MRS Advances © 2020 Materials Research Society
DOI: 10.1557/adv.2020.197

Recycling of plastic waste materials: mechanical properties and implications for road construction

J. A. Panashe [1] and Y. Danyuo [1,*]

[1] *Department of Mechanical Engineering, Ashesi University, [1] University Avenue, Berekuso, Ghana*

Abstract

This paper presents a recent study on recycling poly-ethylene-tetraphylate (PET), known as plastic waste material in Ghana, to wealth. Composites were produced by heating aggregates together with shredded PET plastic waste material, while bitumen was added to the plastic-coated aggregates. The composites produced were reinforced with 4.5 wt%, 9.0 wt%, 13.6 wt%, and 18.0 wt% PET. Mechanical properties of the fabricated composite samples were studied with a Universal testing machine for optimization. The work demonstrated that shredded PET plastic waste material acts as a strong binding agent for bitumen that can improve on the shelf life of the asphalt. From the results, 13.6 wt% concentration of PET was shown to experience the maximum compressive strength and flexural strength. Besides, water resistance was shown to increase with PET concentrations/weight fraction. From the data characterized 13.6 wt% of PET plastic gives the optimum plastic concentration that enhances the rheological properties of bitumen. The implications of the result are therefore discussed for the use of 13.6 wt% PET in road construction.

****Corresponding Author**: Email: yiporodanyuo@gmail.com, Mobile: +233550505434.*

1.0 INTRODUCTION:

Composites are materials obtained through the combination of two or more different materials with identifiable phases and distinct interfaces [1,2]. The main composition of composites comprised of the matrix phase which surrounds and binds the reinforced material or binds fragments of the reinforced materials together [3]. Asphaltic concrete is an example of a composite produced from coarse or fine aggregates and filler materials bounded together with a bitumen [4,5,6]. Bituminous mixture comprised of aggregates bounded with a hydrocarbon binder [6]. Composite materials are often characterized by low weight, high fatigue strength, good resistance to corrosion, resistance to abrasive wear, enhanced hardness and higher impact strength [1-3, 7].
Plastics production and utilization have affected our globe. An estimate of 8300 million metric tonnes of plastics has been produced by 2017 with an annual production rate of fibers and resin alone been estimated to increase from 2 million tonnes to 380 million

tonnes within 1950-2015 [8]. About 9% of the generated plastic waste has been recycled, 12% incinerated, while the remaining 79% is damped in our environment and landfills [9]. Disposability of plastic waste is of global concern. In Africa, the environment has also been challenged with plastics pollution. A report from the World Bank in 2012 indicated that 70 million tons of plastic waste have been produced [10]. Some other challenges include choke gutters which end up causing floods (narrow downflow paths) especially in Accra, the capital town of Ghana. Other major issues with plastic pollution include sickness and poor sanitation [11]. Plastic pollution has also affected aquatic life in marine environments [12,13]. Ghanaians have since developed a strong desire for plastic utilization due to its cost-effectiveness and portability as "sale-packaging" materials. However, the products of these plastics are indiscriminately disposed of after use to litter the environment. Thus, plastic waste materials are becoming a nuisance in Ghana [14]. Recent studies show that plastics waste materials amount to a major proportion of all waste generated throughout the country, thereby replacing leaves, metal containers, and glassware as cost-effective and reliable packaging material [11]. Records from the Accra Metropolitan Assembly have shown that 2,500 tons of waste are been generated daily in the city of Accra alone. This trend is expected to increase with increasing population growth and industrialization. It has also been estimated that plastic waste materials in Accra form 16.5% of all the waste stream in the environment [11]. Plastic recycling for potential applications has been a topic of discussion in recent years due to large quantities of plastics wastes in our environment. Among the compositions of plastics waste, low-density polyethylene has been largely produced. Others include high-density polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyethylene terephthalate (PET), and among others [15]. Though the use of recycled plastics in concrete materials has been challenged with poor bonding with the matrix [16], polymer-modified crack sealers and other types of modifiers have been gaining popularity and are being developed for construction processes. However, many of these modifiers have not been extensively studied for further development. PET aggregates have been reported to contribute poorly toward the elastic modulus of concretes [17]. Concerning the current study, it might be enough to say that research on incorporated recycled plastic pellets to provide an extra binding to plastic (PET)-asphalt concrete mixture on the layered road has not been well studied. Environmental impact and sustainability are increasingly being considered in the design of roadways [18]. However, extensive data on the mechanical, thermal and chemical stabilities has not been sufficiently presented. This current work, therefore, seeks to provide enough characterization on technical data regarding the suitability of recycled PET into asphalt for road construction.

2.0 MATERIALS AND METHODS

2.1 Materials

Waste plastic materials were collected from the canteens and hostels on the Ashesi University campus. AC-10 bitumen penetration grade of 70 was procured from a shop (Mallam Area, Accra, Ghana) with characteristics that correspond to ASTM D3381-09 standards. Aggregates of quartz (size range of 10-15 mm) were supplied by the Ashesi University Logistics team. The aggregate specifications were based on guidelines of the Road and Bridgeworks, by the Ministry of Road and Transport and Highway in Ghana. After user requirements and system properties were defined, competing raw materials were sorted with the aid of CES Edu pack 2013 (Granta Design Limited, Cambridge, UK) [19] from the family of eco-friendly materials. Materials were chosen based on compressive strength, recyclability, miscibility, corrosion resistance, and the availability of raw materials. The chosen characteristics were then scaled using an evaluation criterion.

2.2 Composite Preparation

The collected PET was sorted, de-dusted, washed and sun-dried for a few days. The dried samples of the waste plastic materials were shredded. The quartz aggregates were pre-heated to a temperature of 170 °C, while shredded plastics (PET) of sizes 2.3-2.7 mm were added to the hot aggregates at specified percentages (0 wt%, 4.5 wt%, 9.0 wt%, 13.6 wt%, and 18.0 wt% PET). The process was mixed continuously to ensure uniform distribution of the plastic. When the aggregates were fully coated with PET, bitumen was then added to the samples (PET coated aggregates) at a temperature of 140 °C - 160 °C. The mixtures were thoroughly blended before casting into rectangular and cylindrical molds.

2.3 Mechanical Characterization

Tensile and three-point bending test was performed with MTS universal tensile testing machine (MTS 6, MN, USA). Specimens were placed in the grips of the MTS machine at a specified grip separation and pulled until failure occurred. Measurements were guided by ISO 527 test speeds, typically, 5 mm/min and 1 mm/min for measuring strength and elongation, respectively. The MTS machine itself records the displacement between its crosshead on which the specimen is held. Hence, the engineering strain was determined using the crosshead displacement as given in equation (1). The results were then analyzed with OriginPro software (OriginPro 2017, Northampton, UK). The engineering stress was also obtained from the force-extension curves as given in equation (2):

$$\varepsilon = \frac{\Delta L}{L_0} \qquad (1)$$

$$\sigma = \frac{F}{A} \qquad (2)$$

where L_o is the initial length of the specimen, ΔL is the crosshead displacement, F is the load applied, and A is the cross-sectional area of the specimen. The yield strength was obtained from the stress-strain graph at the 0.2 % offset yield. The modulus of resilience, the area under the elastic portion of the stress-strain graph and was estimated as given in equation (3) [20-22]:

$$E_r = \frac{1}{2}(\sigma_y)(\varepsilon_y) \qquad (3)$$

where σ_y is the yield strength and ε_y is the strain at yielding. The Young's modulus was obtained by taking the gradient within the elastic regime of the stress-strain curve as given in equation (4) [20]:

$$\mathrm{E} = \frac{\Delta\sigma}{\Delta\varepsilon} \qquad (4)$$

In the determination of compressive strength, the specimen's diameter, thickness, and area were 0.03 m, 0.04 m and $7.07 * 10^{-4}\, m^2$, respectively. Experimental samples were deformed monotonically at a loading rate of 3.3 N/s until fracture occurred. A curve of the compressive load (kN) versus crosshead displacement (mm) was used to estimate the peak load. The compressive strength was then estimated using equation (5):

$$\sigma_{comp.} = \frac{F}{A_0} \quad (5)$$

where F is the peak load at the onset of fracture and A_0 is the initial cross-sectional area. Experiments were repeated (n = 5) and average values were reported. Three-point bend loading configuration was used to estimate the flexural/bend strengths and fracture toughness values for the samples. A loading span of 80 mm was used for the entire three-point bend test. The flexural/bend strength σ_{bend} was obtained from equation (6):

$$\sigma_{\mathrm{bend}} = \frac{3FL}{2wh^2} \quad (6)$$

where F is the fracture load, L is the span length (a distance between two outer points of the sample, h is the height/thickness of the sample, and w is its width. The flexural modulus was also calculated as:

$$E_{bend} = \frac{L^3 F}{4wh^3\delta} \quad (7)$$

where δ is the deflection of the beam when a load, F is applied.

A hardness test was conducted using the High Definition (HD) tester. The measuring range of the hardness tester was from 0-100 HD max. To measure the hardness, the samples were indented at five different spots at a dwelling time of 10 s and the average values were the reported.

2.4 Stripping Test

The stripping test was performed on the samples after immersion in a water bath set at 90 °C (Fig. 1). This experiment was then repeated at 24, 48, and 72 h. Records were taken to determine the bitumen (mass) loss from the asphalt as given in equation (8).

$$\%Mass\ Lost = \frac{M_i - M_t}{M_i}\ x\ 100\% \quad (8)$$

where M_t is the instantaneous mass and M_i is the initial mass of the test specimen.

Figure 1: Preparing Samples for Stripping Test.

3.0 RESULTS AND DISCUSSION

3.1 Compression and Flexural Properties

There was a steady increase in the compressive strength from 1.64 MPa (for the control sample) to 7.42 MPa (at 13.6 wt% PET) as shown in Figure 2a. However, an unexpected decrease in the compressive strength was observed at 18.0 wt% with a compressive strength of 0.75 MPa. PET saturation in the bitumen matrix reduces the effective bonding between the two phases. Thus, the interactions between PET-bitumen/PET-aggregate were weaker.

Also, the modulus of elasticity (Fig. 2b) varied from 10.9 MPa (for the control sample) to 123.67 MPa (at 13.0 wt%), while the results again decreased to 10.7 MPa at 18.0 wt% PET for similar reasons (Properties dropped drastically due to saturated PET in the bitumen).

The flexural strength and modulus are also presented (Figs. 2c-d). The result on the flexural strength (Fig. 2c) was optimized at 13.6 wt% PET, followed by 18.0 wt% PET. The flexural modulus of the composites was maximum at 13.6 and 18.0 wt% PET. The essence of reinforcing a matrix is to bridge pre-existing cracks or micro-cracks. An insufficient reinforced phase may not significantly arrest micro-cracks/pre-existing cracks due to weak interaction between the reinforced phase and the matrix which affects the mechanical properties of the structures. The results were enhanced with increasing PET content to some extent (13.6 wt% PET). However, a continuous increase in PET beyond 13.6 wt% PET (such as 18 wt% PET) failed to arrest micro-cracks and hence decrease the compressive and flexural properties due to weak interaction/bonding between the different phases present (bitumen, PET and quartz aggregates).

The composites produced generally supported more compressive loads (Figs. 2a-b) than loading them in the flexural direction (Figs. 2c-d). This is because the area of the specimen increases during compression which therefore requires higher stress to deformation. Thus, an increase in the cross-sectional area increases progressively thereby increasing the load-bearing ability. Similarly, the strain at which failure occurs is greater in compression than it is in bending.

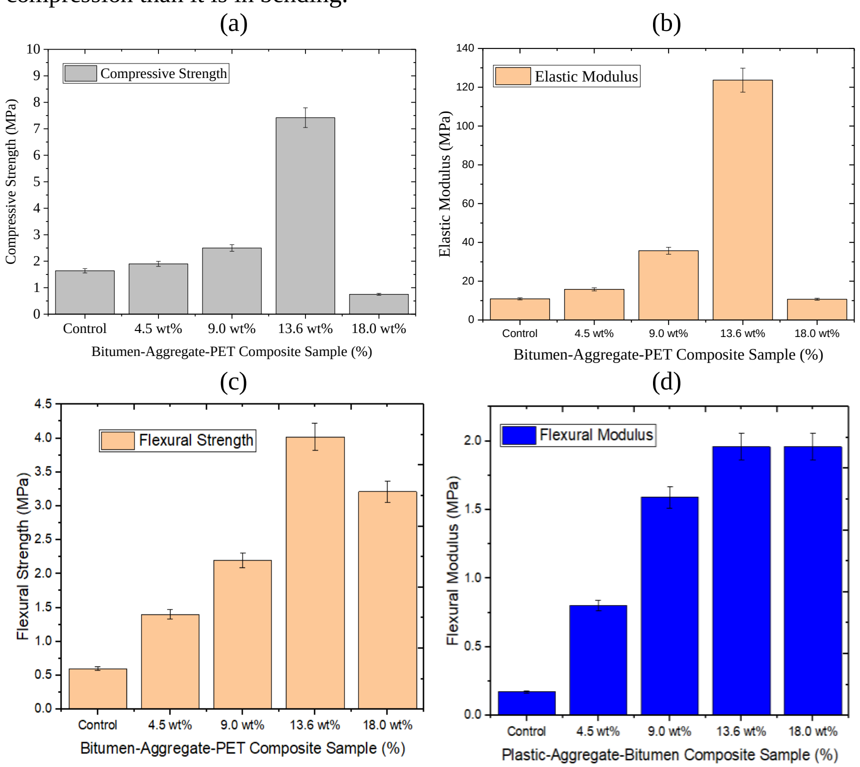

Figure 2: Transverse Loading: (a) Flexural Strength and (b) Flexural Modulus of Bitumen-Aggregates-PET Composites. Error Bars are 5% of Data.

3.2 Hardness and Stripped Data

The hardness values of the composites are presented (Fig. 3a). The hardness of the control sample was 38.42 HD. The addition of PET increased the hardness from 61.55 HD (at 4.5 wt%) to 80.3 HD (at 13.6 wt%). However, at 18 wt% of PET, the hardness of the sample reduced to 68.25 HD. The result shows that PET plastic increases the binding strength of the composite. However, at 18.0 wt% of PET, the matrix and the PET separated causing some portions of the composite to be less hardened.

Stripping is a test performed on samples to determine the mass of bitumen lost from an asphalt (using equation 8). As the PET wt% increased, the rate of stripping decreased (Fig. 3b). There was no sign of stripping for the 13.6 wt% and 18 wt% PET-coated aggregate bitumen after 72 h of immersion. The bitumen and aggregate mixtures lost 2 g of mass (mass loss of 3.3 %) within 72 h. Moreover, water-resistance was increased due to the non-porous nature of PET resulting in less/no erosion of the samples (Fig. 3b). The result implied that the modified composites samples will last longer thereby reducing the formation of potholes on roads. This will also reduce maintenance costs and the overall cost of construction (if PET is recycled for construction).

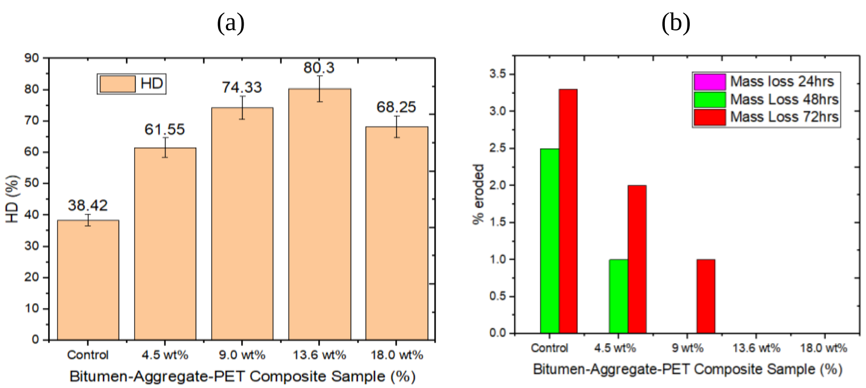

Figure 3: (a) Hardness of Bitumen-Aggregates-PET Composites and (b) Mass Loss Results for Unmodified and Modified Composite Samples.

4.0 CONCLUSIONS

This paper explored the optimization of the compressive and flexural properties of plastic waste for road construction. Material selection for the hybridized composites was done using the Cambridge Engineering Selector (CES). PET (a plastic waste material in our environment) was converted into constructional materials. The composites comprised of PET mixed with coarse aggregates and bitumen to reinforce the strength of asphalt. Material characterizations were carried out on the fabricated composite materials for optimization. Corrosion studies via mass loss were done using the stripping test method. From all the tests conducted, the sample with 13.6 wt% PET content was found to possess optimum desired properties with higher compressive strength and enhanced elastic modulus. Similarly, this same composition reported higher values of flexural strength and flexural modulus, modulus of resilience and hardness. Low values after stripping at 13.5 wt% signify resistance of the material to corrosion. The large quantity of asphalt was produced using the optimum weight percent from the studies (13 wt% PET) to mend portions of a road near “Dufie Hostel” at Ashesi University, Berekuso, Ghana. Observations and monitoring are ongoing to ascertain the durability of the road. The fundamental implication of this result is that PET could be used to complement bitumen to improve road construction. This will help reduce the cost of road construction and as well improve on the shelf-life of roads since the structures presented are more resistant to water absorption. However, the study mainly focused on PET plastic as a substitute for bitumen. More studies are needed to explore other types of plastic waste like polyethylene for possible potential applications such as building materials [23,24].

ACKNOWLEDGMENTS

The authors appreciate the financial support provided by the Ashesi University toward the execution of this project. We are very grateful to the MasterCard Foundation for providing scholarships for the student.

References

[1] Zhang Y., Li Y., Ma H., and Yu T. Tensile and Interfacial Properties of Unidirectional flax/glass Fiber Reinforced Hybrid Composites. Composite Science and Technology. 88 (2013) 172-177.
[2] Josmin P.J., Sant K. M., Sabu T., Kuruvilla J., Koichi G. and Meyyarappallil S.S. Advances in Polymer Composites: Macro-and Microcomposites-State of the Art, New Challenges and Opportunities. Polymer Composites: 1st Edition. Edited by Sabu T., Kuruvilla J., Sant K. M., Koichi G., and S. S. Meyyarappallil. Wiley-VCH Verlag GmbH & Co. KGaA. Chapter 1 (2012) 1-16.
[3] Soboyejo W. O. Mechanical Properties of Engineered Materials. Toughening Mechanisms. Marcel Dekker, New York. (2002) 152.
[4] Niu D., Chen H., Kim Y. R., Sheng Y., Geng J., Guan B., Xiong R., and Yang V. Damage Assessment of Asphalt Concrete with Composite Additives at the FAM-Coarse Aggregate Interfacial Zone. Construction and Building Materials. 198 (2019) 587-596.
[5] Sarkar D., Pal M. Sarkar A. K., and Mishra U. Evaluation of the Properties of Bituminous Concrete Prepared from Brick-Stone Mix Aggregate. Adv. In Mater. Sci. and Engr. 2761038 (2016) 1-7.
[6] Ingham J. P. Bituminous Mixtures. Geomaterials Under the Microscope. Chapter 10. (2013) 171-174.
[7] Berthelot J-M. Mechanical Behavior and Structural Analysis. Composite Materials. 3rd Edition. Springer-Verlag New York Inc. Springer (1999) 646.
[8] Pellegrino C., Faleschini F., and Meyer C. Development in the Formulation and Reinforcement of Concrete (2nd Edition): Recycled Materials in Concrete. Woodhead Publishing Series in Civil and Structural Engineering. (2019) 19-54.
[9] Geyer R., Jambeck J. R., and Law K. L. Production, Use, and Fate of all Plastics ever made. Sci. Adv. 3. e1700782 (2017).
[10] Ritchie H. and Roser M. Plastic Pollution. Our World in Data. Retrieve from: https://ourworldindata.org/platicspollution. (2020).
[11] Ackah R. L., Carboo D., and Gyamfi E. T. Challenges of Plastic Waste Disposal in Ghana: A Case Study of Solid Waste Disposal Sites in Accra. Elixir InterManag. Arts. 49 (2012) 9879-9885.
[12] Wang J., Tan Z., Peng J., Qiu Q., and Li M. The Behaviors of Microplastics in the Marine Environment. Marine Environmental Research. 113 (2016) 7-17.
[13] Hoornweg D. and Bhada-Tata P. What a Waste: A Global Review of Solid Waste Management. Urban Development Series. Knowledge Papers no.15. World Bank, Washington, DC. © World Bank (2012).
[14] Adu-Boahen K., Atampugre G., Antwi K.B. Osman A., Osei K.N. Mensah E.A., and Adu-Boahen A.O. Waste Management Practice in Ghana: Challenges and Prospects, Jukwa Central Region. Int. J. of Development and Sustainability. 3(3) (2014) 530-546.
[15] Siddique R., Khatib J. and Kaur I. Use of Recycled Plastic in Concrete: A Review. Waste Management. 28 (10) (2008) 1835-1852.
[16] Choi Y-W., Moon D-J., and Cho S-K. Effects of Waste PET Bottles Aggregate on the Properties of Concrete. Cement and Concrete Research. 35(4) (2005) 776-781.

[17] Gu L. and Ozbakkaloglu T. Use of Recycled Plastics in Concrete: A Critical Review. Waste Management. 51 (2016) 19-42.
[18] Zapata P. and Gambatese J. Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction. J. of Infrastructure Systems. 11(1) (2005) 1-3.
[19] Granta Design Limited. CES Edupack. Cambridge (2013).
[20] Callister Jr. W. D. Materials Science and Engineering. New York: John Wiley and Sons Inc. 7th Edition. Chapter 6 (2019) 194.
[21] Danyuo Y., Zakariyyah T., Suleman N., Mustapha K., Azeko T. S., Bello S. A., Abade-Abugre M., Yirijor J., Anyidoho V., and McBangonluri F. Effect of Chemically Modified Banana Fibers on the Mechanical Properties of Poly-Dimethyl-Siloxane-Based Composites. J. of Materials and Engineering Structures (JMES). 6 (2019) 547-563.
[22] Mustapha K., Bello S. A., Danyuo Y., and Oshifowora T. Uniaxial tensile response of coconut coir fiber-reinforced polyethylene Composite. Journal of Materials and Engineering Structures (JMES). 6 (2019) 15-23.
[23] Azeko S. T, Kwesi A. E., Danyuo Y., Babagana M. Mechanical and Physical Properties of Laterite Bricks Reinforced with Reprocessed Polyethylene Waste for Building Applications. ASCE J. Mater. Civ. Eng. 30(4) (2018) 04018039.
[24] Azeko S., Kabiru K. Annan E., Odusanya O.S and Soboyejo W. Recycling of Polyethylene into Strong and Tough Earth-Based Composite Building Materials. Journal of Materials in Civil Engineering. 28(2) (2016) 04015104.