ASHESI UNIVERSITY

RECYCLING OF PLASTIC WASTE MATERIALS: MECHANICAL PROPERTIES AND IMPLICATIONS FOR ROAD CONSTRUCTION

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

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(ID: 51572019)

2019

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Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

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(ID: 51572019)

2019

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Name: …………………………………………………

Candidate's Signature: …………………………………………….

Date: …………………………………………………………………

I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University.

Supervisor's Name: ………………………………………………

Supervisor's Signature: ……………………………………………

Date: …………………………………………………………………

Dedication

This report is dedicated to my lovely parents; Sophia and Alfred, and to my brothers; Barnabas and Denzel.

Acknowledgements

Firstly, I would like to thank God, Almighty for pulling me through this project. I would also like to express my profound gratitude to my supervisor, Dr Danyuo Yiporo, for his extremely useful support and guidance. I really appreciate all the help that he gave me. I would also like to thank Joseph Timpabi, Nicholas Tali and Peter for all the technical help offered to me at the mechanical workshop. They were always there to give me the materials, the tools and the tips that I needed to make this project work.

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Finally, a big shout out to myself for making it happen. It is to my uttermost joy and super bounding excitement that I managed to do this work with a growth mindset. Well done, Jennipher!!!!!!!!

Abstract

The main purpose of the project is to convert polyethylenetetraphylate (PET), a known plastic waste material in Ghana, to wealth. Composite samples 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 of 4.5 wt%, 9.0 wt%, 13.6 wt% and 18.0 wt% concentrations of PET. Mechanical and optical characterisation of the fabricated composite samples were studied for optimization. Moreover, corrosive studies via mass loss and thermal degradation studies were performed on the test samples. From the statistical analysis conducted, it was demonstrated that shredded PET plastic waste material acts as a strong binding agent for bitumen making the asphalt last longer. From the results, 13.6 wt% concentration of PET was shown to have the maximum compressive strength. In addition, water resistance was shown to increase with increasing PET concentration of 4.5 wt%, 9.0 wt%, 13.6 wt% and 18.0 wt. The optical characterisation results revealed that the samples with 13.6 wt% PET plastic concentration had lesser voids, lesser discontinuities and maximum bonding strength. From the data analysed, 13.6 wt% PET plastic gives the optimum plastic concentration that enhances the rheological properties of bitumen. The implications of the result are therefore discussed for the used of 13.6 wt% PET in road construction.

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Chapter One

1.0 Introduction

1.1 Introduction and Background Studies

Composites are materials made by combining two or more natural or artificial elements [1]. Most composites are made of two materials comprising of the matrix phase which surrounds and binds fibres or fragments of the reinforced materials together [2].

Asphaltic concrete is an example of a composite material that is made of aggregates (gravel) of sand bound together with bitumen [3]. The binder, bitumen is a dense, highly viscous, petroleum-based hydrocarbon that is found in oil deposits or is obtained as a residue during distillation of crude oil [4]. Composites can either be natural or synthetic. For example, pure plastics can be reinforced to produce a strong versatile material due to their lightweight. Moreover, most composites provide design flexibility, in addition to their high strength to weight ratio [1], [2].

There is no doubt that plastics creation and utilization have affected the four corners of the globe. Similarly, complications of plastics to its disposability are of global concern. Global consumption of plastics materials by estimate was 260 million tonnes per year as of 2008 [5], while current estimates showed 300 million tonnes per year [6]. A recent report from the World Bank in 2012 indicated the production of 70 million tonnes of plastics waste in Africa [7]. This trend is expected to increase with increasing population growth and industrialization. Similar trends are expected in Ghana with "Sodom and Gomorrah" serving as the dumping site for voluminous plastic waste in the country [8].

In Accra, the capital of Ghana, it has been estimated that plastic waste materials form ~16.5% of the waste stream in the environment [9]. Thus, plastic waste materials are becoming a nuisance in Ghana. The non-biodegradability of plastics that are currently used in Ghana shows that plastics can remain for hundreds to thousands of years [10]. According to Plastic Pollution Organization (PPO), no proper reforms have been introduced yet to counteract the harmful effects of plastic in the ecosystem [6]. Microorganisms such as bacteria have been recommended to degrade plastic waste materials if the necessary conditions are provided for bacterial growth and activities [11], [12]. Nevertheless, recycling remains a better plastic waste management tool that provides considerable solutions and influences in the ecosystem [6], [13], [14]. Recycled materials have been used in many applications that include the formation of composite materials for possibilities in the manufacturing and construction industry [15], [16].

1.2 Problem Definition

According to the World Health Organisation (WHO), 6,500 Ghanaians die annually due to exposure to air pollution [17]. In addition to air pollution, there is land pollution that is caused by leachate from landfills, chemical waste from small mining activities and waste littering by Ghanaians [18]. Most of these waste materials end up choking gutters and clogging sewage lines resulting in cholera outbreaks, flooding and fire risks during the rainy season [10], [18]. One major accident that occurred due to rampant plastic pollution is the "June 3rd tragedy" that claimed over 150 Ghanaian lives and left many injured [19]. Moreover, the disposal of waste plastic is a major problem since it is non-biodegradable [20]. Therefore, it is imperative to provide new and efficient waste management techniques that help reduce the impacts of plastic waste on the environment.

1.3 Motivation and Justification

The general public of the Ghanaian community has developed a strong desire for plastic utilization due to plastics' cost-effectiveness and portability as a "sale-packaging" materials (its easily carried about). However, the products of these plastics are indiscriminately leftover after being used to litter the environment. Recent studies show plastics waste materials amount to a major proportion of all waste generated throughout the country [9], thereby replacing leaves, metal containers, and glassware’s as cost-effective and reliable packaging material. This shows the availability of plastic waste materials is not a question to contend with for their utilization for road construction. This in a way will reduce environmental pollution.

Figure 1. 1: Polluted Pacific Ocean and a sample of plastic waste at a landfill in Jamestown, Accra.

According to My Joy Online (media house), 61 % of Ghanaian roads are classified as “poor” [21]. One of such roads is the Berekuso-Kwabenya road shown (Figure 1). Considering the rampant plastic pollution and the poor road conditions in Ghana, it calls for attention to address dilapidated roads where plastic wastes materials are converted into road construction projects to significantly tackle issues of environmental pollution as well as provide solutions to road construction. This will not only minimize-or recycle plastic waste materials but will also provide alternative materials to reduce road construction costs.

Figure 1. 2: A typical pothole filled road in Accra and the nature of Kwabenya-Berekuso road

Therefore, the main goal of the project is to convert polyethylenetetraphylate (PET) and polythene, known plastic waste materials in Ghana, to wealth in the form of improved the quality of roads. Moreover, experimental research has proven that plastic roads are long-lasting and stronger than roads made of asphalt [20], hence the sustainability of this project is assured if it meets the technical, environmental and safety requirements of Ghana.

1.4 Specific Objectives of the Project

The proper utilization of PET in road construction will be optimized to improve on its mechanical properties via tackling the following milestones:

- Recycling of polyethylenetetraphylate (plastic waste material) into road constructional materials.
- Hybrid composite design with SolidWorks and composite fabrication techniques with recycled reinforced materials.

- Mechanical and optical characterisation of fabricated composite materials for optimization
- Determinations of heat transfer coefficient, thermal resistance and thermal degradation analysis of composite specimens to ascertain durability for outdoor applications.
- To conduct corrosion studies (mass loss) on the compositional effect of fibre ratios to ascertain their stability in various chemical environments
- Failure analysis and statistical evaluations of mechanical properties on samples
- Monitoring and evaluation of amended road with the ultimate characterized samples

1.5 Expected Outcomes

This project will enhance the proper utilisation of plastic waste materials in road construction. In other to fulfil this, PET a plastic waste material in our environment will be converted into–constructional materials for mending roads. The hybridized composites design will be guided by materials selection using the Cambridge Engineering Selector (CES). CES will be the first point estimation of competing materials and alternative materials to be considered for the design and construction of the composites. Extensive materials characterisation will be elucidated on fabricated composite materials for optimization and applications. Moreover, thermal degradation and corrosive studies of PET composite specimens will be studied to ascertain durability for outdoor applications. Thus, corrosion studies via mass loss and fibre ratio will be studied to ascertain environmental stability in different corrosive media. Implications of the results will be discussed for the evaluation of PET composites for amended roads. Moreover, the cost of road construction will be reduced due to the incorporation of cheap plastic waste material.

Chapter Two

2.0 Literature Review

2.1 Composite

A composite is a combination of two or more materials [22]. The combined effect enhances its properties far better than the individual materials themselves [2], [22]. A typical example of a composite is Fibre-Reinforced Polymer (FRP) composites, which are made by reinforcing a polymer matrix with engineered, man-made or natural fibre like glass, carbon, aramid or any other reinforcing material [2], [23]. Composites may also contain fillers or nanomaterials such as graphene [24]. It is important to note that the matrix protects the fibres from environmental and external damage and transfers the load between the fibres and the matrix. The fibres, in turn, provide strength and stiffness to reinforce the matrix and help it to resist cracks and fractures [2], [22].

Most composites are designed for particular uses such as added strength, versatility, light-weight, durability and efficiency [2], [24]. Composites also require less maintenance, have thermal insulating properties and can be tailored to suit the application by choice of materials and adding extra functionality [24], [25]. Despite composites being more efficient, the raw materials are often expensive [1].

2.2 Plastic Waste and Environmental Implications

The term plastics applies to a wide range of materials that have the capability to flow such that they can be extruded, moulded, cast, spun or applied as a coating [26]. Plastics are made from the addition of various chemical additives to synthetic polymers via the polymerization of monomers derived from oil or gas [3], [26]. The diversity of polymers and the versatility of their properties facilitate the production of a vast array of plastic products that bring technological advancements, energy savings and offer other societal benefits [27].

Over the past decade, plastics have been favoured and conveniently used in the food and water packaging industry due to portability and low costs [3], [9]. Currently, about 300 million tonnes of plastics are being produced in the world. However, the resources available for the management of waste are inadequate making it difficult to effectively and efficiently manage the plastic waste generated [5], [9]. Less than 14% of the million plastics produced is recycled thereby causing plastics in developing countries like Ghana and Zimbabwe to collect around the city, choking gutters and drainages, threatening aquatic lives, affecting soil fertility and polluting beaches [5], [9]

2.3 Characterisation of Recycled Materials

There are currently 20 different groups of plastics, each with numerous grades and varieties (APME, 2006). Plastics can be either thermoplastics or thermosets. Thermoplastics are the materials that repeatedly soften on heating and harden on cooling, unlike thermosets which cannot be used for repeated heat treatments due to their complex molecular structures [3]. Two of the commonly reprocessed and recycled plastics are polyethene (PE) and polyethene terephthalate (PET) which can be subdivided according to their density, type of process involved in their manufacturing and the additives they contain [3].

2.3.1 Polyethene

Polyethene (PE) is a thermoplastic classified as either low-density polyethene (LDPE) or high-density polyethene (HDPE) [3], [28]. LDPE is soft, flexible, easy to cut, and is used to manufacture film bags, sacks, blow-moulded bottles, food boxes, flexible piping and hosepipes and household articles like bowls and buckets [3]. On the other hand, HDPE is tougher and stiffer than LDPE and is used for toys, jerry cans, crates, dustbins, and other household articles [3]. HDPE can withstand short periods of heating with its melting point ranging from 126 °C – 131 °C but starts weakening at 71 °C.

2.3.2 Polyethylene Terephthalate

PET is a thermoplastic resin of the polyester family that is shatterproof, light-weight and inert material obtained from ethylene glycol and terephthalic [28]. It's used for food and beverage packaging, and personal care products due to its non-reactive properties [29]. PET bottles are usually transparent, but colour may be added to make them opaque. PET bottles are temperature resistant up to 62.8 °C [28]. PET can be commercially recycled through washing and re-melting, or by chemically breaking it down to its component materials to make new PET resin and products like ropes, automotive parts, construction materials, clothing and carpets [29].

2.4 Use of Recycling Plastics into Engineered Structures

Plastics are incredibly versatile materials; they are inexpensive, lightweight, strong, durable, and corrosion resistant, with high thermal and electrical insulation properties [26]. When combined with other substances, plastics produce composites that have incredible properties for engineering structures [29]. For example, in a recent study, reprocessed PE waste has been used to reinforce laterite bricks [16]. The study proved that the bricks reinforced with 20 % volume fraction of PE had improved compressive strength, flexural strength, fracture toughness and high resistance to erosion [16], [13] However, at higher levels of PE reinforcement, the compressive and flexural strength of the composite lowered due to clustering of particles [16].

Another application of plastic waste material in engineering structures has been the use of agro-waste plastic composites in building and automobile industries due to improved mechanical strength, water and oxygen barriers; dimensional stability; low thermal conductivity and high wear resistance [15], [30]. Moreover, plastic waste has been used innovatively in road construction [20]. For instance, in India, plastic waste has been used to successfully pave asphalt roads which perform better than those constructed with conventional bitumen [20]. Moreover, in Ghana, a company called Nelplast has been building road networks using plastic waste material and has been manufacturing roof tiles from the same material [31].

Studies have proved that the rheological properties and quality of bitumen are influenced by mixing in polymeric compounds such as rubber and plastics [32]. One report indicated that bitumen modified by adding about 5-10 % weight waste plastic proportion improves the strength and durability characteristics of pavements [33]. The mixture of bitumen and polymer forms a suitable substitute material for smooth pavement construction as it has higher values of Marshall Stability and Marshall Coefficient [32]. The mixing of asphalt with recycled LDPE or HDPE can be operated using usual equipment and practices and requires no alternative techniques [34], [35].

2.5 Road Construction

2.5.1 Road layering and materials used

Basically, a road comprises four layers of different materials [36]. This includes the:

I) Subgrade material that is clean and free from organic matter [36].

II) Sub-base course that is a layer of granular material laid over the subgrade. Materials used may be either unbound granular materials like crushed stone and crushed slag or cement bound like concrete slate. The quality of the sub-grade course determines the life of the road since it can outlive the road surface [36].

III) A base course that is immediately under the wearing surface. The material in the base course must be of high quality since it is subjected to severe loading as it is immediately under the pavement surface. The main types of base course are the granular base course and the macadam base course which is a mixture of soil particles in size from coarse to fine or a successive layer of crushed rock, respectively [36].

IV) The surface course can be either a concrete pavement or flexible pavement. The concrete pavement consists of concrete material that may/may not be reinforced with steel for increased strength, whilst the flexible pavement comprises of a combination of mineral aggregate with bituminous binder ranging from inexpensive surface treatment to asphaltic concrete [36].

Selection of aggregate size is very important in ensuring the durability and abrasion resistance of the surface layer [37]. However, aggregate size to be selected is based on the surface conditions, traffic size and the type of surfacing material to be used [38]. The most frequently used sizes for road surfaces are between 10 mm and 14 mm [39].

2.5.2 Bitumen

Bitumen is a binding organic material made from the by-products of refined crude oil [40]. It is used in road construction because it is easy to produce, reusable, non-toxic, and a strong binder [40]. Bitumen has a melting point of around 116℃ which is high enough to be safely used for roadway designs and low enough to be heated up without using a large amount of energy [40].

Table 1. 1: The Ghana High Way Authority Specifications for Bitumen AC-20 Grade

Tests	Results
Softening point (°C)	48 – 56
Ductility(cm)	20
Penetration at 25 °C, 100 g, 5 sec	40
Specific Gravity	1.01-1.06
Viscosity at 60 °C (P)	2000 ±400
Flashpoint (°C)	232

2.5.3 Asphalt Concrete Development

Asphalt concrete is a strong, natural, chemically resistant and recyclable material produced from aggregates and bitumen in a thermal mixing process [41], [42]. The viscosity of asphalt cement varies with temperature, and asphalt is graded based on the ranges of viscosity at a standard temperature [42]. Careless temperature and mixing control can cause hardening damage to asphalt cement and if asphalt cement is heated to a high enough temperature, it will reach the flash point temperature where fumes flash in the presence of a spark or open flame [42].

Asphalt concrete paving operations are normally done well below the flash point temperature in either the cold mix operation or the hot mix operation [42], [43]. Hot mix operation involves heating the aggregates to decrease the viscosity of the binding agents, while cold-mix operation involves mixing a quarter inch chip and proprietary oil to the asphalt cement [43], [44]. One main advantage of hot mix operation over the cold mix operation is that it reduces the viscosity of the asphalt for easy mixing and workability. Some of the by-products of asphalt production are dust, sulphur dioxide and smoke which can be controlled by installing enclosures to capture the exhaust and recirculate it for heating purposes [43].

2.6 Mechanical Characterisation

Material selection requires the knowledge of the type of loading, mode of loading, service life, operating or service environment, manufacturing processes to produce component and costs. Material properties depend on the performance requirements (mechanical, thermal etc) and the modes of failure. For a given design, the modulus is used for calculating the deformation and the strength is used to calculate the maximum load carrying capacity [23].

2.6.1 Stress and Strain

Stress is the force acting per unit area over which a force is applied whereas strain is defined as the change in dimension per unit length. Elastic strain is defined as the fully recoverable strain resulting from applied stress. For an elastic material, the slope of a tensile stress-strain curve is the Young's Modulus. For non-linear materials, the slope of the tangent of the stress-strain curve replaces Young's modulus [45].

2.6.2 Tensile Test

The tensile test measures the resistance of a material to a static or slowly applied force [45], [46]. Engineering stress and strain are measured by the following equations:

$$\sigma_e = \frac{F}{A_0} \tag{2.1}$$

$$\varepsilon_e = \frac{\Delta l}{l_0} \tag{2.2}$$

where A_0 is the original cross-sectional area, l_0 is the original distance between gage marks and Δl is the change in length after a force, F, is applied.

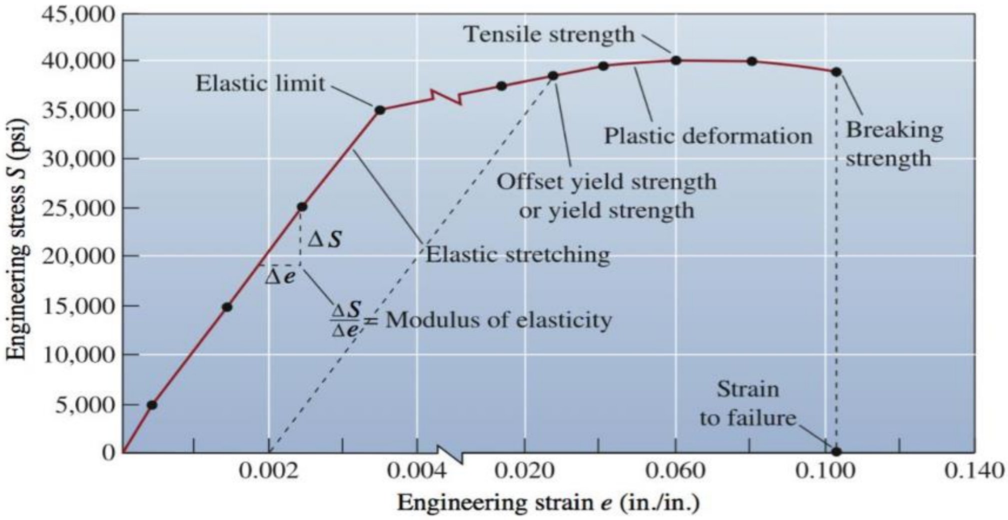


Figure 2. 1: Engineering Stress-Strain Curve (adopted from ww.ttu.ee, 2019)

In most materials, the elastic limit and proportional limit of a material cannot be determined precisely, therefore, they are usually defined as an offset strain value of 2 %. The corresponding value, the yield strength, is defined as the stress at which a predetermined amount of permanent deformation occurs [45]. The tensile strength is the stress obtained at the highest applied force. In ductile materials, one region deforms more than the other resulting in necking [45], [47].

2.6.3 Young's Modulus

The Young's modulus is the slope of the stress-strain curve in the elastic region [45]. It is calculated as:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{2.3}$$

2.6.4 Stiffness

Stiffness is the resistance of a material to deflection. It is measured by Young's modulus E. The higher the value of Young's modulus, the stiffer the material [23], [48]. The stiffness of a structure depends not only on the modulus of the material, but also on its length, diameter, and how it is supported (i.e., boundary conditions) [23].

2.6.5 Modulus of Resilience

Resilience is the ability of a material to absorb energy when it is deformed elastically and release that energy upon unloading (as in spring) [46]. It is the area under the elastic portion of the stress-strain curve and it is measured as [45]:

$$E_r = \frac{1}{2}\sigma_y \varepsilon_y \tag{2.4}$$

The maximum energy which can be stored in a body up to the elastic limit is called the proof resilience. The quantity gives a capacity of the material to bear shocks and vibrations [48].

2.6.6 Toughness

The toughness of a material is its ability to withstand both plastic and elastic deformations. Toughness can be measured by the Charpy test or the Izod test. The corresponding modulus called the modulus of toughness, u_t, is the strain-energy density when the material is stressed to the point of failure. It is equal to the area below the entire stress-strain curve from a tensile test [46], [49]. The higher the modulus of toughness, the greater the ability of the material to absorb energy without failing. A high modulus of toughness is therefore important when the material is subject to impact loads [46].

2.6.7 Fracture Toughness

Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw [45], [49]. Flaws appear as cracks, design discontinuities, voids etc. The stress-intensity factor (K) is used to determine the fracture toughness of most materials. Mode I fracture, K_1, is the commonest condition in which the crack plane is normal to the direction of largest tensile loading [49]. It is calculated as;

$$K_1 = \sigma\sqrt{\pi a B} \quad (2.5)$$

where K is the fracture toughness in $\sqrt{m}$, σ is applied stress in MPa, a is the crack length in meters, B is the crack length and component geometry factor for each specimen

2.6.8 Role of material thickness

Stress states adjacent to the flaw changes with specimen thickness. K_{IC} is a true material property where the thickness of the material has exceeded critical dimension The stress intensity, K_I , represents the level of "stress" at the tip of the crack and the fracture toughness, K_{IC} , is the highest value of stress intensity that a material under very specific (plane-strain) conditions that a material can withstand without fracture [49]

2.6.9 Hardness

Hardness is the property of a material that enables it to resist plastic deformation, penetration, indentation, and scratching. Methods of measuring hardness include the Rockwell hardness test; the Brinell hardness test, the Vickers test and the Knoop test [45] , [48].

2.6.10 Compressive and Flexural Strength

The compressive and flexural strength of the composites can be estimated from the rule of mixtures (ROM) [50], [47].

$$\sigma_C = V_m \sigma_m + V_f \sigma_f \tag{2.6}$$

where σ_C is the composite strength, σ_f is the fibre strength, V_f is the fibre volume fraction, σ_m is the matrix strength, and V_m is the matrix volume fraction.

In the same way, elastic modulus can be formulated by the volume fraction of the fibre and matrix. The ROM equations predict that the elastic modulus for both the longitudinal and transverse loading, respectively as:

$$E_c(u) = E_m V_m + E_f V_f \tag{2.7a}$$

and a transverse loading as:

$$E_c(l) = \frac{E_m E_f}{V_m E_f + V_f E_m} \tag{2.7b}$$

where all the terms have their usual meaning.

2.6.11 The Bend Test for Brittle Materials

The bend test is used in place for the normal tensile test in brittle materials because of the presence of flaws at the surface. A tensile force acts at the middle point when a load is applied at 3 points causing bending. The flexural strength, the strength requires to fracture a specimen in the bend test, describes the material's strength. For a 3-point test, it is defined as:

$$\sigma_{bend} = \frac{3FL}{2wh^2}\ (N/m^2) \tag{2.8}$$

where F is the fracture load, L is the distance between two outer points of the specimen, h is the height of the specimen, and w is the width of the specimen.

The flexural modulus is proportional to the slope of the stress-deflection curve and it is calculated as:

$$E_{bend} = \frac{L^3 F}{4wh^3\delta} \ (N/m^2) \tag{2.9}$$

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

2.6.12 Thermal Properties

Thermal conduction is the phenomenon by which heat is transported from high to low- temperature regions of a substance. Thermal conductivity is the ability of a material to transfer heat and it is defined by:

$$q = -k\frac{dT}{dx} \tag{2.10}$$

where q is the heat flux, k is the thermal conductivity, dT/dx = temperature gradient through a conducting medium.

Thermal stresses are stresses induced in a body because of changes in temperature. The magnitude of stress resulting from a temperature change from $T_0\ to\ T_f$.

$$\sigma = E\alpha_1(T_0 - T_f) \tag{2.11}$$

where E is the modulus of elasticity, α_1 is the linear coefficient of thermal expansion

2.6.12.1 Thermal shock for brittle materials

Crack formation and propagation from surface flaws are more probable when an imposed stress is tensile. Thermal shock resistance is the capacity of a material to withstand failure. Thermal shock resistance is best for ceramics with high flexural strength, high thermal conductivities, low moduli of elasticity and low coefficients of thermal expansion [47]. Thermal shock is approximated by a thermal shock resistance parameter (TSR):

$$\text{TSR} = \frac{\sigma_f k}{E\alpha_1} \qquad (2.12)$$

2.6.13 Chemical degradation

Bitumen ageing is caused by irreversible chemical changes in the binder and reversible physical hardening. Chemical changes are mainly caused by oxidation, loss of volatile components from bitumen and exudation while physical hardening involves re-organization of molecules [51].

2.7 Unresolved Issues

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 researched for further development. For example, from the reviews, most researchers focused only on investigating the effect of one type of recycled plastic polymer rather than a combination of two or three of these polymers. Moreover, no researcher has incorporated the use of recycled plastic pellets to provide extra binding to the plastic-asphalt concrete mixture on the layered road. Environmental impact and sustainability are increasingly being considered in the design of roadways [52], however, extensive data on the mechanical, thermal and chemical stabilities has not been sufficiently presented. This current work will, therefore, provide enough characterisation on technical data regarding the suitability of recycled PET and PE into asphalt for road construction.

2.8 Scope of Work

The goal of the project is to recycle plastic waste material such as plastic carry-bags, plastic sachets, disposable cups and PET bottles as important ingredients to serve as road construction materials. Chapter one presented background studies on the side effects of plastics waste materials on our environment. The motivation and objectives of the project were also presented. The second chapter presented the literature reviews on previous works on the use of recycling plastics into engineered structures as well as presented unresolved issues. The third chapter presented the section on materials and experimental procedures. To strengthen the composite structures, shredded plastics will be mixed with granular materials before the hot asphalt mixture is spread over it. Lab tests will be conducted to investigate the mechanical properties of the plastic reinforced composites. Afterwards, mini-sections of roads, particularly, potholes will be amended with the plastic road specimen and monitored over time. Chapter four will presents results and discuss section, while discussions on the implications for road construction are also presented in chapter five. Conclusion remarks and recommendations for future works are also presented in the fifth chapter of this project.

Chapter Three

3.0 Materials and Methods

3.1 Materials and Methods

The type of materials determines the methodology used in forming the composite. Waste plastic materials were collected from the canteens of the hostels on Ashesi campus and the residential hostels. AC-10 bitumen penetration grade of 70 was procured from a shop (Mallam Area, Accra, Ghana) with characteristics correspond to those of ASTM D3381–09. It was obtained from a shop in Mallam, in Accra, Ghana. The aggregates used 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, Ghana. Materials were chosen depending on their availability, strength, high corrosion resistance including other factors.

3.2 Material Selection

As mentioned in Chapter 1, the main objective of this project is not only to minimize or recycle plastic waste materials but to also provide alternative materials that can possibly reduce the cost of road construction. Thus, this objective informs the user requirements for the plastic-bitumen composite produced. The user requirements for the design are tabulated below (Table 3.1).

Table 3. 1: User requirements versus System property.

User Requirements	System property
1. Low cost	Locally available and abundant material
2. Durable	High compressive strength, low thermal conductivity
3. Little to no maintenance	High corrosive resistance

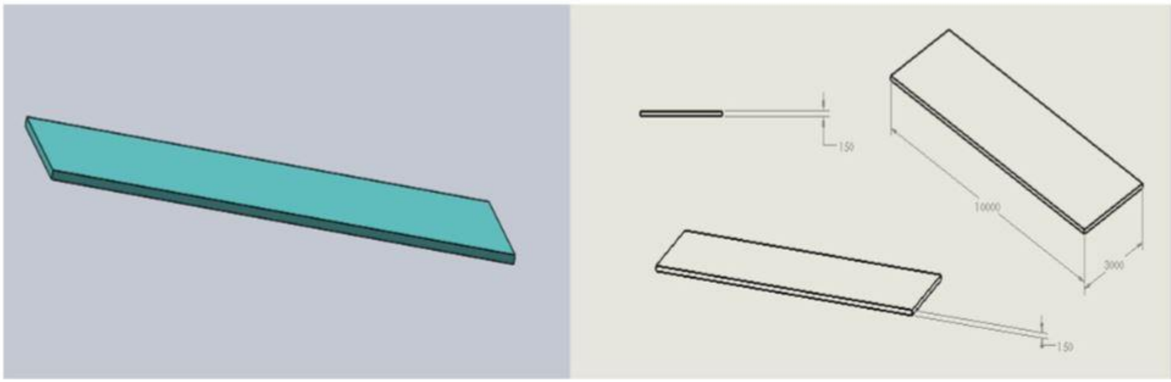
After user requirements and system properties were defined, competing raw materials were sorted with the aid of CES Edupack 2013 [53] from the family of eco-friendly materials. Materials were chosen based on strength, recyclability, miscibility and the abundance of the raw materials. The chosen characteristics were then scaled using the evaluation criteria below (Table 3.2).

Table 3. 2: Evaluation Criteria of Possible Materials to be mixed with Bitumen.

MATERIAL	**Compressive strength**	**Recycle Fraction in current supply**	**Low UV Radiation (sunlight resistance)**	**High Corrosion Resistance**	**Total Performance**
SCALE	**5**	**3**	**4**	**3**	**15**
LDPE	3	2.5	1	3	9.5
HDPE	5	2.5	2	3	12.5
PVC	4	1	3	3	11
PET	5	3	2.5	3	13.5
Rubber	2	0.2	1.5	2	5.7
Wood	3	2.5	3	0.5	9
Asphalt Concrete	1	2.8	4	3	10.8

3.2.1 CAD Design of PET

A CAD design of PET below (Figure 3.1) was done in SolidWorks 2016 to simulate how PET would response to compressive stresses. The design was model to a measurement of 10 m*3 m*0.15 m denoting length, width and thickness of a road pavement respectively. The dimensions were chosen to fit a long truck of 5 m length



Overview of the PET SolidWorks Model

Detailed SolidWorks drawing of the CAD design

Figure 3. 1: SolidWorks design model of PET.

3.3 Experimental Procedures

3.3.1 Preparation of plastics

The collected waste plastics were sorted, de-dusted, washed when necessary and sun-dried for a few days until all were dry. The dried samples of the waste plastic materials were shredded into a length of 2 cm and a thickness of 2.5 mm to enhance their surface area of contact with the aggregates during mixing.

3.3.2 Preparation of composite

The aggregates were heated to a temperature of 170 °C, while shredded plastic (PET) of sizes 2.3 mm-2.7 mm were added to the hot aggregate at a specified percentage with constant mixing to ensure even distribution of the plastic. When it was observed that the aggregates were fully coated with PET, bitumen was added to the samples (PET coated aggregates) at a temperature of 140 °C and 160 °C. The mixtures were thoroughly blended prior to casting into rectangular moulds. Summary of the various compositions of the composites design for optimization are presented (**Table** 3.3).

Table 3. 3: Showing Fibre Volume Fraction.

Composite Codes	**Aggregate-Bitumen-PET Mass (g)**	**Aggregate-Bitumen-PET Mass Ratios (wt%)**
A (Control Samples)	500A:50B:0P	91:9:0
B	475A:50B:25P	86.4:9:4.5
C	450A:50B:50P	82:9:9
D	425A:50B:75P	77.3:9:13.6
E	400A:50: B:100P	72.7:9:18

Aggregates^{A}, Bitumen^{B}, PET^{P}

3.4.0 Mechanical Characterisation

To determine the mechanical properties of the composite, a tensile test and a three-point bend test were performed with a universal tensile testing machine. The data obtained from the experiments were collected and then analysed as presented in the next sections.

3.4.1 Ultimate tensile strength and Strain at necking

Specimens were placed in the grips of a tensile test machine (MTS 6) at a specified grip separation and pulled until failure (Figure. 3.1). For ISO 527 the test speed is typically 5 or 50 mm/min for measuring strength and elongation and 1 mm/min. An extensometer was used to determine elongation and tensile modulus. The results were then analysed with OriginPro software [54]

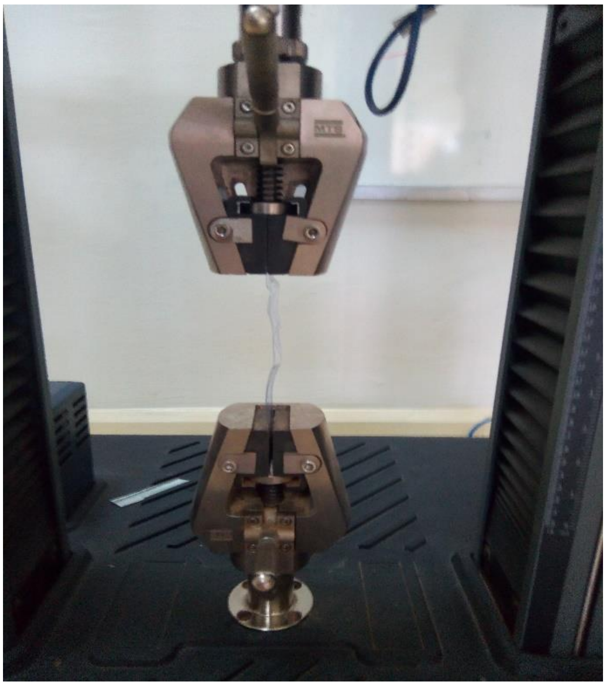


Figure 3. 2: Tensile Test Setup

The strain (ε) and stress (σ) were respectively obtained from the force extension curves as given:

$$\varepsilon = \frac{\Delta L}{L_0} \quad (3.1)$$

$$\sigma = \frac{F}{A} \quad (3.2)$$

where Lo is the initial length of the specimen, ΔL is the change in length, F is the maximum load attained, and A is the cross-sectional area.

The yield strength was also obtained from the graph and values produced when the tensile test was conducted. As described in chapter two, the modulus of resilience is the area under the elastic portion of the stress-strain graph and was estimated as [47]:

$$E_r = \frac{1}{2}(\sigma_y)(\varepsilon_y) \quad (3.3)$$

where, σ_y is the yield strength and ε_y is the strain at yielding. The Young's modulus was obtained by taken the gradient elastic regime of the stress-strain curve as [47]:

$$\mathrm{E} = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (3.4)$$

3.4.2 Maximum Load at Fracture

In the determination of compressive strength, the compression specimens of diameter, thickness and area of 0.03 m, 0.04 m and $7.07 * 10^{-4}\, m^2$ respectively were deformed at a loading rate of 3.3 N/s until fracture occurred by the separation of specimens into two or more pieces. A curve of compressive load (kN) versus compressive displacement (mm) was used to estimate the peak load, FA. The compressive strength was then estimated using the following equation:

$$\sigma = \frac{F_A}{A_0} \quad (3.5)$$

where, F_A is the peak load at the onset of fracture and A_0 is the initial cross-sectional area. Five compressive tests were done (Figure. 3.3) for each specimen condition and averaging enhanced data quality.

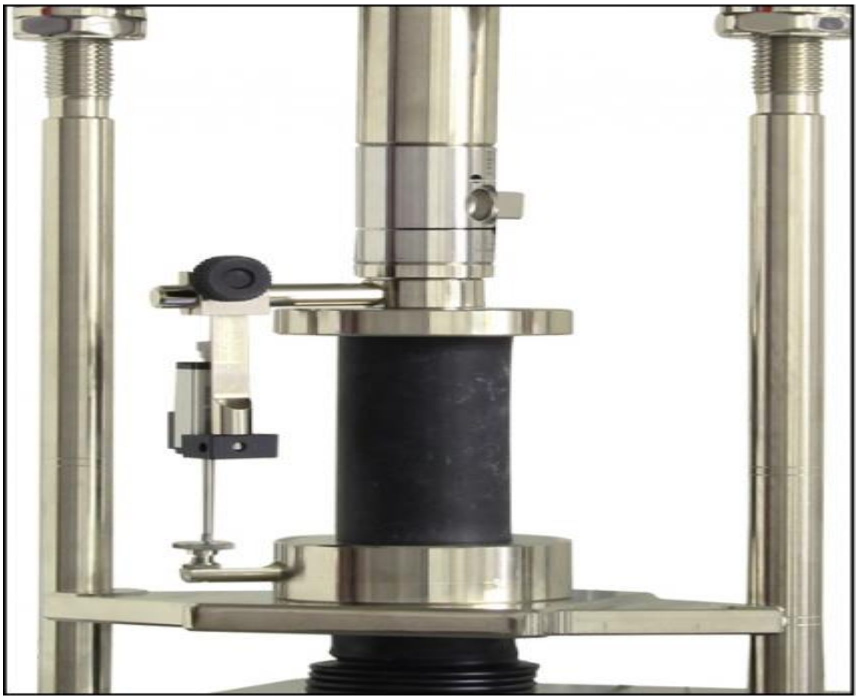


Figure 3. 3: Setup of Compression test.

3.4.3 Flexural Strength

A three-point bend loading configuration was used to estimate the flexural/bend strengths and fracture toughness values of the samples. A loading span of 80 mm was used for the entire three-point bend test. The mechanical properties were measured (bitumen takes 3 days to dry before vehicles are allowed to use it) days after the fabrication of the specimens. The specimens were loaded monotonically at a loading rate of 3.3 N/s. For each matrix and composite formulation, five specimens were tested. The flexural/bend strength, σ_{bend}, was obtained from:

$$\sigma_{\text{bend}} = \frac{3FL}{2wh^2} \qquad (3.6)$$

where F is the fracture load, L is the distance between two outer points of the specimen, h is the height of the specimen, and w is the width of the specimen.

The flexural modulus was also calculated as:

$$E_{bend} = \frac{L^3 F}{4wh^3\delta} \ (N/m^2) \qquad (3.6.2)$$

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

3.4.4 Hardness Test

The hardness testing of the different samples was done using the High Definition (HD) tester. The measuring range of the hardness tester was from 0-100 HD max. To measure the hardness values, the samples containing different plastic concentrations were indented at five different spots and the average values were reported.

3.4.5 Corrosive Studies via mass loss

A stripping test was performed on the plastic waste coated aggregate-bitumen mix. Samples of different plastic concentrations were measured to a weight of 60 g each and immersed in 100 ml of water in different beakers. The beakers were put in a water bath at 90 °C (The water bath was created by conditioning a hot plate stove so that a constant temperature of 90 °C would be maintained) and tested at different intervals of 24 h, 48 h and 72 h. After each time interval, readings were taken to determine the bitumen (mass) loss from the asphalt.

$$\%Mass\ Lost = \frac{M_i - M_t}{M_i}\ x\ 100\% \qquad (3.8)$$

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

The image below (Figure. 3.4) shows one of the steps taken to determine the rate of stripping from the asphalt mixture.

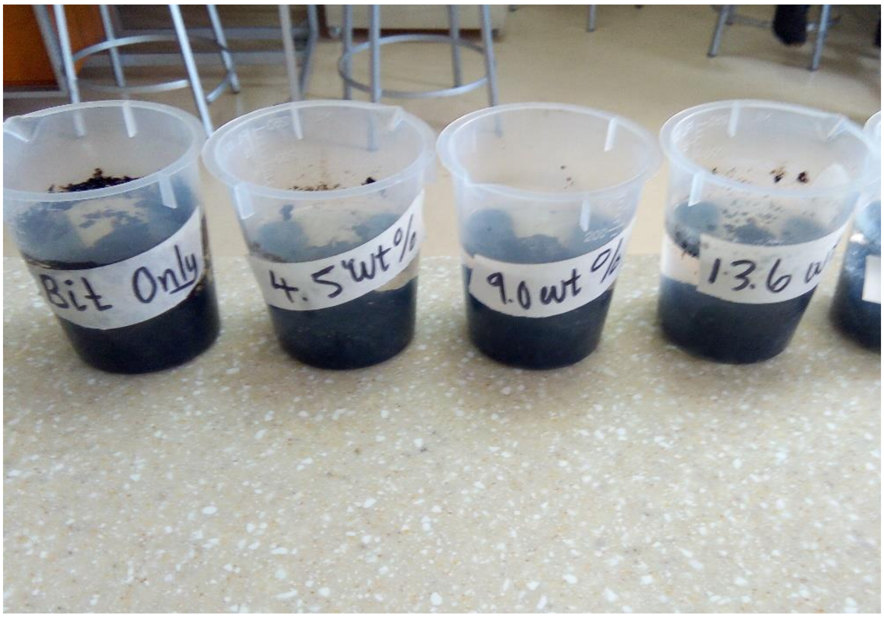


Figure 3. 4: Preparing Samples for Stripping Test.

3.4.6 Optical Characterisation

Optical characterization is the use of light to probe the physical and chemical properties of a substance. A phone camera of 13 Megapixels (Infinix Hot S) was used to investigate the effect of adding plastic to a road composite mixture. To do the optical characterisation, pictures of 3-day dried composite samples for the different volume fractions of PE were captured and studied to compare the changes.

Chapter Four

4.0 Results and Discussion

4.1 Material Selection

After user requirements system properties were defined, and competing raw materials were sorted with the aid of CES Edupack, by selecting the family of eco-friendly materials. The results obtained are presented (Figure. 4.1a-c).

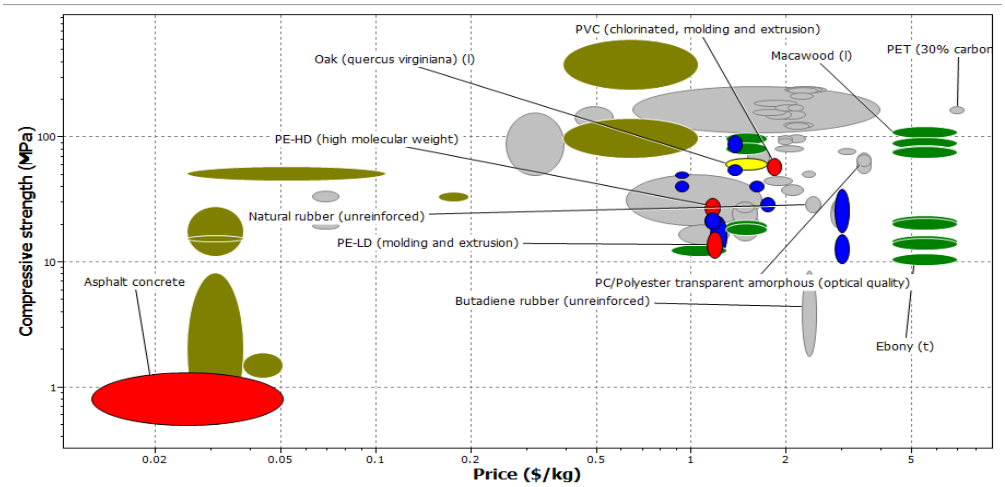
PET had a high compressive strength of ~120 MPa followed by polyvinyl chloride (PVC), high-density polyethene (HDPE) and low-density polyethene (LDPE) with compressive strengths of 80 MPa, 30 MPa and 20 MPa, respectively (Figure. 4.1a). Concrete had a relatively low compressive strength of around 1.0 MPa.

With regards to the recycle fraction (Figure. 4.1b) in current supply of the possible materials, PET had the highest percentage of recyclable materials followed by asphalt concrete and PE. Due to its abundant supply, PET and asphalt concrete were chosen to be suitable materials for recycling into road structures.

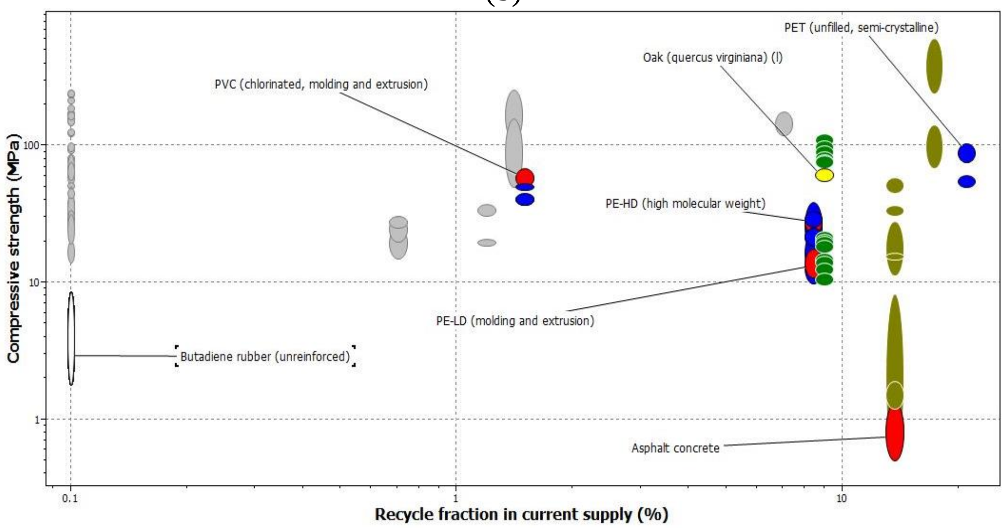
In the presence of weak acids, cross-linked PE was found to be in the acceptable zone to work with. Asphalt concrete, PET, PVC, HDPE and LDPE were found to be highly resistant to weak acids (Figure. 4.1b).

Asphalt concrete had the highest resistance to thermal degradation followed by PET (Figure. 4.1c). HDPE had a fair resistance to thermal degradation and LDPE had the lowest resistance. The basis of materials selection guided the design criteria based on Pugh matrix presented in chapter three (Table 3.2). From the Pugh matrix, PET had the highest total performance of 13.5, followed by HDPE and PVC with a total performance of 12.5 and 11, respectively.

(a)



(b)



(c)

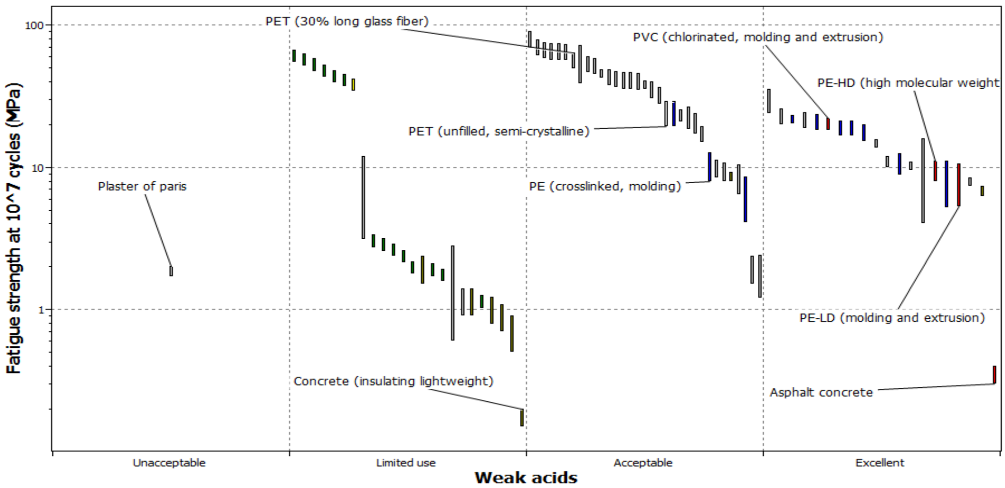


Figure 4. 1: Materials Sorting: (a) Compressive strength versus price, (b) Compressive strength versus recycle fraction in current supply, and (c) Ability of materials to withstand weak acids.

(d)

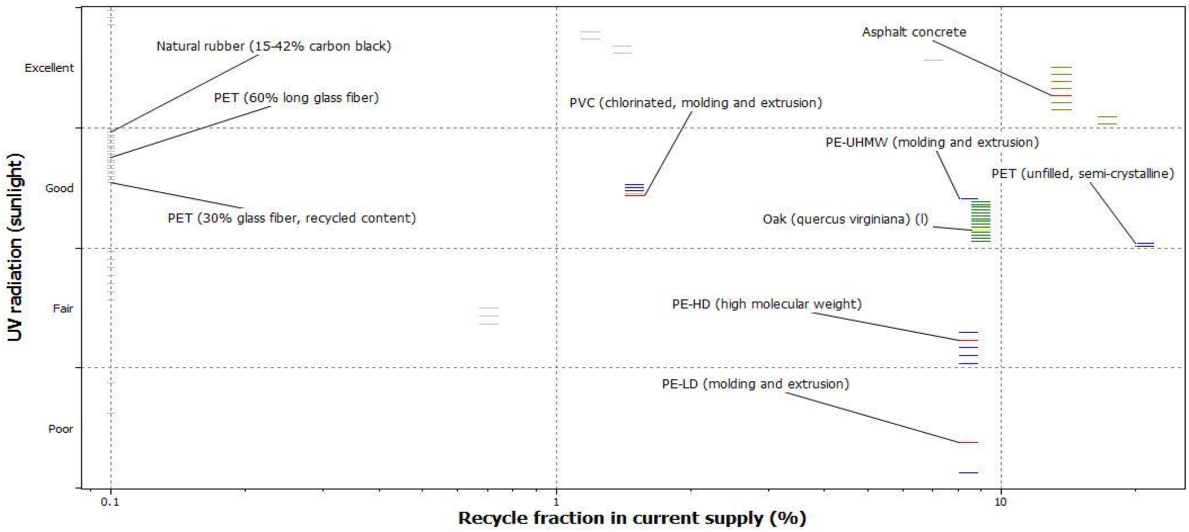


Figure 4.1: Materials sorting, (d) Thermal resistance versus recyclability.

4.2 SolidWorks Analysis

The CAD design of PET subjected to a vertical load of 150 KN equivalent to possible heaviest loaded vehicles applied on roads. PET had a maximum displacement of 3.687 x10^{-4} mm under the 150 kN vertical load. The displacement is within the acceptable data range implying that PET has a very good compressive strength that can withstand heavy loads. It is therefore a good material to use for road construction purposes as it does not deform easily.

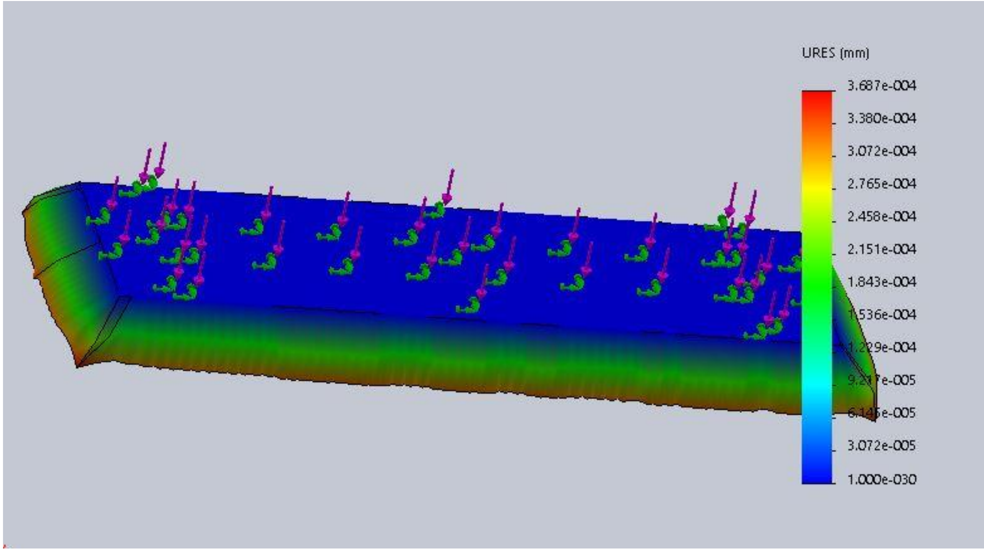


Figure 4.2: SolidWorks Simulation for PET displacement under a 150KN load.

4.3 Tensile Test for PET

To determine the properties of the PET plastic material being used, a tensile test was conducted, and the results were tabulated as follows (Table 4.1). At a peak load of 245.8 N, PET was found to have a peak stress of 0.10 MPa and a strain at breaking of 0.112. The modulus of resilience was found to be 1.485 MPa.

Table 4. 1: Results from Tensile Test.

Characteristic	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Length (mm)	62	74	54	57	58	**61**
Thickness (mm)	0.246	0.23	0.2	0.244	0.215	**0.227**
Width (mm)	12.54	12.62	14.46	12.3	12.04	**12.792**
Area (mm^2)	3.085	2.916	2.892	3	2.59	**2.8966**
Peak Stress (GPa)	0.1	0.1	0.1	0.1	0.1	**0.1**
Peak Load (kN)	0.208	0.229	0.235	0.227	0.33	**0.2458**
Strain at break (mm/mm)	0.072	0.13	0.124	0.131	0.101	**0.1116**
Modulus (GPa)	1.618	1.506	1.468	1.316	1.519	**1.4854**

4.4 Hardness of Samples

The hardness values of the composites are presented (Figure. 4.3). The hardness of the samples increased steadily from 38.42 HD with the control sample. 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% plastic concentration, the hardness of the sample reduced to 68.25 HD. The results show that PET plastic increases the binding strength of the composite. However, at 18.0 wt% the matrix and the fibre separate causing some portions of the composite to be less hard than the other portions with maximum bonding within them.

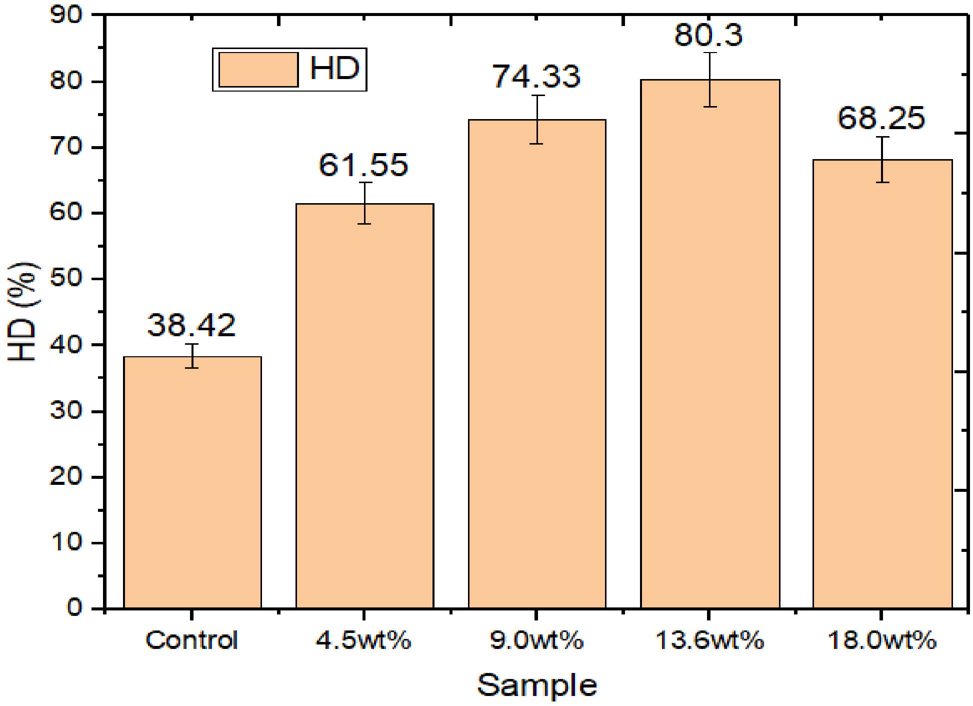


Figure 4. 3: Hardness of Bitumen-Aggregates-PET Composites.

4.5 Mechanical Characterisation

The summary results from the compression analysis of both the modified and unmodified asphalt samples are presented below (Table 4.2)

Table 4. 2: Summary from Compression Test Results.

Characteristic	Control	4.5wt%	9.0wt%	13.6wt%	18.0wt%
Compressive Strength (MPa)	1.64	1.90	2.50	7.42	0.75
Peak Load (kN)	1.16	1.44	1.77	5.24	0.53
Strain at breaking (mm/mm)	0.15	0.11	0.07	0.06	0.07
Modulus of elasticity (MPa)	10.9	15.8	35.71	123.67	10.71

As shown in Figure. 4.4 below, there was a steady increase in compressive strength and modulus of elasticity from 0 wt% to 9.0 wt%. At 13.6 wt% there was a sharp increase in the strength and modulus of elasticity of the samples at 7.42 MPa and 123.67 MPa respectively. At 18.0 wt%, the strength and modulus of elasticity of the composite dropped drastically due to saturated PET concentration which reduced the properties of the composites.

(a) (b)

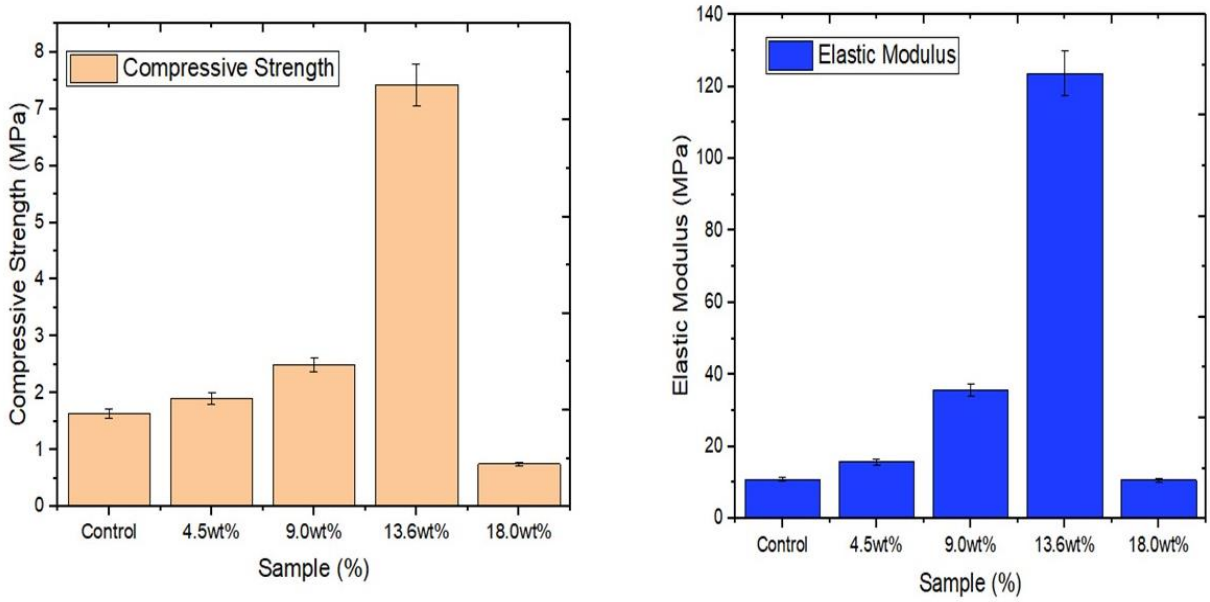


Figure 4. 4: Transverse Loading: (a) Compressive Strength and (b) Modulus of Elasticity of Bitumen-Aggregates-PET Composites.

A summary of results from the bend test is shown in Table 4.3 below.

Table 4. 3: Results from 3 Point Bend Test.

Characteristic	Control	4.5wt%	9.0wt%	13.6wt%	18.0wt%
Flexural Strength (MPa)	0.6	1.4	2.2	4.02	3.21
Load at fracture (KN)	0.044	0.176	0.350	0.502	0.502
Flexural Strain(m/m)	0.07	0.06	0.06	0.07	0.07
Flexural Modulus (MPa)	0.172	0.801	1.59	1.958	1.958

The sample of 13.6wt% had the highest flexural strength followed by the 18.0 wt%. The highest flexural modulus values were recorded at 13.6 wt% and 18.0 wt%.

(a) (b)

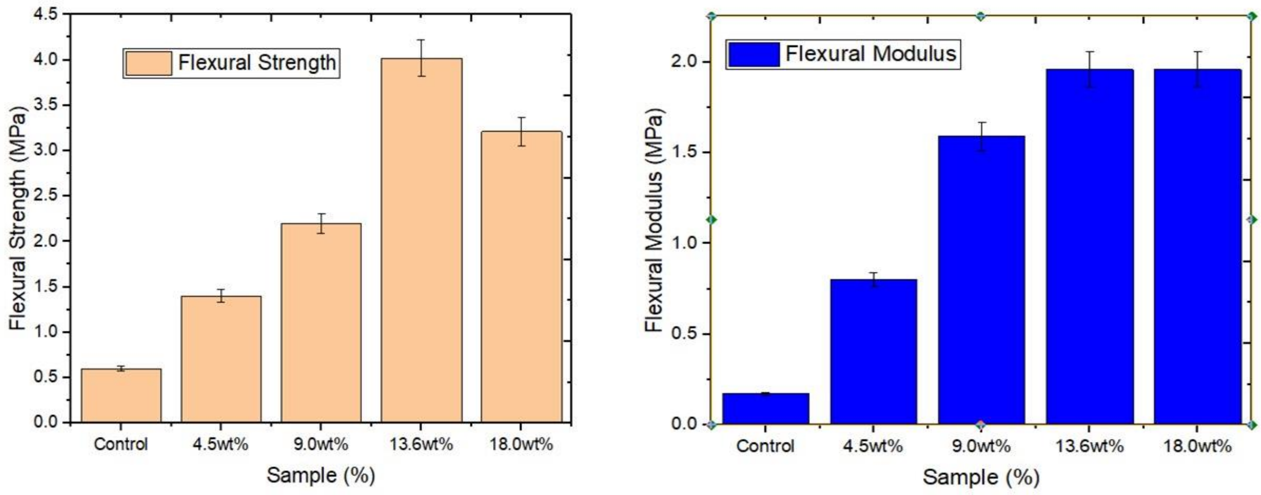


Figure 4. 5: (a) Flexural strength and (b) flexural modulus of composite samples.

The results from the compressive and the bend test analysis indicate that an increase in PET concentration results in a general increase in the compressive strength, elastic modulus, flexural strength and flexural modulus of the composite samples. This is because the plastic increases the binding strength of the aggregates thereby causing it to be strong and rigid. When more plastics were added, the voids within the aggregates were filled thereby causing the composite to be resistant to bending. At higher levels of PET, the strength and modulus fell due to the agglomeration of PET particles.

4.6 Mass Loss

4.6.1 Stripping

As the plastic wt% increased, the rate of stripping also decreased (Figure. 4.6). There was no stripping for the 13.6 wt% and the 18 wt% plastic coated aggregate bitumen even after 72 h of immersion. The bitumen and aggregate mix lost 2 g of mass, with a mass loss of 3.3 % within 72 h. The results show that adding plastic to aggregates increases the binding strength of the blended samples. Moreover, water resistance of the samples increased due to the non-porous feature of plastics resulting in less to no erosion of the samples. These results imply that modified composite samples will last longer thereby reducing the formation of potholes on roads and overall maintenance services and costs.

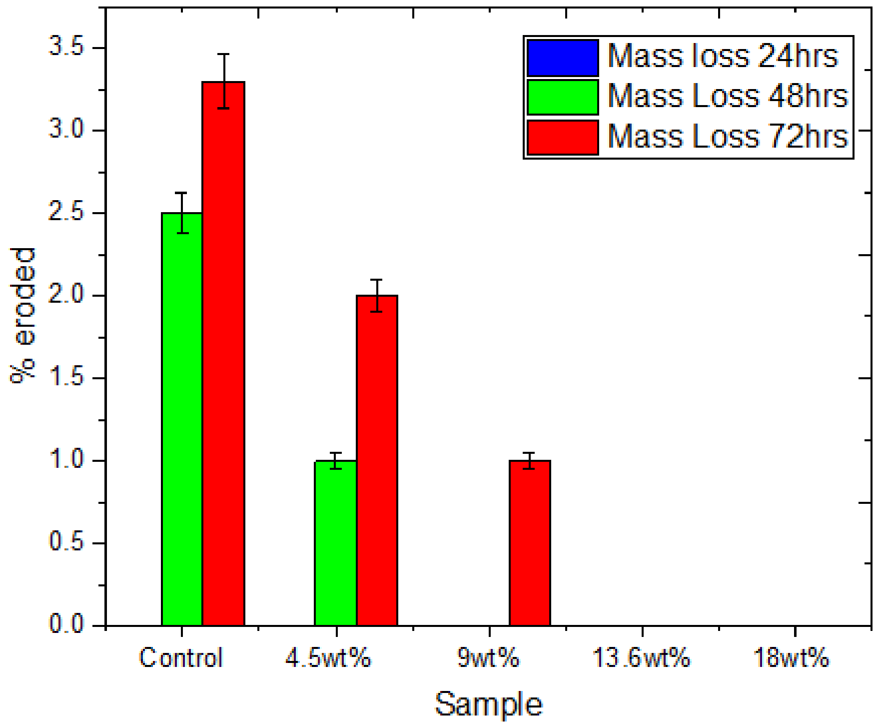


Figure 4. 6: Mass loss results for unmodified and modified composite samples.

4.3 Optical Analysis

From the sample pictures captured in Figure. 4.7, there was no notable difference amongst the samples of 0 wt% plastic – 13.6 wt% plastic. However, from eye observation, as the plastic concentration increased from 0 wt% to 13.6 wt%, the bonding between the aggregates increased and the samples became more intact with lesser voids between the particles. The waste plastic concentrations increased cohesion and adhesion between the aggregates thereby increasing the overall compactness of the samples.

Figure 4. 7: Composite samples formed from 13.6 wt% and 18 wt% plastic concentration.

Figure 4.7 above depicts that at 18 wt% plastic concentration, the binding of the samples decreases, and undissolved plastics become concentrated at certain parts of the sample. This means that at above 14 wt %, the saturation point of plastics as a binder would have been reached resulting in the agglomeration of particles in the sample. The agglomeration of particles reduces maximum bonding between particles thereby reducing the overall strength of the composite

Chapter Five

5.0 Conclusions, Limitations and Recommendations

5.1 Concluding Remarks

This project explored the optimization of the mechanical properties of plastic waste materials for their usage in road construction. To fulfil this, PET, a plastic waste material in our environment was converted into constructional materials that can be used to mend roads. The material selection for the hybridized composites designs was done using the Cambridge Engineering Selector (CES). PET came out first with a performance of 13.5/15.

The simulation study in SolidWorks under a vertically distributed load of 150 kN reported a maximum displacement of 3.687×10^{-4} mm. This implied that PET has a very good compressive strength.

PET was fabricated together with aggregates and bitumen, to reinforce the strength of asphalt. Afterwards, extensive material characterisations were carried on fabricated composite materials for optimization and applications. Corrosion studies via mass loss were also done via the stripping test method. From all the tests conducted, the sample with 13.6 wt% concentration was found to possess the optimum desired features, which is, high compressive strength, high modulus of resilience, high hardness value and high corrosion resistance. Large quantities of asphalt were produced using the optimum values obtained from the characterisation studies to mend portions of the road near Dufie Hostel in Ashesi.

Observations have been carried out by monitoring, to ascertain the durability of the road. Calculations were also done to determine the reduction in the cost of road construction due to the incorporation of cheap waste plastic material. For every 1 km of road, approximately 600 000 PET plastic bottles are used and about 10 tonnes of bitumen are saved. The bitumen saved is equivalent to $3 500.

5.2 Limitations

This project had several limitations. Firstly, there was a lack of adequate equipment within the Ashesi vicinity to conduct the study to a full extent.

There was a lack of time and resources for the development of a mechanized system to properly mix the aggregates and bitumen to ensure sufficient bonding strength. In addition to the lack of a mechanized system, it was very hard to create moulds to hold composite samples during fabrication. These challenges posed difficulties in removing the composite samples thereby reducing the number of samples that could be fabricated in a given time.

Normally, aggregates used for road construction should be of different sizes to ensure compaction and bonding between the composite materials. However, the aggregates obtained for this study were only of one size range thereby causing the composite samples produced to have minimum bonding strength due to the air spaces between them.

Secondly, the testing machines available could not do a proper hardness test like the Brinell hardness test and the SENB test for determining the fracture toughness of the composite samples. The Marshall Stability analysis was not also done due to lack of availability of testing materials as well.

Lastly, the study only explored one approach, the cold mixing method, of mixing asphalt concrete. If other methods were explored, a proper analysis could have been conducted of which method is best to produce plastic roads.

5.3 Recommendations

The experimental results obtained in this study will help in the recycling of plastic waste here in Ghana. However, the study mainly focused on PET plastic as a substitute for bitumen. More studies need to be explored to determine the optimum percentage of values needed for other types of plastic waste like polyethylene.

Another suggestion would be to investigate if large percentages of plastics can be used for road construction. If plastics are solely used in road construction, infrastructural features like drains and connecting pipes can be put underneath the roads to reduce flooding in urban areas. Moreover, wiring devices and sensors can also be placed for highway management purposes like traffic light control.

With relation to the base layer of the road itself, plastic pellets can be added to the aggregates to increase the bonding strength of the layer. To make the process easier, machines can be constructed to automate the process from shredding plastics, to mixing the asphalt mixture to layering the composite on the road surfaces.

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