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Recycling of polyethylene terephthalate (PET) plastic bottle wastes in bituminous asphaltic concrete

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Abstract: This research sheds light on the concept of eco-friendly road construction which comprises eco-design, eco-extraction, eco-manufacturing, eco-construction, eco-rehabilitation, eco-maintenance, eco-demolition, and socioeconomic empowerment. It also revealed the challenges being faced in its adoption and the benefits derivable from its application. Furthermore, the effects of recycling PET plastic bottle wastes produced in North Central Nigeria in bituminous asphaltic concrete (BAC) used in flexible pavement construction were also evaluated. The mix design consists of 60/70 penetration-grade asphaltic concrete (5%), 68% coarse aggregate, 6% fine aggregate, and 21% filler using the dry process at 170°C. The optimum bitumen content (OBC) for conventional BAC was obtained as 4% by weight of total aggregates and filler. Polymer-coated aggregate (PCA)-modified BAC seems preferable because it has the potential to utilize more plastic wastes with a higher optimum plastic content (OPC) of 16.7% by weight of total aggregates and filler compared to

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The group's key research activities include eco-friendly road construction, waste management, development of innovative materials for the construction and energy industries, water resources management, geotechnics and highway.

Recycling of post-consumer plastic bottle wastes in bituminous asphaltic concrete used in flexible pavement construction portends an opportunity to solve the menace arising from such wastes. Furthermore, the research presents an eco-friendly road construction medium for sustainable road construction in both developed and developing countries especially in the face of declining financial budgets for road infrastructures.

PUBLIC INTEREST STATEMENT

Plastic wastes constitute a great nuisance to the environment in both developed and developing countries. This research showcased an environmentally-friendly way of utilizing these wastes for road construction in two different ways. First, utilizing molten plastic bottle wastes to coat the aggregates used in flexible road construction and second, using molten plastic wastes to replace the asphalt cement. The results showed that the bituminous asphaltic concrete produced using the plastic-coated aggregates was able to utilize more plastic wastes compared to the plastic-modified bitumen. However, the plastic-modified bitumen experienced more stability, although they were close. In summary, bitumen produced using the two methods were found to exhibit better properties compared to the conventional bitumen. It is recommended that government and road construction companies should embrace recycling of plastic wastes in road construction to get rid of these wastes and improve the safety and service lives of our roads.

that of 9% by weight of OBC achieved by PMB-BAC. For both PMB- and PCA-modified BAC, an increase in air void, void in mineral aggregate, and Marshall stability were observed. Eco-friendly road construction which recycles PET wastes should be encouraged by government considering its potential environmental and economic benefits.

Subjects: Earth Sciences; Engineering & Technology; Environment & Agriculture; Environmental Studies & Management

Keywords: bituminous asphaltic concrete; eco-friendly road construction; plastic wastes; polyethylene terephthalate; polymer-coated aggregates; polymer-modified bitumen; recycling

1. Introduction

1.1. Eco-friendly road construction and recycling

Sustainable, eco-friendly road construction is increasingly receiving more attention globally in both developed and developing countries and among various stakeholders such as private and public sectors and governments. It is driven largely in part by the increase in demand and opportunities to green our infrastructures and reduce environmental impacts of road construction, tightening budget for road infrastructures, and innovative practices that are continuously churned out across the globe. It is also spurred by the increase in demand for eco-cities and eco-developments that are more environmentally friendly than before (Flynn, Yu, Feindt, & Chen, 2015). Eco-friendly road construction can also be viewed as a response of stakeholders to the calls for sustainable development which arose from growing awareness of the negative impact of road construction on our environment.

de Rezende, Camapum-de-Carvalho, and Palmeira (2015) and Safiuddin, Jumaat, Salam, Islam, and Hashim (2010) attributed the birth of eco-friendly construction to increasing cost of construction materials due to high demand, scarcity of raw materials, and high price of energy, which led to the search for alternative construction globally, while Wahlstrom et al. (2014) cited increasing costs and new restrictions for landfilling. The authors classified recycled materials into five categories, namely: organic agricultural industrial wastes, inorganic industrial wastes, mining/mineral wastes, non-hazardous wastes, and hazardous wastes.

Obstacles to recycling in construction include concerns about quality variations in the wastes, inadequate information on the properties of the products manufactured with the recycled wastes, lack of technical standards for use of recycled materials as input materials in new construction products, and poor awareness about the important elements and necessary actions in promoting recycling of wastes (Vieira & Pereira, 2015; Wahlstrom et al., 2014). Other difficulties encountered in recycling are labor costs, lack of government awareness and support toward recycling, and limited real-life applications of recycled materials to allow for evaluation of their performance (Jin & Chen, 2015; Safiuddin et al., 2010).

Benefits of recycling are numerous. USEPA (2009) cited reduction of material hauling and disposal costs and preservation of landfill capacity which leads to elongation of landfill design life and sometimes cheaper materials compared to virgin materials. Recycling also helps in greening our infrastructures by conserving natural resources, making our infrastructures more durable due to high-performance mixtures, decreasing energy use, reducing greenhouse gas emissions and air pollution, minimize water consumption and groundwater contamination as well as reduction in fuel consumption of vehicles (Celauro, Bernardo, & Gabriele, 2010; Thiel, Stengel, & Gehlen, 2014; USEPA, 2009; Wahlstrom et al., 2014).

Safiuddin et al. (2010) also identified creation of secondary industries which utilize these wastes to produce construction materials, while Essawy, Saleh, Zaky, Farag, and Ragab (2013) noted reduction of the need for extraction of virgin materials, minimize consumption of virgin materials, and environmental protection.

Materials recycled in road construction include fly ash, silica fume, ground-granulated blast furnace slag, reclaimed asphalt pavement (RAP), and plastic wastes such as polyethylene terephthalate (PET), polystyrene (PS), polyvinyl chloride (PVC), foamed polystyrene (FP),low-density polyethylene (LDPE), high-density polyethylene (HDPE), and reclaimed concrete (RC) [Kashiyani, Pitroda, & Umrigar, 2013; Gadja & Vangeem, 2001]. USEPA (2009) stated that fly ash, bottom ash, foundry sands, RAP, RC, and ground rubber tires can be utilized in base course while bottom ash, foundry sand, glass, RAP, RC, blast furnace slag, steel slag and scrap tires can be used in the granular base and sub-base. The authors also stated that fly ash can be used to improve stability of sub-grade.

From literatures, it is noted that the recycled wastes can function as fine aggregates (FA), coarse aggregates (CA), and supplementary cementing materials (SCM), depending on the properties of the wastes intended to be optimized and the desired applications.

Recycling and eco-friendly road construction have the capacity to reduce carbon emission by one-third (Keijzer, Leegwater, de Vos-Efftung, & de Wit, 2015). Benefits of pavement recycling include reduction of costs of new construction and rehabilitation projects and reduction of construction time delay (Praticò, Vaiana, Giunta, Iuele, & Moro, 2012). Recycling of RAP leads to increase in design life of pavements from 2 to 18 years to an average of 35–50 years, 50% conservation of asphalt and aggregates, minimized delays for motorists, timely restoration of traffic, 4.5% fuel savings from smooth roads, 15% reduction of energy consumption, and 10–15% reduction of road damage (Abreu, Oliveira, Silva, & Fonseca, 2015; Giani, Dotelli, Brandini, & Zampori, 2015; NAPA, 2015; Settari, Debieb, Kadri, & Boukendakdji, 2015).

To facilitate the uptake of recycling in construction generally and in road construction in particular, Knoeri, Binder, and Althaus (2011) identified the need for stakeholder interactions especially with those involved in decision-making in various organizations. Mallick, Radzicki, Zaumanis, and Frank (2014) recommended optimal combination of local and non-local recycled aggregates to reduce exhaustion of natural aggregate stocks.

Eco-friendly road construction is one that is beneficial or non-harmful to the environment and is energy and resource efficient. For any road construction to be eco-friendly, it must imbibe certain basic elements, namely: eco-design, eco-extraction, eco-manufacturing, eco-construction, eco-rehabilitation, eco-maintenance, eco-demolition, and socioeconomic empowerment without compromising all performance standards. In terms of eco-design, it means the construction design must make provision for utilization of waste materials and must be designed to minimize negative impact on the environment. Eco-extraction means there should be minimal extraction and minimal use of virgin materials.

Furthermore, eco-manufacturing means that the manufacturing of the road construction materials should be done at low temperature, should have reduced odor, smoke, fuel consumption, and emissions. Eco-construction means eco-friendly, recycled products should be utilized, should minimize delay of traffic and inconvenience to traffic users while health and safety of the workers is given a high priority, minimal contamination of run-off, reduced impact on natural habitations such as noise, air pollution, and vibration, and optimal use of locally available materials (FEHRL, 2008).

Eco-construction also includes utilization of alternative and innovative technologies such as geotextiles, geopolymers, low-carbon concretes, enzymes, and natural and synthetic chemicals to improve and stabilize the soil structure such as the subgrade, sub-base, and base course and alternative bitumen materials such as vegecol, ecopave, greenpave technology, and coolpave (Newman et al., 2012).

Socioeconomic empowerment entails collaborative, participatory approach via sharing best practices which leads to socioeconomic empowerment of local communities through their inclusion in the design and construction processes and their training and development which engender local road ownership and expertise (Klatzel, 2000). In addition, adoption of phased construction, utilization of indigenous knowledge and local labor as well as decentralized project management through the use of community-based organization contribute to the socioeconomic empowerment of affected and engaged communities.

Eco-rehabilitation and eco-maintenance imply recycling of the reclaimed asphalt (RAP) and reclaimed concrete (RC) using innovative technologies such as cold in-place recycling, full-depth reclamation of the old pavement and perpetual pavements that last 50 years compared to the conventional 20 years, warm-mix asphalt (WMA), and half-WMA (HWMA) (Chomicz-Kowalska & Maciejewski, 2015; Giani et al., 2015; Hashemian, Kavussi, & Aboalmaali, 2014; Miller & Bahia, 2009; Molenaar, 2013; Montanelli, 2013; Pradyumna, Mittal & Jain, 2015; Praticò, Vaiana, & Giunta, 2012).

Countries such as Denmark, the Netherlands, the USA, and India have made recycling of wastes in construction a national priority (Miller & Bahia, 2009; Wahlstrom et al., 2014). The recycled wastes have been found useful in construction of low-volume roads especially in rural areas (Leite, Motta, Vasconcelos, & Bernucci, 2011).

Global plastic production reached an unprecedented record of 299 million metric tons in 2013 which represents 498% increase compared to 50 million metric tons produced in 1976 as shown in Figure 1 and is presently estimated at 260–297.5 million metric tons (Lytle, 2011). The annual volume of globally traded plastic wastes estimated at 15 million metric tons in 2015 is expected to reach 85 million tons by 2020 (Velis, 2014). While the top-five exporters such as Hong Kong, the USA, Japan, Germany, and the UK have effective (plastic) waste collection systems, the top world importers which include China ($6.1 billion), Hong Kong ($1.65 billion), followed by the USA, the Netherlands, and Belgium utilize the recycled plastics for closed-loop recycling in bottles (11%), sheets (49%), fibers (34%), and other products (6%) (World Recovered Plastics, 2010). The above figures suggest that the global plastic trade which utilizes about 29–33% of the post-consumer plastic wastes is not enough to extract its resource value.

In terms of plastic consumption rate, China was the highest (48%), followed by Europe (20%), NAFTA (19.4%), rest of Asia (16.4%), Middle East and Africa (7.3%), and Latin America (4.8%) as shown in Figure 2. The high production level and high consumption rate of plastics are fueled by the low cost of virgin plastics and its versatility which has encouraged its usage in diverse applications ranging from agriculture to processing, to automobile, building construction, communications, and information technology, to mention a few.

Figure 1. Production of plastics worldwide from 1950 to 2013 in million metric tons (www.statistica.com).

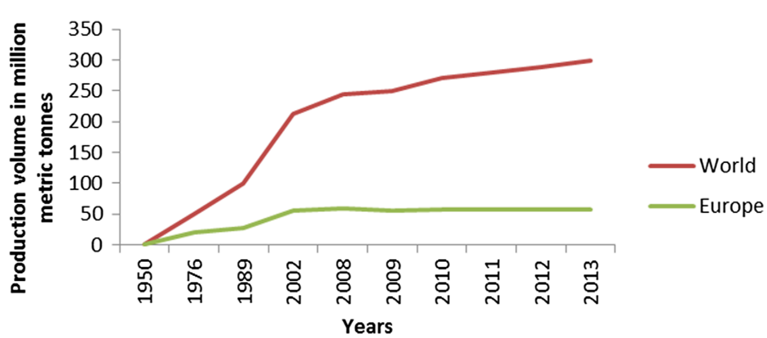


Figure 2. Distribution of global plastic production in 2013 by region (www.statistica.com).

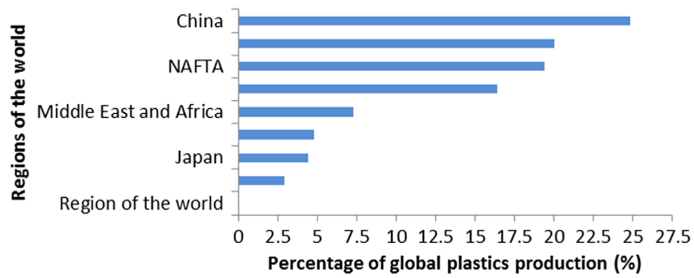
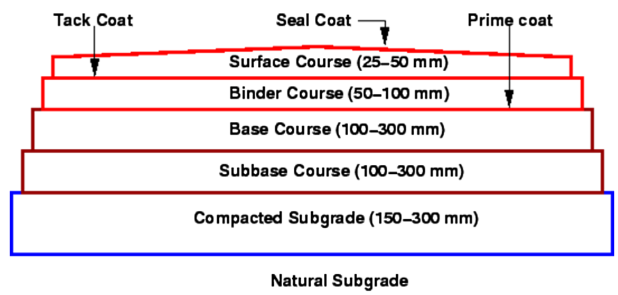


Figure 3. Layers in a flexible pavement.



With increase in global population, urbanization, and industrialization as well as lifestyle changes, the challenges posed by plastic wastes, which constitute 2–25% of municipal solid wastes (Sojobi & Owamah, 2014), will continue to grow as well as the complexity in the management for curtailing these wastes. Furthermore, disposal of plastics in landfills gives room for grave concern owing to the low recovery of post-consumer plastics from waste stream which is <15% in most developing countries, its short life span, its poor biodegradability, the dangerous and carcinogenic gases produced during incineration as well as the reduction in lifespan of landfills, loss of inherent resource value as well as drainage problems emanating from poor plastic waste disposal.

On the other hand, there is increasing pressure for high-performance pavement and renewed interests to improve properties of ordinary bituminous asphaltic concrete (BAC) owing to repeated failures of flexible pavements, increasing vehicular traffic, increasing axle loads, increasing requirement to reduce construction costs as well as maintenance costs of flexible pavements, and elongate service life of roads and low maintenance culture in developing countries (Ahmadinia, Zargar, Karim, Abdelaziz, & Ahmadinia, 2012; Essawy et al., 2013; Kalantar, Karim, & Mahrez, 2012; Moghaddam, Soltani, & Karim, 2014).

The common failures associated with ordinary BAC, which are often used in surface and binder courses in flexible pavements shown in Figure 3, include rutting, bleeding, polish, cracking, ravelling, potholes, and shoving (Appiah, 2013; Neal, 2013). In addition, unmodified BAC which is increasingly subjected to environmental demands has temperature susceptibility at both high and low temperatures (Yusoff, Breem, Alattug, Hamim, & Ahmad, 2014; Zhang, Wu, Cao, Zhang, & He, 2013).

1.2. Review of literature

Utilization of wastes from polyethylene terephthalate (PET), which constitutes 55–60% of plastic bottles (Rahman & Wahab, 2013), to modify conventional BAC will help remove post-consumer plastic wastes from the waste stream and likewise help enhance the properties of ordinary BAC. Recycling of the PET wastes in unmodified BAC used in flexible pavements will significantly mop up the plastic wastes from the waste stream since flexible pavements constitute 92.3% of paved roads globally (Blazejowski, 2011). Thus, incorporation of plastic wastes into BAC performs dual functions of improving the flexible pavement performance and reducing environmental pollution.

Worldwide, the demands of a modern road system have exceeded the capacity of conventional BAC and since it is more economical to prevent damage (Arabani & Faramarzi, 2015), many researches have been done to improve the properties of ordinary BAC as well as ordinary asphalt.

Ahmadinia et al. (2012) demonstrated that utilization of 1.18-mm PET size improved rutting resistance and stiffness of stone mastic asphalt and produced lower binder drain down. Ahmadinia, Zargar, Karim, Abdelaziz, and Shafigh (2011) also obtained appropriate optimum PET waste content as 6% by weight of bitumen content. They opined that removal of non-biodegradable waste materials enhances ecosystem balance, conserves natural resources and energy as well as contributes to financial savings.

Fang et al. (2013) investigated the use of packaging waste polymer and organic montmorillonite and found that the polymer content caused a decrease in penetration and increase in viscosity while the organic montmorillonite lowered the viscosity but increased resistance to cracking.

Yu, Jiao, Ni, and Yang (2014) showed that asphalt modified with 40:1 ratio of crumble rubber and polypropylene powder was weaker in terms of softening point, elastic recovery, and fatigue performance compared to SBS (styrene butadiene styrene) asphalt but exhibited similar high and low temperature performance and water durability compared with SBS asphalt. They recommended a mixing temperature of 170–180°C to assure workability. The authors also found that the stability of PRA depends on storage temperature, storage time, property of base asphalt, and modifier content.

Zhang et al. (2013) showed that LLDPE-g-MAH (linear low-density polyethylene grafted with maleic anhydride) incorporated into high-density polyethylene (HDPE)/SBS asphalt performed the roles of dispersion agent and compatilizer in the asphalt mix by decreasing the interfacial tension between the asphalt and HDPE/SBS and connecting the asphalt and modifier. They stated that a good compatibility between the polymer and asphalt prevents separation during storage, pumping, and application to achieve the desired pavement properties.

Yusoff et al. (2014) recommended the addition of 4% nanosilica to improve the moisture susceptibility of PMA (polymer-modified asphalt), increase the strength, and enhance fatigue and rutting resistance while Nuñez, Domingos, and Faxina (2014) demonstrated that addition of 1.25 mass of LDPE and polyphosphoric acid increased rutting resistance of asphaltic concrete with very high strain recovery. This was corroborated by Moghaddam et al. (2014) who showed that PET-modified asphaltic concrete is flexible, has lower stiffness compared to conventional asphaltic concrete, and the Marshal quotient (MQ) decreased with increase in PET content.

Nobinur Rahman, Ahmeduzzaman, Sobhan, and Ahmed (2013) also utilized PET as partial replacement for fine aggregates (FA) in concrete and reported that 20% PET content recorded the highest resistance to permanent deformation.

Sengoz, Topal, and Isikyakar (2009) compared the effects of SBS, EVA (ethylene vinyl acetate), and EBA (ethylene butyl acrylate) as modifiers in bitumen. They concluded that EBA seems to perform better in terms of reduced temperature susceptibility and increased resistance compared to SBS and EVA. They concluded that increase in viscosity in polymer-modified bitumen affects mixing, laying, and compaction of the mixture. Shu and Huang (2014) reported that crumb rubber tire improved the resistance of asphalt pavement to rutting, fatigue cracking, and low-temperature cracking which enables it to perform better than conventional asphalt roads.

Despite these advantages, polymer modification of BAC still faces several drawbacks such as high cost, low-aging resistance, poor storage stability, and poor elasticity which can be overcome by saturation, sulfur vulcanization, antioxidants, hydrophobic clay minerals, and reactive polymers (Zhu, Birgisson, & Kringos, 2014).

Sol-Sánchez, Moreno-Navarro, García-Travé, and Rubio-Gámez (2015) also reported that open BAC is more appropriate for road pavements in regions experiencing high rainfall. They also found that air void content has a long-term impact on BAC. Qian and Lu (2015) recommended the use of open-graded epoxy asphaltic concrete (AC) in flexible pavements since they exhibited good resistance to moisture damage and provided excellent performance functions as pavement surface such as permeability, friction, and resistance to high-temperature deformation and low-temperature cracking. However, they need improvement to avoid reorientation of aggregates under repeated heavy wheel loads.

Furthermore, Nazirizad, Kavussi, and Abdi (2015) utilized Iterlene In/400-S to improve resistance to stripping of asphaltic concrete while Karahancer et al. (2014) reported that methyl methacrylate improved the tensile strength and also reduced the moisture susceptibility of AC. Essawy et al. (2013) reported that polypropylene (PP) performed better than polyethylene (PE) as a modifier for hot-mix asphalt (HMA) and reduced the temperature susceptibility of HMA. Also, Fang, Liu, Yu, Liu, and Lei (2014) found that low-content addition of organic montmorillonite (OMMT) into the composite of waste package polyvinyl chloride and asphalt allowed for more dispersion which produced better compatibility between PVC and asphalt and better high-temperature storage stability and reduced temperature susceptibility of modified asphalt.

Xiao, Amirkhanian, Wang, and Hao (2014) demonstrated that the rheology of polymer-modified asphalt (PMA) depends on polymer type, asphalt source, and test temperature. They found that oxidized PE and propylene-maleic anhydride require lower mixing and compaction temperature and that crumbed-rubberized-modified asphalt has higher fail temperature compared to unmodified asphalt.

Fini, Oldham, and Abu-Lebdeh (2013) reported that AC produced by mixture of crumbed scrap tire and swine manure improved the low-temperature property of the crumb rubber manure (CRM) binder, reduced the binder viscosity, and enhanced pumpability. Also, Lo Presti (2013) encouraged the use of recycled tire rubber to modify BAC utilizing the wet-process no-agitation method. In addition, Cong, Xun, Xing, and Chen (2013) found that crumb rubber (CR)-modified asphalt has higher toughness and decreased susceptibility to cracking at low temperature but poor storage stability. With increase in CR contents, viscosity was found to increase while the stiffness decreased. de Almeida Júnior, Battistelle, and Bezerra (2012) also reported that scrap rubber tire is a potential substitute to SBS. The scrap rubber tire-modified asphalt had higher softening point and higher elastic recovery of 55% compared to 35 in ordinary asphalt. With increase in tire contents, it was found that density increased while ductility decreased.

Shafabakhsh and Sajed (2014) recommended the use of glass wastes <4.75 mm to replace fine aggregate in AC and obtained optimum bitumen content (OBC) at 15% glass content. The resulting “glasphalt” had higher strength and higher resistance to water damage as a result of superior interlocking and greater roughness of glasphalt samples. Morova (2013) also investigated the use of basalt fibers to improve hot-mix AC. Optimum results were obtained at 5% OBC and 0.5% optimum basalt fiber addition. The fiber altered the viscoelasticity of the AC, enhanced the dynamic modulus, and provided resistance against rutting and reflective cracks.

Das and Banerjee (2013) reported that the use of jute in AC produced strength enhancements of 380, 552, 710, and 800% at 4, 8, 12, and 16% fiber contents. The jute composite was found to confer higher stiffness and resistance to road cracking and crack propagation as well as higher resistance to biodegradation. In addition, Kar (2012) recommended the use of sisal fiber in BAC and SMA (stone mastic asphalt). Optimum fiber contents for both BAC and SMA were obtained as 0.3%, while the OBC for both BAC and SMA was obtained as 5 and 5.25%, respectively. The sisal fiber improved the MS, drain down characteristics, and indirect tensile strength (ITS) in both BAC and SMA, although SMA was better in terms of ITS and creep characteristics. Arabani and Faramarzi (2015) also recommended the use of well-dispersed carbon nanotubes (CNTs) with high tensile strength to curtail the generation and propagation of micro-cracks, to improve the resilient modulus and permanent deformation of HMAs, and improve the fatigue life.

Abreu et al. (2015) demonstrated that asphaltic mixtures produced with recycled asphalt (RA) mixed with motor oil and HDPE exhibited increased durability, better rutting resistance, longer fatigue life, and lower stiffness modulus. They recommended 50% RA, 7.55% motor oil, and 4% HDPE. Kakar, Hamzah, and Valentin (2015) recommended the combination of *in situ* testing, material selection criteria, and proper mix design to prevent moisture damage in AC. The authors stated that developed countries such as the UK have shifted to preventive measures to reduce construction/maintenance costs of flexible pavements and inconveniences to commuters.

Musa and Haron (2014) investigated the use of LDPE carry bag wastes in AC. The optimum LDPE waste content obtained was 10% by weight of bitumen content. The LDPE reduced the pavement deformation, increased fatigue resistance, and provided better adhesion between asphalt and aggregates. Moghaddam, Karim, and Soltani (2013) obtained highest Marshall stability (MS) at 5% AC and 0.6% plastic bottle. MS and Marshall flow (MF) were found to increase with increase in plastic content. Plastic-reinforced AC had lower optimum asphaltic content (OAC), increased fatigue life, better adhesion, improved flexibility, and postponement of crack creation and propagation.

Nobinur Rahman et al. (2013) recommended the 10% PE and 7.5% PVC by weight of bitumen to obtain optimum AC properties. With increase in plastic contents, penetration, ductility, flash point, fire point, and bulk specific gravity of the modified hot-mix AC were found to decrease. Oliviero Rossi et al. (2015) demonstrated that additives/modifiers in BACs shifted the viscoelastic–sol transition temperature (TR) by about 40°C higher than the unmodified BAC and that TR increases with addition of modifier contents and with aging process. They also found that decrease in penetration depth of PMB (polymer-modified bitumen) is attributable to embrittlement of the asphalt which makes it susceptible to fracturing or cracking and resistant to healing. Munera and Ossa (2014) recommended multicomponent polymers to optimize the properties of BAC which achieved better performance compared to single additions of plastics. They provided a chart which can be used to identify cheap materials with improved properties.

BAC is a composite material comprising asphalt cement used as binder and mineral aggregates as well as fillers. BAC is used in road surfaces, airport and parking lots, and can be mixed in three ways, namely: HMA, WMA, and cold-mix asphalt (CMA) (Kar, 2012). Modification of conventional BAC can take three forms, namely: replacement of aggregates in ordinary BAC with plastics, plastic coating of aggregates, and plastic addition to BAC to produce PMB-modified BAC. Likewise, Rahman and Wahab (2013) utilized PET waste as fine aggregate in concrete and obtained higher resistance against permanent deformation but lower stiffness compared to conventional mixture.

Awwad and Shbeeb (2007) utilized HDPE and LDPE to coat aggregates in AC. OAC and optimum modifier content (OMC) were obtained as 5.4 and 12% by weight bitumen, respectively. The HDPE-modified BAC had higher bulk density, reduced porosity, and water absorption and improved soundness. These results were also corroborated by Chavan (2013) who reported that polymer-coated aggregate (PCA)-modified bitumen prepared using PP reduced water absorption, increased resistance to wear and tear owing to better adhesion, and produced reduction of abrasion of the aggregates in BAC. Sultana and Prasad (2012) reported that the OMC for both PCA modified with LDPE and PMB modified with PP was 8 and 6%, respectively. Sreejith (2009) likewise demonstrated that aggregates coated with plastics reduced aggregate impact value, reduced aggregate crushing value, Los Angeles Abrasion, and void with increase in polymer coating.

For PMB, Justo and Veeraragavan (2002) reported that addition of 8% of by weight of processed plastic to modify BAC resulted in savings of 9.6 kg of bitumen per cubic meter of BAC. Modarres and Hamedi (2014) reported that PCA-modified BAC exhibited 50–60% higher Marshall stability values compared to PMB, indicating higher binding strength. Rongali, Singh, Chourasiya, and Jain (2013)

Table 1. Summary of different recycled plastics and other materials in bituminous compositions

S. No.	Author(s)	Materials	OBC/OPC	Remarks
1	Ahmadinia et al. (2012)	PET plastics bottle wastes post-mixing with SMA	OPC=4–6% by wt. of OBC	Higher resilient modulus, higher rutting resistance, prevention of excessive draindown, reduction in tensile strength, and tensile strength ratio
2	Ahmadinia et al. (2011)	PET plastic bottle wastes in SMA	OPC=6% by wt. of bitumen	Improved resistance against permanent deformation due to increased Marshall quotient (MQ), increased VIM, decreased specific gravity, and reduction in compatibility
3	Fang et al. (2013)	Waste packaging PE (WPE) + OMMT	NO OBC NO OPC	Improved dispersion of OMMT and WPE in asphalt, reduction in melting point range, improvement in low-temperature cracking resistance, increased melting point of composite, and decrease melting point temperature range, reduction in thermal stability with increase in OMMT content. Increase in softening point leads to high temperature stability which promotes cracking resistance
4	Yu et al. (2014)	Aged plastics + crumble rubber	NO OBC NO OPC	PRA is more environmentally friendly in terms of energy consumption and GHGs. It exhibits comparable low- and high-temperature performance and water susceptibility with SBS. SBS is superior in terms of softening point, elastic recovery, and fatigue performance
5	Zhang et al. (2013)	HDPE/SBS + LLDPE-g-MAH (modification of asphalt)	NO OBC NO OPC	Improvement in low-temperature performance. LLDPE-g-MAH had no effect on high-temperature property, rheological character, and viscoelastic characteristics of HDPE-/SBS-modified asphalt. However, LLDPE-g-MAH increased susceptibility to rutting
6	Yusoff et al. (2014)	PG-76 + nanosilica	4% Nanosilica by wt of asphalt	Nanosilica reduced susceptibility to moisture damage and increased the strength of asphaltic mixture (AM), increased the fatigue life and rutting resistance of PMA, and promoted reduction in susceptibility to oxidative long-term aging
7	Nuñez et al. (2014)	LDPE + PPA	NO OBC NO OPC	Improved fatigue resistance (AC+PPA), increased recovery and lower susceptibility to permanent strain (rutting) (AC>AC+PE>AC+PE+PPA), prone to rutting under unexpected temperature, and/or loading conditions. PPA achieved better fatigue resistance than PE modification
8	Moghaddam et al. (2014)	Post-consumer plastics (Dry method)	NO OBC NO OPC	Pet-modified performance better under dynamic load than static loading
9	Nobinur Rahman et al. (2013)	Pet pellet granules as partial fine aggregate (FA) replacement	OBC=5% of mass of AM OPC=5% of mass of AM	Improved resistance to road failures, improved road performance and service life of roads, and better performance in terms of permanent deformation
10	Sengoz et al. (2009)	SBS, EVA, and EBA as PMBs	NO OBC NO OPC	Decrease in plasticity Index (PI), and increase in softening point with increase in polymer contents. Less temperature susceptibility with increase in plastic contents and greater resistance to permanent deformation. Increased viscosity which makes mixing, laying, and compaction of mixture more difficult
11	Shu and Huang (2014)	Crumb rubber	NO OBC NO OPC	Increased resistance to rutting, fatigue cracking and low-temperature cracking, storage instability, and phase separation. Need to modify operations to handle the mixtures
12	Qian and Lu (2015)	Epoxy resin	OBC=5.5% by mass of aggregates	High-temperature stability and durability, low-temperature cracking resistance, and satisfactory friction resistance. Major disadvantage is high cost
13	Nazirizad et al. (2015)	Hydrated lime and Iterlene In/400-S	OBC=5.6% by wt of mix; 0.4% Iterlene In/400-S	Increased resistance to moisture and stripping and increased indirect tensile strength (ITS)
14	Karahancer et al. (2014)	MMA, HMDSO, and SiCl4 in the presence of radio frequency (RF) and microwave (MW)	OBC=5% by wt of asphalt binders	Higher stability and greatest tensile strength increase with MMA. Reduction in moisture susceptibility. MMA-MW showed the highest ITS strength and Marshall stability results
15	Essawy et al. (2013)	Polypropylene (PP) and polyester fibers	OPC=5%	Increase in hardness, specific gravity, dynamic viscosities, and decrease in penetration with increase in polymer contents. The better modifies is PP waste, although both are suitable for paving road. Also, reduced temperature susceptibility. Modifiers lowered the asphalt content required. However, polyester waste was found very tough

(Continued)

Table 1. (*Continued*)

S. No.	Author(s)	Materials	OBC/OPC	Remarks
16	Fang et al. (2014)	Waste package polyvinyl chloride(PVC) and OMMT	No OBC No OPC	Improved high- and low-temperature performance/stability of the modified asphalt. Better dispersion of PVC. OMMT should be added in small quantity for improved performance
17	Xiao et al. (2014)	SBS, oxidized PE, propylene-maleic anhydride, and recycled crumb rubber	No OBC No OPC	Viscoelastic properties of BAC are affected by polymer type, asphalt source, and test temperature. One percent reduction in polymers could be offset using 0.5% PPA. Bitumen used should promote lower mixing and compaction temperature and energy consumption
18	Fini et al. (2013)	Biobinder from swine manure and crumb rubber	No OBC No OPC	BMR improved low-temperature property of the CRM binder as well as viscosity reduction which allows for lower mixing, compaction temperature, energy consumption, and better pumpability
19	Lo Presti (2013)	Review of recycled tire rubber (RTR)	High-viscosity RTR-MB (8–10% binder content); No agitation RTR-MB (5–6% binder content)	Asphalt–rubber pavement is more cost-effective than conventional pavement w.r.t. maintenance and road-user costs. Recommended use of high-viscosity RTR-MBs in open-graded asphalt mixes and no-agitation RTR-MBs in dense-graded asphalt mixes. Recommended the use of HV RTR-MBs for long-term performance. Poor information, lack of training of personnel and stakeholders, and poor local policy prevent the full actualization of RTR-MBs technologies
20	Cong et al. (2013)	0.425-mm crumb rubber (CR)	No OBCNo OPC	Addition of CR increases SP, elastic recovery, viscosity, rutting resistance, and decreases penetration and ductility. However, CR-modified asphalt binder has poor storage stability and swelling properties. Recommended the use of soft asphalt with CR
21	de Almeida Júnior et al. (2012)	Scrap tire rubber (STR)	No OBC No OPC	Potential substitution of SBS with STR requires proper care during storage and transportation with potential 10% expenditure savings. STR had elastic recovery of 55% > 3% of ordinary asphalt
22	Shafabakhsh and Sajed (2014)	4.75-mm crushed glass material	OBC = 5.5–6%; OGC = 15%	Glass particles inhibit rutting phenomena, fatigue cracking as well as reduction of permanent deformation
23	Morova (2013)	Basalt fibers	OBC = 5% OFC = 0.5%	Fiber reduces the stability values while VMA and flows increased with increase in fiber content
24	Das and Banerjee (2013)	Jute fiber	No OBC No OPC	The jute fiber enhanced interfacial bond with asphalt and caused reduction in strength. It confers higher stiffness, resists road cracking and crack propagation, and promotes higher resistance to biodegradation. Use of yarn with negligible crimp is required
25	Kar (2012)	Sisal fiber	0.3% OFC by wt. of total mix; OBC: 5% (BAC); 5.25% (SMA)	Improved Marshall stability, drain down characteristics, and indirect tensile strength
26	Arabani and Faramarzi (2015)	Carbon nanotubes (CNT)	No OBC No OPC	Reduction of permanent deformations and improved fatigue life of CNT-modified HMAs at lower temperature and higher CNT contents
27	Abreu et al. (2015)	Reclaimed asphalt (RA), used motor oil (UMO), HDPE	7.5% UMO, 4% HDPE & 50% RA	Improved performance with UMO acting as rejuvenator of aged binder and HDPE as stabilizer
28	Musa and Haron (2014)	LDPE carry bag wastes	OBC = 4.94% by wt of total mix OPC=10% of OBC	LDPE improved the stability, flow, and air voids. It also reduced pavement deformation, increased fatigue resistance, and provided better adhesion between asphalt and aggregates. It also reduced the amount of bitumen used in construction
29	Moghaddam et al. (2013)	2.36-mm PET bottles wastes	OBC = 6% OPC=0.5%	Lowers OBC results with plastic addition. Other benefits include improved fatigue life, improved flexibility of mixture, and postponement of crack creation and propagation
30	Munera and Ossa (2014)	Multicomponent blends of PE wax, SBS, and CR	No OBC No OPC	Provided chart for optimal selection of blends of cheap materials depending on intended material properties and applications
31	Rahman and Wahab (2013)	3-mm pellet granules of PET bottle wastes	OPC = 5% total wt of mixture OBC =5% AM; 20% max. replacement	Improved permanent deformation resistance which leads to increased service life of road

(*Continued*)

Table 1. (*Continued*)

S. No.	Author(s)	Materials	OBC/OPC	Remarks
32	Awwad and Shbeeb (2007)	HDPE and LDPE (Grinded and Ungrinded)	OBC= 5.4% OPC=12% by wt of OBC	Grinded HDPE performed better than LDPE. Grinded HDPE had the max. stability. The plastic contents reduced the density and slightly increased the air voids and voids of mineral aggregates which will increase rutting resistance of asphalt mixture and provide better adhesion between asphalt and aggregates
33	Chavan (2013)	Plastic wastes [Polypropylene (PP)]	OBC=4% by wt of total mix	Reduction in aggregate impact value (AIV) and crushing values and increase in specific gravity. Plastic coating can be used to improve performance of poor quality aggregate
34	Sultana and Prasad (2013)	PP, LDPE, and HDPE	OAC=4%, OPC=8% (PCA), 6% (PMB), 8% (LDPE, PCA, and PMB)	PCAs are more stable than PMBs and allow the use of more polymer content and can be used in adverse situations. Better improvement occurs when used in flexible pavements than rigid pavements. Addition of plastic caused increase in softening point and reduction in penetration and ductility values
35	Sreejith (2009)	2.36–4.75-mm PE carry bags	OPC=10% (PCA), OPC= < 2% (PMB)	PCA allowed for more polymer content with higher OPC. Both recorded improved Marshall stability and antistripping properties. PMB experienced improved softening point, decreasing penetration and ductility, while PCA recorded improved bonding between PCA and bitumen, reduced porosity, and improved aggregate impact value (AIV). The disadvantages of PMB are that it requires storage in freeze for ≤6 h at180°C which requires the use of high-power stirrer to maintain the temperature. The disadvantage of PCA is burning of plastic wastes produces air pollution and health hazards. The advantage is that there is no maintenance cost for ≤5 years for PCA-modified asphalts roads
36	Rongali et al. (2013)	Fly ash and Plastic wastes	OPC=0.75% by wt of total mix OBC = 5.3% (Fly ash), and 5.4% (Fly ash plastic waste composite)	The composite had higher indirect tensile strength ratio (ITSR), lower rutting depth, lower permanent deformation, higher resilient modulus, improved creep modulus, and creep recovery owing to the pozzolanic properties of fly ash and elastic properties of plastic wastes

utilized fly ash as mineral filler in HMA. The optimum plastic content (OPC) was obtained as 0.75% while the OBC was obtained as 5.3% which resulted in better resistance to moisture damage, higher recovery, higher resilient modulus, and reduction in rutting behavior of modified BAC (Table 1).

The aim of this paper is to proffer an eco-friendly way to recycle plastic bottle wastes in BAC used as surface and binder courses in road construction.

2. Experimental program

Standard procedures were followed in preparation of the BAC. Several tests were conducted to measure the physical properties of the BAC constituent materials and were compared with recognized standards. In addition, properties of plastic waste-modified BAC were evaluated and compared with ordinary, unmodified BAC using conventional aggregates. Both the modified and unmodified BACs were compared against recommended standards.

2.1. Materials

Asphalt cement of 60/70 penetration grade utilized as binder was obtained from K.K. Hassan Construction Company in Akure, Ondo State. The fine aggregate (sand) used was obtained from Ekiti State and was sieved with 1.18-mm sieve and retained on 600-μm sieve to obtain very fine aggregates. The granite chippings and stone dust used as filler were obtained from Omu Aran town in Kwara State. The coarse aggregate (granite) was also obtained from Ekiti State and was retained on a 4.75-mm sieve. They are crushed rocks which are angular in shape, free from dust and particles, clay, and organic matters. The post-consumer plastic bottle wastes identified as PET were sourced from different waste generation points such as cafeteria, halls of residence, University guest house, and University college buildings within Landmark University in Omu Aran, Kwara State, Nigeria. A portable gas cooker was used to melt the plastic wastes, heat the aggregates, and prepare the BAC at appropriate test/mixing temperatures.

2.2. Mix design and sample preparation

The laboratory experiments were conducted in the Geotechnics and Highway Engineering Laboratory of the Department of Civil Engineering, Landmark University in Kwara State.

The aggregate composition of the BAC was proportioned such that the aggregates form about 95% of the BAC mix, while bitumen/modified bitumen formed 5% of the BAC mix. The aggregate proportion varied until it corresponded to the range specified by the BS EN 13108-1:2006 shown in Figure 4. The resulting BAC composition was 68% coarse aggregate (CA), 6% fine aggregate (FA-sand), 21% filler, and 5% asphaltic cement binder in order to achieve the desired mix that meets the requirements of BS EN 13108-1(2006). The plastic content varied in the proportion of 0% (control), 5, 10, and 20% for polymer-modified bituminous (PMB) asphaltic concrete and 10, 20, and 30% for polymer-coated asphaltic (PCA) BAC. The desired air void limit was 3–6% (Kar, 2012) (Table 2).

Dry process was preferred and utilized in the mixing process for BAC preparation because it allowed for utilization of more plastic wastes in BAC. Dry process was also used by Ahmadinia et al. (2011) and Moghaddam et al. (2014). The OBC for conventional BAC without polymer modification was first determined using the Marshall design method. The engineering properties tested were Marshall stability, density, % air void, flow, and VFB. Bitumen ranging from 1, 2, 3, 4 to 5% was added by weight of the total aggregate mix comprising coarse and fine aggregates and filler and thoroughly mixed to obtain a homogenous BAC. For each conventional BAC mixture, five samples each were prepared and tested to obtain the average for all the parameters for each % addition of bitumen content. OBC was derived from the mean of the bitumen content corresponding to maximum stability, bitumen content corresponding to maximum density, bitumen content closest to 4% air

(a) (b)

Figure 4. (a) Ball and ring test for softening point (b) Penetration test on bitumen.

Table 2. Specification for aggregates used in BAC mix design (BS EN 13108-1, 2006)

D	4	5 (5.6)	8	11 (11.2)	16	22 (22.4)	32 (31.5)
Sieve size (mm)							
1.4 D[a]	100	100	100	100	100	100	100
D	90–100	90–100	90–100	90–100	90–100	90–100	90–100
2	50–85	15–72	10–72	10–60	10–50	10–50	10–50
0.063	5–17	2–15	2–13	2–12	0–12	0–11	0–11

Note: a = where the sieve calculated as 1.4D is not an exact number in the ISO 565/R 200 series, then the next nearest sieve in the set shall be adopted.

void, bitumen content corresponding to maximum flow, and bitumen content corresponding to minimum VFB.

Furthermore, the plastic wastes were first shredded and heated in the oven to 170°C for a duration of 60 minutes. Likewise, the coarse aggregates were heated to 170°C in the oven after which they were coated and mixed with the molten plastic wastes at a temperature range of 160–180°C to form plastic-coated aggregates. The plastic contents added to the heated aggregates were in the proportions of 10, 20, and 30% by weight of total aggregate and filler. After thorough coating with the plastic wastes, hot asphalt cement alongside the filler was then added to the PCA and was thoroughly mixed to obtain PCA-modified BAC.

For PMB-modified BAC, three trays containing equal amounts of the total aggregates and filler used in obtaining the OBC were prepared. However, the bitumen content to be used in mixing was reduced by 5, 10, and 20% by weight of the OBC. The total aggregates and filler were then mixed with the reduced asphalt cements. Corresponding amounts of plastic wastes obtained from the shredded plastics equal to each reduction of 5, 10, and 20% by weight of the OBC were weighed and heated to 170°C and added to the mixture and thoroughly mixed to obtain PMB-modified BAC.

For both PCA- and PMB-modified BAC mixture, five samples each were prepared and tested to obtain the average for all the parameters for each % plastic content. OPC was derived from the mean of the plastic contents corresponding to maximum stability, plastic contents corresponding to maximum density, plastic contents closest to 4% air void, plastic contents corresponding to maximum flow, plastic contents corresponding to minimum VFB, and plastic contents that satisfy minimum VMA requirement of 13%.

2.3. Tests and standards for BAC constituents

2.3.1. Tests and standards for aggregates

Sieve analysis was used to determine the particle size distribution of the coarse and fine aggregates and fillers used in the BAC mix. The test was carried in compliance with IS: 2386 Part 1 (1963) which was a known weight of aggregate exceeding 1000 g and preferably is poured into a well-arranged set of test sieves. With the aid of an electrically powered mechanical shaker which vibrated the whole arrangement for 10 min or more, an accurate result of the particle size was obtained. The aggregate retained on each test sieve was used to calculate the grain size distribution of each aggregate.

The specific gravity (G_s) of each of the aggregates was calculated using the pycnometer method in compliance with ASTM 1429 (2003). Bulk density was calculated as the mass of aggregate or material that filled a container which is leveled at the top surface divided by the volume of the container.

Moisture content (MC) was also calculated and it revealed the natural water content of the aggregates. Also, water absorption (WA) was carried out to determine the ability of the aggregates to absorb water. The test was carried out on plastic-coated and uncoated aggregates in compliance with AASHTO T85 (2004) and IS: 2386 (Part III)-1963. Aggregate crushing value (ACV) is the mass of the material expressed as a percentage of the test sample, which is crushed fewer than 2.30 mm under a compressive load of 400 KN. The test was carried out on plastic-coated and uncoated aggregate in accordance with IS 2586 and in compliance with BS EN 487 (2009) and BS EN 932-1 (1999).

Aggregate impact value (AIV) test was also carried out on plastic-coated and uncoated aggregates in accordance with BS 812-Part 112 (1990). The AIV is the percent of fines produced from the aggregate sample after subjecting it to a standard amount of known weight, height, and prescribed number of times. This test simulates the resistance to impact of aggregates in field conditions (Table 3).

Table 3. Standard requirements for aggregates (Moghaddam et al., 2014)

Properties	Standards	Requirements
Coarse aggregates (CA)		
Los Angeles abrasion (%)	ASTM C131 (2014)	<30
Flakiness index (%)	BS EN 933-3 (1997)	<20
Elongation Index (%)	BS 812-105.2 (1990)	<20
Aggregate crushing value (%)	BS 812-110 (1990)	<30
Bulk specific gravity (g/cm^3)	ASTM C127 (2007)	–
Absorption (%)	ASTM: C127	<2
Fine aggregates (FA)		
Absorption (%)	ASTM C128 (1997)	<2
Soundness (%)	ASTM C88 (1999)	<15
Bulk specific gravity (g/cm^3)	ASTM: C88	–

2.3.2. Tests and standards for bituminous binder

The softening point of the bituminous binder was determined using the ring and ball method according to BS 2000 Part 58 (1983). It measures the susceptibility of blown asphalt (binder) to temperature changes. Penetration index test measures the distance in tenths of a millimeter, which a standard needle would penetrate vertically into a sample/binder under standard conditions of temperature, load, and time. The test was carried out in accordance to ASTM D5 procedure. The average of three penetration readings was taken as the representative value. Penetration test for bitumen containing 0, 5, 10, and 20% polymer contents was determined.

The ductility of the bituminous binder was measured by the distance in mm to which a sample of bitumen will elongate before breaking when a standard briquette specimen of the material is pulled apart at a specified speed and a specified temperature of 25°C ± 0.5 as regulated by the ductility machine. Ductility tests for bitumen containing 0, 5, 10, and 20% polymer contents were also determined (Table 4, Figure 5).

2.3. Tests and specifications for BAC (modified and unmodified)

Tests carried out on BAC for our study were density, air void, percentage volume of bitumen (V_b), voids filled with bitumen (VFB), Marshall stability (MS), and flow. They were utilized in calculating the optimum binder content (OBC) of the conventional BAC, PMB-, and PCA-modified BAC because they significantly influence the properties of BAC. The standards for conventional SMA and BAC are shown in Tables 5 and 6.

Table 4. Specifications for bituminous binder (Sengoz et al., 2009)

Parameters	Standards	Specification limits
Penetration at 25°C (0.1 mm)	ASTM D5 (1997)	50–70
Softening point (ºC)	ASTM D36 (1995)	24–46
Viscosity (135°C, Pas)	ASTM D 4402 (2015)	–
Thin film oven test (% change of mass)	ASTM D 1754 (2014)–EN 12607-1	0.5 max
Retained penetration (%)	ASTM D EN 1426	48 min
Ductility (25°C, cm)	ASTM D 113 (1999)	–
Specific gravity	ASTM D 70 (2003)	–
Flash point (°C)	ASTM D92 (2005)	230 min

Figure 5. Ductility tests on bitumen binder (asphaltic cement).

Table 5. Specifications for preparing conventional SMA and BAC (Kar, 2012)

Properties	SMA	BAC
Aggregates	Gap-graded	Well-graded
Mass of CA (%)	75–80	50–60
Mass of FA (%)	20–25	40–60
Mass of Filler (%)	9–13	6–10
Binder type	60/70	60/70, 80/100
Min. binder content by weight of mix (%)	>6.5	5–6
Stabilizing additives by weight of mix (%)	0.3–0.5	–
Air voids (%)	3–4	3–6
Layer thickness (mm)	25–75	30–65

Table 6. Standard requirements for BAC (de Almeida Júnior et al., 2012; Kar, 2012; Musa & Haron, 2014)

Parameters	Standards/References	Specifications
Softening point	ASTM D36 (1995)	60–70 minimum
Penetration (0.1 mm)	ASTM D5 (2006)	40–70
Flash point (°C)	AASHTO-48 (2004)	235–260 minimum
Stability (kg)	Musa and Haron (2014); Kar (2012)	Min. 1000 kg or 9KN
Flow (mm)	Musa and Haron (2014); Kar (2012)	2–4
Air voids (%)	Musa and Haron (2014); Kar (2012)	3–6
VMA (%)	Musa and Haron (2014); Hislop and Coree (2000)	Min. 13
VFA (%)	Musa and Haron (2014)	70–85
Elastic recovery (%)	de Almeida Júnior et al. (2012)	85 min
Viscosity at 135°C (Pas)	ASTM D 4402 (2015)	Max. 3 Pas
Dynamic shear (kPa)	AASHTO T315 (2004)	Min. 1 kPa
Mass loss	AASHTO T240 (2003)	1% max

3. Results and discussion

3.1. Grain size particle distribution

The BAC can be described as coarse dense-graded HMA since >60% of the aggregates were coarse aggregates and it is suitable for all pavement layers and traffic conditions. Large aggregate sizes provide better aggregate interlocking and storage skeleton structure for the BAC and also provide high porosity which is needed for both high permeability and high traction and are usually aimed to achieve high surface drainage and durability (Qian & Lu, 2015). Also, Sol-Sánchez et al. (2015) supported the use of coarse open-graded BACs in road pavements, especially where long rainy periods are expected. On the other hand, small particle BACs experience reorientation under repeated wheel

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loads (Qian & Lu, 2015). Also, HMAs have the advantages of resistance to permanent deformation, fatigue and low-temperature cracking, skid, moisture damage, and improved workability and durability (Kar, 2012). The functions of the filler were to increase stiffness, improve workability, moisture resistance, and aging characteristics of HMA. They also play important roles in air voids and VMA (Kar, 2012). The stone dust, fine aggregate (sand), and granite chippings were all found to have < 5% fines as shown in Table 7. Based on their coefficient of uniformity (Cu) and coefficient of curvature (Cc) (Sojobi & Owamah, 2014), which were found to be 6 and 0.55, 1.36 and 1.0, and 4.8 and 4.03, respectively, they were classified as well-graded clean stone dust, poorly graded clean sand, and poorly graded clean granite chippings

3.2. Moisture content, specific gravity, and bulk density

Sand was found to have the highest moisture content followed by stone dust. Hence, it is important that the sand and stone dust used in BAC should be protected from moisture. Granite chippings were found to have the highest bulk density of 1.37 g/cm^3 and the highest specific gravity of 1.37 followed by sand with specific gravity of 2.4 and bulk density of 1.34 g/cm^3. No minimum limit is specified for bulk specific gravity for coarse and fine aggregates by ASTM C127 and ASTM C88, respectively, as shown in Table 8. Also, when the CA and FA are heated at a high temperature of 170°C, most of the moisture content is lost for both PCA- and PMB-modified BACs. The specific gravity of the fine aggregates used was 2.6 g/cm^3 which was close to that of 2.63 g/cm^{3}fine aggregate used by Moghaddam et al. (2014) in PET-modified BAC.

3.3. Water absorption, aggregate impact value, and aggregate crushing values (ACV) for modified and unmodified aggregates

The water absorption of the unmodified and modified aggregates ranged between 1 and 2% which was within the specified limit of <2% by ASTM C127 and ASTM C 128 for CA and FA, respectively, as depicted in Table 9. The plastic coatings were found to reduce water absorption for stone dust, sand, and granite chippings with increase in plastics coating. Furthermore, the AIV were found to increase with increase in plastic coatings for all the aggregates as shown in Table 10. Compared to their various controls with 0% plastic coating, stone dust recorded the highest AIV increase of 241.4% at 20% plastic coating, followed by 74.3% for sand, and 5.7% for granite chippings. The aggregate impact of granite chippings which ranged between 51 and 53.9% was greater than the specified limit of 30%

Table 7. Grain size particle distribution for aggregates used in BAC

Sieve size (mm)	% Finer		
	Stone dust	FA (Sand)	Granite chippings
4.75	90.8	94.8	7.1
2	80.6	91.83	6.76
1.18	63.6	83.53	6.56
0.6	32.4	15.64	3.25
0.425	31.2	15.36	3.25
0.3	17.5	6.19	2.25
0.075	3	0.14	0.25
Pan	0	0	99.95

Table 8. Aggregate characterization for moisture content, specific gravity, and bulk density

Aggregate type	Moisture content (%)	Specific gravity	Bulk density (g/cm^3)
Stone dust	3.30	2.3	1.23
Sand	4.50	2.4	1.34
Granite chippings	0.30	2.6	1.37

Table 9. Water absorption, aggregate impact value, and aggregate crushing value for modified and unmodified aggregates

Aggregate types	% Plastics	Water absorption (%)	Aggregate impact value (%)	Aggregate crushing value (%)
Stone dust	0	2	11.6	10.4
Stone dust	5 (PCA)	1.5	16	18
Stone dust	10 (PCA)	1.5	25	22.6
Stone dust	20 (PCA)	1	39.6	40
Sand	0	1.5	15.49	13.7
Sand	5 (PCA)	1.5	18.4	14.9
Sand	10 (PCA)	1	21.3	18.9
Sand	20 (PCA)	1	27	24.9
Granite chippings	0	1.5	51	49.9
Granite chippings	5 (PCA)	1	52.1	49
Granite chippings	10 (PCA)	1	52	49.8
Granite chippings	20 (PCA)	1	53.9	50.7

Table 10. Properties of conventional bituminous binder

Parameters	Average values
Penetration at 25°C (0.1 mm)	84
Softening point (⁰C)	47
Ductility at 25°C (cm)	50.33
Specific gravity	1.02
Grade	60/70

recommended by Reyes et al. (2008) and 35% recommended by Summer (2000). Summer (2000) stated that lower the AIV of an aggregate, the better its suitability for use in road surfaces and that aggregates with AIV below 10% are regarded as strong materials while aggregates with AIVs more than 35% are regarded as weak for use in road surface. The other aggregates, namely: stone dust and sand, had AIV ranges of 11.6–39.6% and 15.49–27% which were within the recommended range. In addition, the results also revealed that stone dust and sand must not be given more than 10% and 20% plastics coatings, respectively.

Furthermore, the ACV of all the aggregates were found to increase with increase in plastic coatings. At 20% plastics coating, stone dust recorded the highest increment of 284.6%, followed by 81.8% for sand, and 1.6% for granite chippings. Likewise, the results revealed that stone dust must not be coated up to 20% to achieve required ACV limit. Correlation studies revealed that AIV is highly correlated to ACV with correlation value of 0.996. This implies that AIV is an accurate predictor of the ACV of an aggregate and vice versa.

3.4. Penetration, softening point, and ductility values of unmodified and modified bituminous binder

The properties of the conventional bituminous binder are presented in Table 10. The penetration value of 8.4 mm was very close to 8.43 obtained by Ahmadinia et al. (2012) and higher than 6.3 mm obtained by Sengoz et al. (2009); but all were found to exceed the range of 5.0–7.0 mm specified by ASTM D 5EN 1426. Also, the softening point of 47°C was very close to 47.7°C obtained by Ahmadinia et al. (2012) but was lesser to 49°C obtained by Sengoz et al. (2009) and was close to the upper limit of 46°C specified by ASTM D 36 EN 1427. The ductility value of 50.33 cm obtained for the

Figure 6. Penetration values for different polymer contents in bituminous binder.

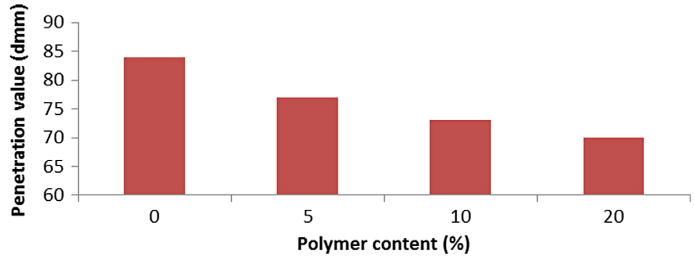


Figure 7. Softening point values for different polymer contents in bituminous binder.

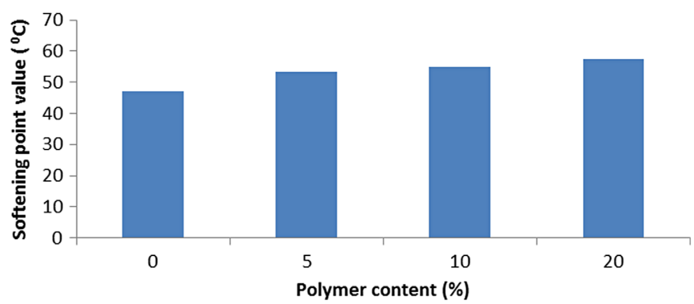
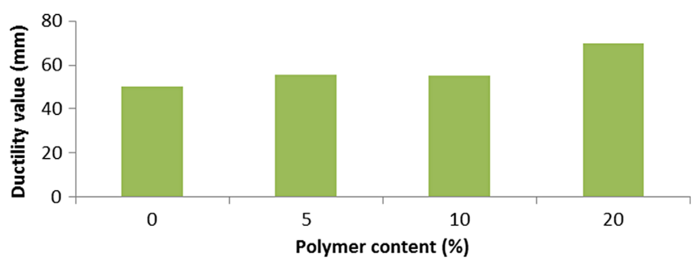


Figure 8. Ductility values for different polymer contents in bituminous binder.



conventional binder was half of 100+ obtained by Ahmadinia et al. (2012), although no limit was specified by ASTM D 113 for ductility. The specific gravity of the binder was 1.02 and was close to 1.03 obtained by Sengoz et al. (2009). Asphalt of penetration grade of 60/70 was used. 60/70 grade asphalt was also used by Essawy et al. (2013), Morova (2013) as well as Musa and Haron (2014) and Kar (2012).

Laboratory results demonstrated that penetration values of the PMB decreased with increase in plastic contents as shown in Figure 6. The penetration values at 5, 10, and 20% plastic contents were 7.7, 7.3, and 2.0 mm, respectively. Conversely, the softening points and ductility were found to increase with increase in plastic contents as shown in Figures 7 and 8.

The reduction in the penetration values indicates increase in stiffness of the PMB with increase in plastic content, a condition which was also reported by Essawy et al. (2013) and Fang et al. (2013). The reduction indicates an increase in the viscosity of the PMB (Fang et al., 2013). At high temperature, the stiffness modulus of the polymer phase is usually higher than that of asphalt and contributes to the increase in viscosity (Essawy et al., 2013). The corresponding decrease in penetration values at 5, 10, and 20% plastic contents compared to the conventional asphalt was 8.3, 13.1, and 76.2%, respectively.

The softening point was also observed to increase with increase in plastic content, a condition which was also reported by Essawy et al. (2013). The corresponding increase in softening points at 5, 10, and 20% plastic contents compared to the conventional asphalt was 13.3, 17, and 22.34%, respectively. Fang et al. (2013) stated that the higher the softening point, the more stable the asphalt is at high temperature. This implies that the polymer content in PMB improved the high-temperature stability of the asphalt. The increase of 17% in softening point is higher than 10% increase recorded with polyethylene by Essawy et al. (2013). The penetration index (PI), calculated using penetration and softening point values, reflects the temperature susceptibility of the asphalt. The corresponding PIs for the conventional bitumen and the PMB at different plastic contents of 5, 10, and 20% were 118.8, 122.1, 122, and 90.7, respectively. This showed that the PMB showed high PI value at 10%, beyond which it decreased considerably by 25.7% at 20% plastic content. The PI values obtained were far higher than the PI of −3.81 reported by Fang et al. (2013) with waste polyethylene.

The ductility values obtained at 0% (control), 5, 10, and 20% plastic contents were 50.33, 55.66, 55, and 70 cm, respectively, which represent an increase of 10.59, 9.28, and 39.08%, respectively. No limit was specified for ductility by ASTM D 113. The ductility values were found to increase with increase in plastic contents. Considerably high ductility values were obtained which confer high durability (Fang et al., 2013). The ductility value of the base asphalt used by Fang et al. (2013) was 62.8 cm and is higher than the ductility value of 50.33 cm obtained in our study.

These changes in the properties of the PMB are attributed to release of asphaltenes content and the decrease of aromatic and resin contents with increase in plastic content and the dispersion of the polymer phase in the asphalt which increases the cohesion as well as the elasticity of the asphalt and consequently enhances its engineering properties (Essawy et al., 2013). Also, softening point and ductility were found to have high correlation with a high value of 0.8192. This showed that softening point influences significantly the ductility of asphalt and can be used to predict ductility of asphalt and vice versa.

3.5. Laboratory results for OBC for conventional BAC

The OBC for conventional BAC without polymer modification was determined using the Marshall design method. The engineering properties tested were Marshall stability, density, % air void, flow, and VFB. Bitumen was added by weight of the total aggregate mix comprising coarse and fine aggregates and filler ranging from 1, 2, 3, 4 to 5%. For each BAC mixture, five samples each were used to obtain the average for each % addition of bitumen. The OBC for conventional BAC was obtained using five parameters, namely:

Bitumen content corresponding to maximum stability = 5%

Bitumen content corresponding to maximum density = 4%

Bitumen content corresponding to 4% air void = 3%

Bitumen content corresponding to maximum flow = 4%

Bitumen content corresponding to minimum VFB = 4%

The resulting optimum bitumen (OBC) for conventional BAC was obtained as 4% by weight of total aggregate mix comprising coarse and fine aggregates and filler. This result corresponds well with the 4% obtained by Chavan (2013) and Sultana and Prasad (2012), but was less than 4.5% obtained by Jassim, Mahmood, and Ahmed (2014), 4.94% obtained by Musa and Haron (2014), and the 5% obtained by Nobinur Rahman et al. (2013), Rahman and Wahab (2013), and Essawy et al. (2013).

3.6. Laboratory results for OPC for PCA- and PMB-modified BAC

The OPC for PMB-modified BAC was obtained as 9% by weight of OBC replacement from the average of plastic contents corresponding to parameters such as maximum Marshall stability (MS), maximum density, closest to 4% air void, maximum flow, minimum VFB, and minimum VMA that satisfied the minimum VMA requirement of 13%. For PCA-modified BAC, the OPC was obtained as 16.7% and was found greater than the OPC for PMB. This result indicates that PCA has more ability to optimize PET use in BAC than PMB which corroborates the findings of Sultana and Prasad (2012).

The 16.7% OPC for PCA-modified BAC was higher than the 15% OPC by weight of total aggregate obtained by Jassim et al. (2014), the 12% OPC by weight of bitumen obtained by Awwad and Shbeeb (2007) using PCA produced with grinded HDPE, 10% PCA-OPC obtained by Sreejith (2009) produced with pulverized PE carry bag wastes, and 8% PCA-OPC obtained by Sultana and Prasad (2012) with LDPE.

The 9% OPC for PMB-modified BAC was close to 9.7% PMB-OPC obtained for Ahmad (2014) with shredded LDPE, lower than the 10% PMB-OPC obtained by Nobinur Rahman et al. (2013) for polyethylene (PE), higher than the 8% PMB-OPC obtained by Sultana and Prasad (2012) with LDPE, and the 5% OPC obtained by Nobinur Rahman et al. (2013), higher than 4 and 5% PMB-OPC obtained by Abd-Allah, El-sharkawi Attia, Abd-Elmaksoud Khamis, Mohammed DeefAllah, and Deef-Allah (2014) for polyvinyl chloride (PVC) and HDPE, respectively.

From literatures, it was observed that the OPC and OBC values obtained and cited by different researchers depend on the type of plastic used, the state/size of the plastics before blending (grinded and pelletized), the mixing process utilized (wet, semi-wet, dry, or variants of these three methods), the reference adopted for reporting the % replacement, OBC and OPC (by weight of OBC, by weight of total aggregates, and by weight of total mix), the type of BAC used (SMA, HMA, WMA, and CMA), the grade of the binder (bitumen) (30/40, 50/70, 60/70, and 80/100), the method used in computing the OBC and OPC (utilizing some or all of the parameters such as MS, density, air void, flow, VFA, and VMA), and the type and size of aggregates and fillers used . This implies that comparison of results should be done with caution since each of these factors will affect the OBC and OPC values obtained, alongside other properties of conventional BAC and modified BAC.

The Marshall values for PMB-modified BAC increased with increase in plastic contents and were 3,876, 4,076, and 4,425 kg for 5, 10, and 15% plastic contents, respectively. Also, the Marshall values for PCA-modified BAC increased correspondingly from 3,680, 3,780, and 4,320 kg for 10, 20, and 30% plastic contents, respectively. When the composite values of our research (4,244 kg and 4,033 kg for PET-PMB and PET-PCA, respectively) were compared with other composite values obtained for other researchers as depicted in Figure 9, the Marshall values were lower compared to results obtained by Essawy et al. (2013) with polyester (5,290 kg) and 4,410 kg obtained for Kumar and Mahendran (2014) with HDPE-PCA. Our composite Marshall values were higher than the values obtained by Abd-Allah et al. (2014) with PVC-PMB (2497 kg), Sreejith (2009) with PE Foam-PAC (2372 kg), Punith, Veeraragavan, and Amirkhanian (2011) with LDPE-PMB (1771.3 kg), Sreejith (2009) with LDPE-PCA (1700 kg), Musa and Haron (2014) with LDPE added to the mix (1304 kg), and Ahmad (2014) with shredded LDPE-PMB(980.3).

Figure 9. Comparison of composite Marshall values and median of plastic contents for various plastic wastes.

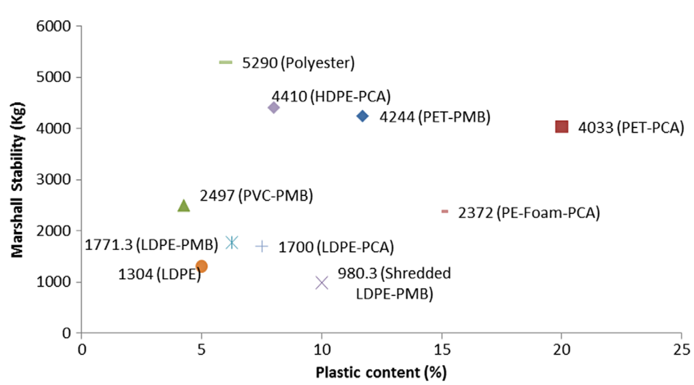
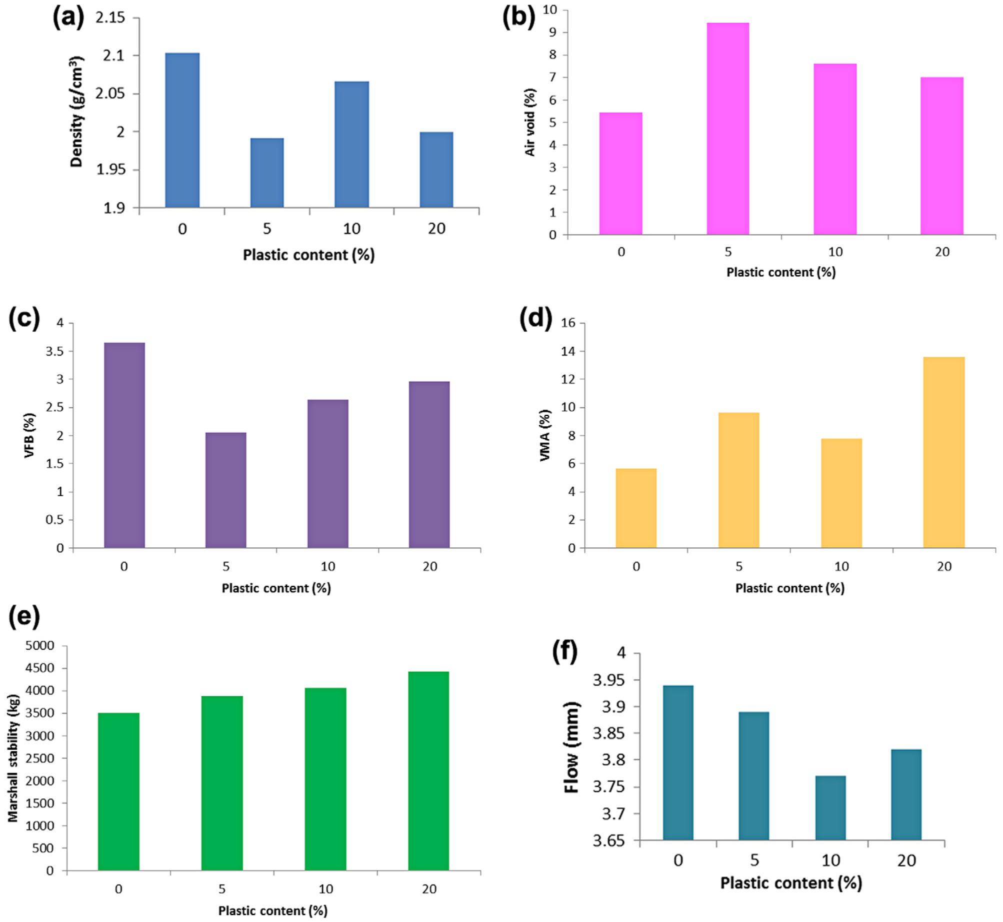


Figure 10. Physical properties of conventional and modified PMB-modified BAC.

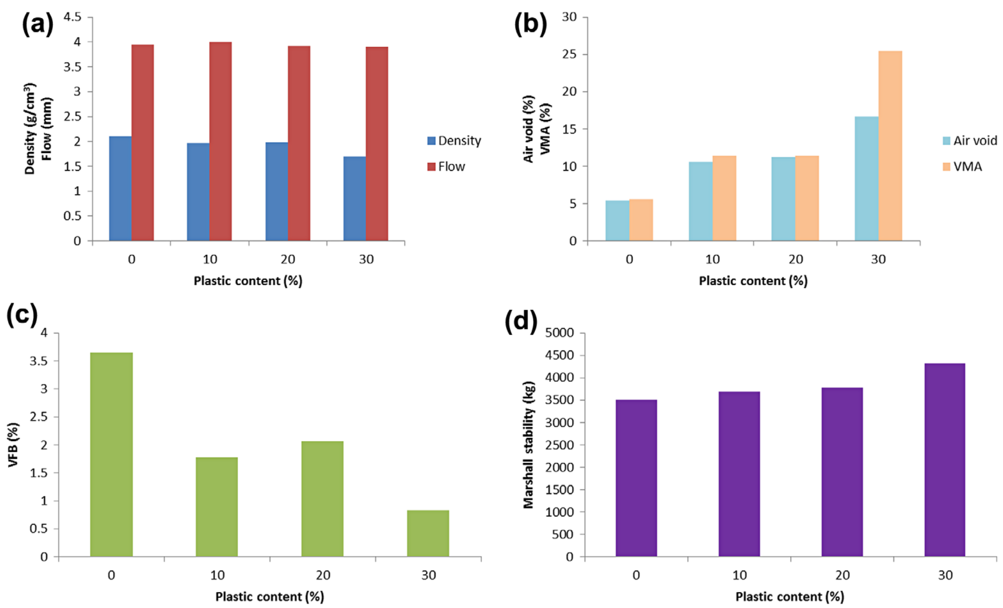


The composite Marshall stability (MS) values were obtained by multiplying each plastic content with corresponding Marshall stability (MS) values and divided by the sum of all the plastic contents used in the analysis. The composite Marshall values and mean plastic contents obtained for all the research considered give a representative value and were plotted to allow for accurate and unbiased comparison of the Marshall stability values of each plastic type. Figure 9 also revealed that the MS for BAC varies depending on the type of plastic used, the mixing process adopted, and the range of plastic content investigated.

MS for both PMB and PCA was found to increase with increase in plastic contents in Figure 10 which corroborates the findings of Ahmadinia et al. (2011). The corresponding increase in MS compared to the conventional bitumen at 5, 10, and 20% plastic contents for PMB was 10.74, 16.2, and 26.43%, respectively. The corresponding increase in MS compared to the conventional bitumen at 10, 20, and 30% plastic contents for PCA was 5.14, 8, and 23.43%, respectively. MS values obtained with PMB were higher than those of PCA-modified BAC because of the greater dispersion of PET in PMB which confers more stiffness and consequently more stability.

The densities of PCA-BAC at 10 and 20% PET contents of 1.97 and 1.98 g/cm^3 were lower compared to densities of 2.07 and 2.00 g/cm^3 at corresponding 10% and 20% PET contents for PMB-BAC because PCA-BAC utilized greater amount of plastic wastes which has low density and the greater increase in air void experienced by PCA-BAC. Also, corresponding reduction in density compared to the conventional BAC (2.10 g/cm^3) for PCA was 5.24, 1.43, and 4.76% at 5, 10, and 20% PET contents and 6.19, 5.71, and 19.05% at 10, 20, and 30% PET contents for PCA-BAC. Both PCAs were found to experience decrease in density with increase in plastic contents.

Figure 11. Physical properties of conventional and PCA-modified BAC.



Flow of 4 mm and 3.92 mm experienced by PCA at 10% and 20% plastic contents was higher compared to that of 3.77 mm and 3.82 mm at the same plastic contents. Also, flow in PCA was fairly stable within a range of −0.51–1.52% of that of unmodified conventional BAC (3.94 mm). On the other hand, flow reduction in PMB was between 1.27 and 4.31%.

For PCA, air void (AV) was found to increase with increase in plastic content as depicted in Figure 11. The AV for 10, 20, and 30% plastic contents was 10.62, 11.23, and 16.63%, respectively. For PMB, the AV increased to 9.43% at 5% plastic content and then decreased up to 7% at 30% plastic content as shown in Figure 10, which corroborates reduction in air voids obtained by Punith et al. (2011).

Our study also revealed that the voids filled with bitumen (VFB) in PMB increased with increase in plastic contents, while that of PCA experienced a decline. The VFB in PMB which ranged from 2.05 to 2.96% was greater than that of PCA which ranged from 0.83 to 2.07%.

In addition, VMA in both PMB- and PCA-modified BAC was found to increase with increase in plastic contents which supports the findings of Ahmadinia et al. (2011). The VMA for PMB at 5, 10, and 20% plastic contents was 9.62, 7.79, and 13.57%, respectively which corresponds to increase of 70.87, 37.30, and 141.03%, respectively, compared to VMA of 5.63% for control. The VMA for PCA-modified BAC was 10.81, 11.41, and 16.81% at 10, 20, and 30% plastic contents, respectively.

Correlation studies likewise were used to investigate the relationship among the various parameters used. For both PCA and PMB, air void (AV) was found to be very strongly correlated to VMA and MS. This indicates that air void is an accurate predictor of VMA with high correlation values of 0.9956 and 0.9579 for PMB and PCA, respectively. This indicates that air void is an accurate predictor of VMA as shown in Tables 11 and 12. In addition, for PCA, it was found that AV was very strongly negatively correlated to density (−0.9976). This implies that the greater the air voids, the lower the density of PCA-modified BAC.

Furthermore, the correlation studies revealed that VMA for PCA was very strongly positively correlated to MS (0.9575) and very strongly negatively correlated to density (−0.9671) and VFB (−0.9727), while for PMB, it was only strongly correlated to MS (0.8960) and strongly negatively correlated to density (−0.8365).

Table 11. Correlation coefficients for PMB-modified BAC

	AV	VMA	MS	Flow	Density	VFB
AV	1	0.9956	0.8698	−0.39055	−0.8840	−0.4279
VMA		1	0.8960	−0.3906	−0.8365	−0.3594
MS			1	−0.7763	−0.6262	−0.3519
Flow				1	0.1825	0.3597
Density					1	0.7218
V_b						1

Table 12. Correlation coefficients for PCA-modified BAC

	AV	VMA	MS	Flow	Density	VFB
AV	1	0.9579	0.9962	−0.5426	−0.9976	−0.8863
VMA		1	0.9575	0.4253	−0.9671	−0.9727
MS			1	−0.6034	−0.9893	−0.8730
Flow				1	0.4839	0.2079
Density					1	0.9110
V_b						1

Our correlation studies also revealed that for PCA, MS was very strongly negatively correlated to density. This implies the lower the density of PCA-BAC, the higher the MS, which corroborated our earlier result findings displayed in Figure 11. This implies density is an accurate predictor of MS for PCA-modified BAC. MS was found to be strongly negatively correlated to VFB with correlation value of −0.8730, while density is strongly positively correlated to VFB with correlation value of 0.911 as shown in Figure 11.

In summary, PMB- and PCA-modified BAC exhibited some similarities as well as some differences in their properties with increase in plastic contents. It also revealed that for both PMB- and PCA-modified BAC, the air void, VMA, volume of bitumen, and density must be carefully formulated with the PET plastic waste contents to obtain desirable plastic-modified BAC with excellent physical and mechanical performance.

4. Economic and environmental implications

Based on the results from this study and the fact that PET wastes constitute 55–60% of plastic (Rahman & Wahab, 2013), and that 92.3% of paved roads globally are flexible pavements (Blazejowski, 2011), post-consumer PET plastic bottle wastes could be considered for modification of BAC. Utilization of these wastes in flexible pavement construction and road rehabilitations would significantly mop up several million metric tons of the PET wastes from the waste stream which would have positive effects on the environment such as reduction of environmental pollution and burdens from greenhouse gas emissions and littered plastics, reduction of drainage problems arising from drainage networks blocked by PET wastes, elongated service lives of landfills, and conservation of natural resources used in production of BAC such as asphalt. It also enhances ecosystem balance by the removal of non-biodegradable PET wastes from the ecosystem (Ahmadinia et al., 2011) and prevention of bioaccumulation of plastics in food chains. Likewise, utilization of the PET-modified BACs in flexible pavements would significantly improve the service lives of our roads with economic implications such as provision of extra source of income for waste managers, reduction of construction and maintenance costs of flexible pavements, reduction of accidents, and facilitation of smooth and enjoyable rides for commuters. The financial savings as a result of reduction of construction and maintenance costs of flexible pavements can be used for other developmental programs by the government. For developed countries, regulations and monitoring to enforce the utilization of the PET wastes by road construction firms would need to be put in place similar regulations put in place in the UK, reported by Kakar et al. (2015), and 35% composition of rubberized tire in total weight of asphalt required for asphalt pavements in California, reported by Lo Presti (2013). Utilization of PET wastes in industrial construction and production projects was also supported by Ahmadinia et al. (2012).

5. Conclusions

This research showcased the importance of eco-friendly road construction in our quest toward achieving sustainable development in the twenty-first century. It sheds light on the concept of eco-friendly road construction and likewise revealed the factors responsible for its emergence, the obstacles being faced in its adoption by stakeholders, and the benefits derivable from embracing eco-friendly road construction.

Eco-friendly road construction comprises eight basic elements, namely: eco-design, eco-extraction, eco-manufacturing, eco-construction, eco-rehabilitation, eco-maintenance, eco-demolition, and socioeconomic empowerment. Our research also highlighted various waste materials which are applicable in various aspects of road construction, which include plastic wastes. For eco-friendly road construction to be embraced especially in developing countries, there is a need for collaboration among all stakeholders and decision-makers in all levels of government, and support from government in terms of financial support for research and development as well as regulation, monitoring, and enforcement.

In addition, this study evaluated the effects of recycling PET plastic bottle wastes produced in North Central Nigeria in BAC used in flexible pavement construction. The mix design consists of 60/70 penetration-grade asphaltic concrete (5%), and aggregate composition comprising 68% coarse aggregate, 6% fine aggregate, and 21% filler. Based on the results from this study, the following conclusions could be made:

(1) PCA-modified BAC optimizes more PET recycling in BAC with a higher OBC of 16.7% compared to 9% OBC achieved with PMB-modified BAC, even though PMB-modified BAC recorded higher Marshall stability at corresponding plastic contents. Even though both can be used, utilization of the PET plastic bottles wastes in PCA-modified BAC seems to be preferable.

(2) For both PMB and PCA, higher Marshall stability was obtained at higher plastic contents. Air void was found to increase with increase in plastic contents for PCA, but was found to decrease for PMB with increase in plastic contents.

(3) Parameters such as the air void, VMA, volume of bitumen, and density of the BAC must be carefully formulated with the PET plastic waste contents to obtain desirable plastic-modified BAC with excellent physical and mechanical performance.

(4) For PMB, addition of the PET plastic wastes seems to reduce the penetration values, increase the softening point, ductility as well as the plasticity index.

(5) For PCA-modified BAC, the plastic contents seem to produce a reduction in the density, an increase in air void, VMA, and Marshall stability.

(6) Effective solid waste collection systems need to be put in place to encourage source separation of the plastic wastes and the prompt collection by waste management authorities.

(7) To enhance the recycling of the PET plastic bottle wastes in flexible pavement construction and maintenance by road construction companies, effective regulations, monitoring, and support to facilitate its uptake are required especially in developed countries.

(8) Utilization of PET plastic bottle wastes could have positive environmental and economic benefits considering the potential effects of removal of several million metric tons of PET wastes from the waste stream and the potential financial savings emanating from elongated service life of roads, reduction of accidents, conservation of natural resources, and income from trading in such wastes.

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