of the raw material and rubber quality. USA is currently known to produce 1 million tonnes of scrap tires piles that are usually dumped in landfills, roadsides, lakes, rivers, and open grounds(Sofi, 2018). These rubber wastes can be a potential material for use in road construction materials as asphalt fillers, insulating materials, and use in aggregates(Deshmukh & Kshirsagar, 2017; Mohajerani et al., 2020). The asphalt rubber mixtures have been widely studied as construction materials in roads and pavements (Picado-Santos et al., 2020). A study reported the effect of recycled rubber waste tires (Styrene butadiene styrene) in developing concrete to construct rigid pavements (Bonicelli et al., 2017). In this study, no effect on the mechanical strength and tensile strength of the concrete materials was observed. However, another study reported the manufacturing of asphalt concrete from scrapped tire rubbers as fine aggregates for the construction of pavements (Sugiyanto, 2017). These aggregates were used to develop surface layers of the road to generate large voids filled with bitumen and provided resistance to deformation. It also prevented rutting at high temperatures and high loading conditions. A similar study was performed to examine the effect of ground tire crumb rubber in asphalt mixtures upon addition with amorphous carbon powder (Ziari et al., 2019). The results revealed the increase in resilient modulus and indirect tensile strength of the asphalt mixes along with resistance to rutting, fatigue, and cracks.It can be concluded from the studies that the asphalt rubber mixture technology shows better performance as an energy-saving process with a good life cycle.

Biomass or biological wastes are generally obtained from biomass including agricultural wastes and organic wastes. Bio-oils can be derived from the pyrolysis of plant oils and numerous other biomass materials including wood wastes, bagasse, paper wastes, grass, sawdust wastes, municipal waste, crop straw, and agricultural residues, animal wastes, etc.(Kumar et al., 2020; Mohan et al., 2006). Bio-oils possess comparable properties to the asphaltic materials produced from crude oils. Bio-oils can be preferably used as bio binders that can be a substitute for petroleum-based asphaltic binders(Su et al., 2018).Bio-asphalts possess amazing properties such as renewability, sustainability, non-toxic to the environment, and economical in production. Numerous early studies, as well as current work, focus on bio-oils as one of the best binders in asphalt pavements. For example, the applications of bio-oils obtained from waste cooking oils (Adesina & Dahunsi, 2021; Azahar et al., 2016; Zhang et al., 2017), fish oil and rapeseed oils (Guarin et al., 2016), date seeds (Alattieh et al., 2020), wood wastes (Ingrassia et al., 2020), biodiesel (Santos et al., 2020), swine manure (Al-Sabaeei et al., 2020), castor oil (Zeng et al., 2016), and palm oils (Kousis et al., 2020)have been extensively investigated for bio-binders in road and highway engineering. The main drawback of bio-oils derived bio-asphalt is that they can depress the high-temperature performance of the asphaltic binders. The long-term working ability of bio-asphaltic based roads and pavements still needs to be assessed.

Industrial wastes from the metal casting industry, steelworks, and coal industryare thought to be good alternatives as construction materials in the road industry. Metal shavings are wastes obtained from metal machinery or turnery. These wastes have been mixed with recycled asphalt mixtures for producing eco-friendly materials for pavement construction (González et al., 2018). The metal shavings werefound to be evenly distributed in the mixture. The addition of shavings increased the air voids of the mixture.Apart from metal shaving, ferrochromium metallic slags from the metal industry have also been evaluated as aggregates in pavement layers(Gökalp et al., 2018). They were found to provide more protection against weathering, fragmentation, rutting, and abrasion when compared with traditional aggregates. Steel slagsfrom industries can be used as coarse aggregates in concrete for constructing the base and sub-base of pavements(Ferreira et al., 2016). It possesses amazing properties such as good stability, strong bearing, and shear strength, and provides resistance to impact(Aziz et al., 2014; Hainin et al., 2015; Yüksel, 2017). A similar study evaluated the use of steel slags as aggregates in the asphaltic mix for microwave deicing of road pavements against freezing (Gao et al., 2017). Recent works have incorporated steel slags as one of the components for coarse aggregates for road construction (Díaz-Piloneta et al., 2021; Gao et al., 2021; Lou et al., 2020). Besides these wastes, colliery spoils obtained during coal mining has also been applied for production of cement concrete in road pavement structures (Nath et al., 2018; Suescum-Morales et al., 2019).

IV. ENVIRONMENTAL AND ECONOMIC IMPLICATIONS OF WASTE UTILIZATION

The application of waste materials as discussed above in road development can pose certain implications on production costs and economics, environment, and working performance. Since most of the paved roads are made on flexible patterns consisting of multiple layers of asphalt or bitumen with different thicknesses, the plastic wastes and rubber wastes are considered to be most suitable for road construction (Sojobi et al., 2016). The type of waste material to be chosen for road construction possess its own advantages and diasadvantages as shown in Table 1. Most of the wastes today is due to littered plastics and rubbers. A focus on the use of these materials as alternatives in road construction will reduce plastic pollution, conserve natural aggregates, minimizes the use of resources, and manages waste disposal. From the environmental perspective, the use of solid wastes for road construction and maintenance can reduce environmental pollution. The use of waste materials in the road sector can impact the energy consumption, emission of greenhouse gases, and overall consumption of natural resources (Noll et al., 2019). The usage of these waste resources has majorly reduced the need for landfills and dumping grounds, that helps in cutting down greenhouse gases emission. Bio-oils from agricultural wastes and biomass are eco-friendly substitutes for bio-asphalt production since they are more efficient than other asphalt rejuvenators (Kousis et al., 2020). The life cycle appraisal (LCA) of roads and highways is one of the most popular approaches for studying the production of materials, construction, utilization, maintenance and rehabilitation, and end-of-life stages. LCA can also be applied for road construction using different categories of waste materials (Balaguera et al., 2018). In terms of economics and production costs, the reuse of selected waste materials in the construction and development of roads is quite appreciable. This is mainly due to the inexpensive, renewable nature, and easy availability of waste materials in developing countries. Further, a lot of literature is available on the use of plastic wastes and rubber wastes as an alternative for road construction(Gopinath et al., 2020; Trimbakwala, 2017). However, LCA assessment of municipal solid wastes and industrial wastes is rarely performed and must be recommended for expanding their usage on roads. Regarding the performance of alternative materials in road construction, the use of waste type can impact road durability, performance, and fatigue conditions. The waste material to be used can posecertain effects on the structural, physical, mechanical, and general working of roads and highways. Moreover, the performance metrics such as CBR, Marshall stability, tensile strength, loading capacity, resilient modulus, etc. must be assessed to formulate the composition of the asphaltic concrete(Poulikakos et al., 2017).

V. CONCLUSION

The present work reviews the utilization of waste materials in road and highway construction. It is a practicable technology that needs more acceptance and adoption. The main criteria to choose an optimum waste material depends upon the performance of the material in road pavement as compared to traditional material, availability and accessibility of the material, the requirement for any expensive choice for its complete exploitation, nature of the waste materials, and need for any pre-treatment before using it for construction proposes. The obtained wastes can be applied as construction materials in the form of aggregates, reinforcement fibers, filler material, additives, and binders. Despite all the ongoing research and practical applicability of waste materials in developing roads, there are still research gaps and challenges faced by the researchers and contractors that must be investigated in near future for constructing roads with high performance. Proper testing of the materials must be conducted in the laboratory stage before on-field application to counter any undesirable expansions. Also, the workability of asphaltic concrete with wastes should be checked before use. Regarding the practical adoption of waste utilization technology in road development, the designers and contractors must be convinced for including new materials in their conventional aggregates. There is still a lack of research on the small-scale construction industries about road engineering using wastes. Also, the LCA assessment of flexible pavements is more available than those of rigid pavements. The improper waste disposal and mismanagement of wastes can also cause hindrances in the collection and processing of wastes materials. Nonetheless, the waste materials must be free from the presence of any toxic or hazardous substances. The usage of waste materials in engineered materials must not be confined tolaboratory conditions alone. Overall, it can be concluded that the conversion of wastes into road construction materials is sustainable and economical technology that should be encouraged as it not only provides strength and durability of roads but also puts less burden on the environment thereby saving energy.

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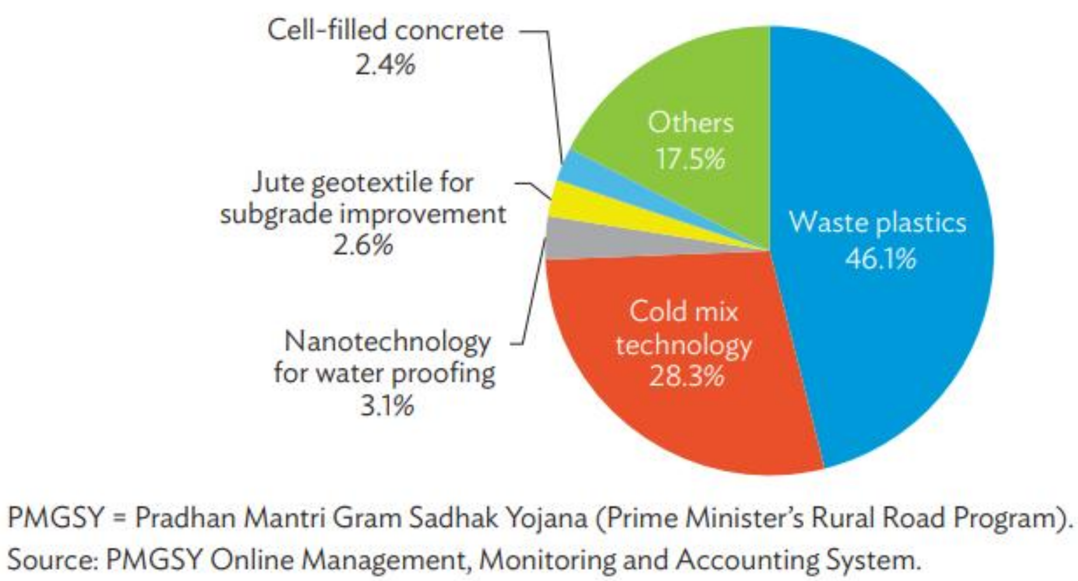

Fig. 1 New Technologies and Innovative Approaches Used in Building Rural Roads in India Under the PMGSY, January 2019. Note that the use of plastic wastes is the most used technology in the newer methods adopted for road construction.

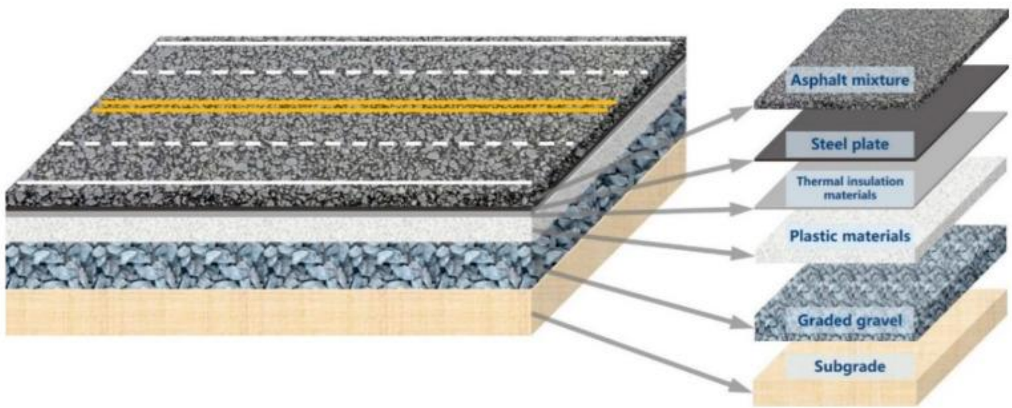

Fig. 2 Development of Asphalt steel plastic (ASP) pavement structure (Jiang et al., 2021).

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Table 1: A list of the advantages and limitations of the utilization of waste materials in road construction.

S.no.	Waste material used	Advantages	Drawbacks	Applications in road construction
	Plastic wastes	• Reduction in emission of greenhouse gases • Abundant availability • Cheap	• Need for more resources to convert plastic wastes into a suitable form for use	• Bitumen modifier • Development of asphalt mix • Aggregates
	C&D wastes	• Conserve natural resources • Conserve landfill space	• High capital costs • Contamination possible	• Asphaltic concrete • Sub-base and capping layers of road

		• Less energy consuming • Reduce waste disposal		
	Bottom ash wastes-	• Less energy use and • Less energy derived emissions	• Leaching • Generates pollution	• Aggregate in asphalt mixture • Filler material • Embankment construction
	Glass wastes	• Easy recycling • Highly durable	• More CO_2 emission compared to landfilling.	• Glass fiber reinforcement • Filler • Cementitious material
	Rubber tires wastes	• Available in large amounts • Reduced effect on landfill	• More costs in the case of asphalt rubbers	• Bitumen modifier • Aggregates
	Bio-oils (biomass)	• Biological wastes • Non-toxic and non-hazardous • Energy saving • Eco-friendly	• Unsteady physical and chemical properties • High oxygen and water content. • High energy consumption • Low yields	• Bio-asphalts • Bio-modifier
	Metal industry waste/steel slag	• Reduced environmental pollution	• May be toxic • Pollution in the soil and groundwater by heavy metal leachates.	• Base/ Subbase material • Subgrade stabilizer

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Rahul Mehlawat, et. al. "Recent progress in the utilization of waste materials for road construction." *International Journal of Engineering Research and Applications (IJERA)*, vol.11 (8), 2021, pp 13-27.