AN ASSESSMENT OF THE STRENGTH AND DURABILITY CHARACTERISTICS OF RECYCLED PLASTIC PAVERS

By

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ABSTRACT

The generation of waste is reaching record highs and displays a consistent uptrend over the last decade, and despite high generation rates, landfilling is still the dominant disposal method for waste in South Africa. However, these materials may have potential for reuse in several applications, and industries are considering their viability. One such industry is the construction and engineering industry, which has seen an increase in research into the application of waste materials.

This study explores the use of HDPE, PP, and glass waste as an alternative material for making concrete pavers. The study uses local waste materials to assess the density, durability, and mechanical strengths of the resulting paver, called Eco-pavers, and compares them to regular concrete pavers for accuracy. The pavers are made of a 50/50 blend of recycled plastic and glass aggregate, which has not been widely studied as a replacement for cement or stone aggregate.

The Eco-pavers demonstrate a low water absorption rate of 0.28%, compared to the 4.5% of concrete pavers. After immersion testing in various chemicals over a 180-day period, the pavers show no signs of degradation either structurally or visually. The Eco-pavers are suitable for use as impermeable pavers, as they did not allow any infiltration during the permeability test. The flexural strength assessment resulted in an average breaking stress of 7.9 MPa, which is greater than the prescribed minimum. However, the pavers' average compressive strength is 12.47 MPa, which is below the minimum criterion of 35 MPa for pavers, and therefore needs improvement.

In summary, this study explored the use of recycled plastic and glass waste in manufacturing Eco-pavers as an alternative to traditional concrete pavers. The resulting pavers demonstrated low water absorption, chemical resistance, and impermeability, making them suitable for impermeable applications. However, the compressive strength of the pavers needs improvement. While their short-term use is unlikely to release microplastics, further research is needed to determine their long-term impact.

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ASTM	American standards for testing methods
C & CI	Cement and concrete institute
CH_4	Methane
CO_2	Carbon dioxide
DEA	Department of environmental affairs
f_c	Compressive strength
f_{cf}	Flexural strength
H_2SO_4	Sulphuric Acid
HDPE	High Density Polyethylene
HPP	Homo-polymer polypropylene
HRC	Rockwell Hardness rating
IS	Indian Standards
ISO	International Organization for Standardization
ITZ	Interfacial transition Zone
LDPE	Low-Density Polyethylene
MSW	Municipal Solid Waste
NEMA	National Environmental Management Act
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PPS	Permeable pavement systems
PS	Polystyrene
SA	South Africa
SANS	South African national standards
SAWIC	South African waste information centre
SEM	Scanning electron Microscopy

T_g	Glass transition temperature
T_m	Melting Temperature
TEM	Transmission Electron Microscopy
TOC	Total organic carbon
UV	Ultraviolet
UV-A	Ultraviolet Medium energy irradiation
UVB	Ultraviolet High energy irradiation
VOCs	volatile organic compounds
WM	Waste management
Δ	Change in property relative to control
$\bar{x}$	Mean value

CHAPTER ONE: INTRODUCTION

1.1. Background and Problem Statement

In the past decade, global waste generation has been steadily increasing due to an increase in the population (Kaza et al., 2018). To compensate for this, societies have had to evolve their waste management strategies to incorporate sustainable methods, which include the reuse and recycling of waste. Within South Africa, landfilling is still seen as the primary waste management (WM) option. The South African Department of Environmental Affairs (DEA) reported that 90% of South Africa's waste had been landfilled in 2017. This consequently places a burden on landfills and given the current pitfalls of landfills which include limited landfill capacity and availability, environmental degradation due to landfill emissions, leaching and new legislation, proves that this method of WM is not sustainable (Garner, 2009; DEA, 2018). Therefore, this suggests that WM through economic, ecologically beneficial, and legal ways is a critical sustainability-driven problem (Abdul-Rahman, 2014).

Waste management in South Africa is governed by the National Environmental Management Act (NEMA) of 1998, which states that "*…waste is to be avoided, or where it cannot be altogether avoided, minimized and reused or recycled where possible or otherwise disposed of in a responsible manner*". Despite the fact that there are several organizations in South Africa that are recycling plastic waste, the South African Waste Information Centre (SAWIC) (2020) reports that only 12,4 million tonnes of plastic waste are recycled whilst 15 million tonnes of plastic waste are disposed of annually. It highlights the fact that municipal solid waste is steadily becoming a concern, with glass and plastic being highlighted by this thesis due the high volumes being discarded either into landfills or the environment.

The construction industry serves as a large generator of waste through various activities, including construction and cement manufacturing. According to Andrew (2018), cement is one of the main sources of carbon emissions, and the demand for cement is steadily rising as a result of urbanization and building. It is crucial to consider viable alternatives for building applications since the cradle-to-production processes, which include the extraction, shipping, treatment, and manufacture of the material, are so energy- and resource-intensive. Mistry and Parolkar (2017) reported that river sand, a natural material used in the manufacturing of cement concrete, is the most depleted natural resource on the planet after water.

Considering the need for alternatives to cement and the increased waste material being generated, it is suggested that regular municipal waste can be used to partially or fully replace materials used in industrial settings and produce favourable alternatives. This concept has seen a rise in interest as research surrounding this has increased as of late. This study explores the characteristics of a composite material consisting of waste plastic and glass as an alternative to concrete pavers. This would not only provide a sustainable channel to route waste plastic and glass, but further to that, decrease the reliance on cement and aggregate from natural resources. This study is centred on the development of environmentally friendly resources, with a particular emphasis on novel, non-traditional, and creative applications of recycled materials.

1.2.Significance of Research

The purpose of this research is to evaluate the characteristics of the "Eco-pavers", comprising of waste material, in comparison to standard pavers, with respect to durability and strength. The use of eco-friendly materials would lead to a reduction in the strain placed on energy resources, which would, in turn, lead to a smaller carbon footprint for the pavement manufacturing industry. Additionally, the use of these materials would open up new possibilities for the recycling and repurposing of plastics. This adoption will be accompanied by a plethora of possible benefits in the economic, environmental, and social realms, including but not limited to the following list of advantages:

- Promoting environmentally friendly municipal solid waste management,
- Protecting priceless landfill airspaces,
- Advancing knowledge and filling research gaps, and
- Protecting the environment by reducing cement manufacture and plastic waste disposal

1.3. Research Questions

To ensure that the study remains focused and objective-driven, the following research question is proposed:

How do the strength and durability characteristics of the Eco-pavers compare to that of standard concrete pavers, and what potential do they have under environmental conditions?

1.4. Aims and Objectives

The research aims and objectives are summarized as follows:

1.4.1. Aim

- Investigate the strength and durability characteristics of plastic pavers in comparison to concrete pavers.

1.4.2. Objectives

- As part of a thorough analysis of the relevant literature, compile a list of the pertinent qualities and characteristics of pavers as well as plastic and glass material and identify any environmental concerns surrounding this use of plastic in the environment.
- Incorporate similar conditions in the experimentation that could be experienced in the intended environment of application, i.e., saturation through rain or flooding, exposure to petroleum through machinery leaks or spills, cleaning agents, etc.
- Investigate the strength and durability properties of the pavers under these conditions once identified.
- Analyse all sets of results and compare them with the control (conventional) paver to explain its viability.

- Investigate how the different mechanisms of failure of the paver may affect the environment based off the release of microplastics or other debris and pollutants during experimentation.

1.5. General Approach and Limitations

The pavers were cast at an external facility, with limited accessibility, due to the equipment required for manufacturing them. Due to this, a small number of pavers were able to be cast, with the mix ratio being fixed at the point at which the mix became fluid enough to pour into a mould. These pavers were then used to conduct the various experiments which would provide insights into its characteristic behaviour and properties, and inform on the implications of using this composite material in the environment, with respect to the possible release of microplastics and/or pollutants.

Moreover, the study did not examine the long-term effects of ultra-violet exposure due to the lack of testing equipment and the high cost of outsourcing to external laboratories. Furthermore, the study had limited time to conduct experiments, driven by a deadline to submit the thesis, resulting in only short-term effects of chemical attack on the pavers being investigated. Consequently, the study's findings were limited to the short-term effects of chemical attack.

1.6. Thesis Structure

The outline of the forthcoming chapters is as follows:

Chapter One introduces the research subject by outlining the need for sustainable approaches in the concrete industry and improved WM strategies. Following this is a short summary of the relevance of the study, the research questions, goals, objectives, and the overall thesis structure.

Chapter Two provides a comprehensive analysis of the existing literature and highlights significant results in the studied area. It is essential that a thorough comprehension of the subject matter is achieved, and this is done through the literature review. The background of pavers, from their history to the different types of pavers currently available, is explored. Furthermore, an evaluation of pavers made of other materials is conducted, and the relevant traits of those pavers are noted such as the strength and durability characteristics. Plastic and glass recycling as well as management solutions are highlighted. In addition, the different degradation mechanisms of plastics are investigated. The chapter concludes with an overview of the topics covered.

Chapter Three outlines the experimental process necessary to adequately achieve the aims and objectives of the thesis. The methodological approaches are discussed, namely the qualitative and quantitative approaches of the thesis. The chapter also provides a brief overview of the manufacturing process of the pavers. Using the knowledge obtained from the literature, the relevant properties are determined, and methods of experimentation are identified and outlined. Applicable design codes are identified, and any additional specific preparation required for each experiment will also be discussed. The chapter also outlines the limitations of the study.

Chapter Four presents the results obtained through following the methodology and experimentation. The chapter contains the analysis and graphical presentation of the findings which are further discussed in-depth to gather insights surrounding the properties and behaviour of the pavers. The emphasis is on the performance of the materials under each test and determining the durability characteristics of the Eco-pavers. Areas of application of the pavers are also presented in this chapter.

Chapter Five presents an overview of the findings of the study. The chapter highlights the different areas and findings of the thesis that confirm completion of the objectives set out in Chapter One. Scope and recommendations for further research are also presented.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

The literature review in this chapter represents the theoretical framework for this study. As such, it introduces the background of pavers and investigates their properties. The standards relevant to this study as well as the critical characteristics of pavers are explored. The materials used in the paver are further investigated and their possible environmental implications are discussed.

2.2. Pavers and Associated Materials

Pavers are a popular alternative to concrete flooring for outdoor use and are made from various materials such as interlocking concrete, bricks, and permeable pavement. According to Du et al. (2015) and Han et al. (2019), interlocking concrete pavers are among the most popular types of pavers due to their ease of installation, replacement, and maintenance, as well as their mechanical performance. Porous pavement, which is a type of paver that allows for water to infiltrate, is also gaining popularity due to its environmental benefits (Bucholz & Boyle, 2005). The shaping of paving blocks can be customized to fit specific requirements, making them suitable for a variety of outdoor spaces, including footpaths and surface finishes.

2.2.1 Materials Used in Pavers

2.2.1.1 Concrete

Concrete pavers consist of cement, water, and aggregate and are generally unreinforced, according to Sharma and Batra (2016). Ghafoori and Mathis (1997) suggested that concrete pavers generally exhibit high density and strength however tend to have poor pore structures. It has also been observed that this is one of the most prevalent materials used for pavers.

2.2.1.2 Clay Brick

Brick pavers are formed by casting clay in forms and thereafter heat curing them (ASTM International, 2017). They are typically cast in the shape of rectangles unless otherwise specified. Unlike bricks used in the construction of walls, brick pavers are solid, without holes or gaps, and have a smooth finish.

2.2.1.3 Alternative Materials

It has been observed that there are various studies investigating different materials that can be used to manufacture a paver. Gungat et al. (2021) evaluated the use of plastic waste in paver blocks. In addition, Nandi and Ransinchung (2020) examined the use of recycled asphalt pavement aggregates in the production of paver blocks. Abdulla et al. (2021) investigated the use of plastic as a partial replacement for aggregate in a concrete paver block. Experiments were also conducted with other materials, including building and demolition debris (Jesus et al., 2021). However, no research specifically examining the usage of plastic in pavers with crushed glass as aggregates were located in the literature.

2.2.2 Pavement Systems

A pavement system refers to the use of pavers to create a durable and functional surface for various purposes (Huang & Lee, 2006). Pavement systems are implemented to serve specific functions, such as providing safe and efficient transportation for vehicles or pedestrians (Karamihas & Anderson, 2003), improving the aesthetics of outdoor spaces, or preventing soil erosion (Ksaibati & Bell, 2011) and at times, pavements and pavers can be used interchangeably as pavements are comprised of several pavers or concrete. The two most common types of pavement systems, according to some studies (e.g., Gharabaghi et al., 2013; Scholz and Grabowiecki, 2006), are porous and permeable/pervious pavement. These types of pavement systems offer several benefits, including reducing stormwater runoff and improving water quality (Chen et al., 2016). The following sections will cover these types of pavement systems in more detail**.**

2.2.2.1 Permeable Pavement Systems (PPS)

Permeable pavement systems were developed as a sustainable drainage system solution. The PPS design is such that it collects, treats, and infiltrates surface-runoff to support groundwater recharge, and a general permeable pavement system can be seen in Figure 2-1. Scholz and Grabowiecki (2006) suggest that further benefits of PPS include reduction of surface run-off and pollutant control from surface run-off where contaminated water may infiltrate into the underlying soil. According to Mullaney and Lucke (2014), these pavement systems are suited to footpaths, residential driveways, shopping areas, and bicycle tracks. It is further stated that they are not suitable for high traffic areas, heavy load traffic, or areas containing sediments on the surface as this could be detrimental to the structural integrity and reduce the infiltration of the pavement system.

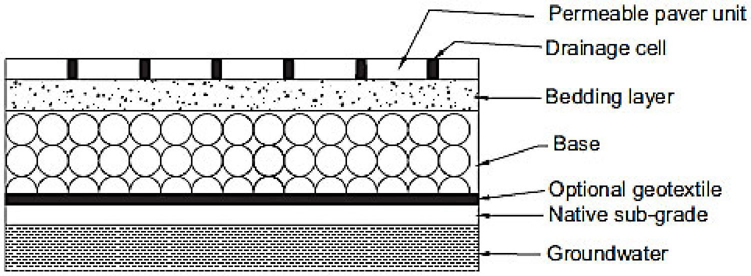

Figure 2- 1: Permeable pavement system (Scholz and Grabowiecki, 2006).

There are many types of permeable pavement systems; however, for this thesis, the focus shall be placed on permeable interlocking pavers. Mullaney and Lucke (2014) state that these pavers are designed such that there is sufficient open space between the pavers to allow water to infiltrate into the pavement structure.

2.2.2.2 Porous Pavement Systems

Pervious pavers, also known as porous pavement, generally include laying concrete pavers/blocks over a bed of aggregate stone with joints or gaps between the pavers (see Figure 2-2). These joints are used such that water can infiltrate to the void space beneath the paver surface and can then be filtered to the underlying soil (Scholz and Grabowiecki, 2006).

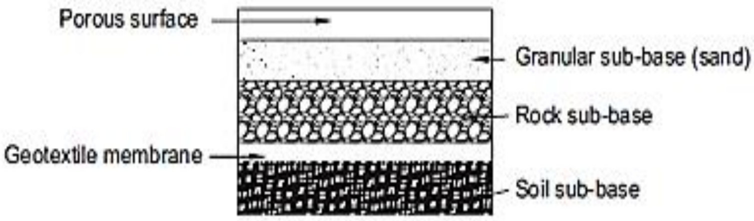

Figure 2- 2: Porous/Pervious pavement system (Li and Hunt, 2013)

2.3. Investigation of Standards

The main objective of this thesis, as highlighted in Chapter One is to determine the strength and durability characteristics of pavers made with recycled material. To determine these characteristics, relevant standards are investigated.

2.3.1. Standards for Pavers

The following standards have been identified for testing pavers:

- American standard of testing methods (ASTM C936-08): Standard Specification for Solid Concrete Interlocking Paving Units
- Indian Standards (IS) 15658 (2006): Precast concrete blocks for paving
- South African National Standards (SANS) 1058 (2012): Standards for concrete paving

A comparison between these testing methods is presented in Table 2-1.

Table 2- 1:Comparison of paver performance measures assessed by different standards

Standard		**ASTM C936-8 (2006)**	**IS 15658 (2006)**	**SANS 1058 (2012)**
Materials Covered		Cement and aggregate mix	Cement and aggregate mix	Cement and aggregate mix
	Visual Inspection	X	X	X

Measures of performance assessed	Tensile splitting strength		X	X
	Abrasion resistance	X	X	X
	Water Absorption	X	X	X
	Flexural Strength		X	
	Freeze-Thaw Durability	X	X	
	Compressive Strength	X	X	

A key observation from the analysis of standards for pavers is that the focus of these standards and the recommended measures are directed towards concrete pavers, and do not serve as generalized standards for pavers of varying material. The Indian Standards (IS 15658: 2006) are comprehensive as they cover the widest range of metrics for concrete pavers from those investigated and outline the methods of testing as well as the minimum viable requirements in detail.

2.3.2. Standards for Plastics

From Section 2.3.1 of Chapter Two, it is observed that there are no standards assessing the properties of pavers made of plastic. Therefore, an investigation into plastic-specific methods of testing is conducted to address properties that have not appeared in the paver standards and whose testing methods might differ from those regarding concrete. An overview of relevant standards for plastics is presented in Table 2-2.

Table 2- 2: Relevant standard for performance measures of plastic (Gabriel et al., 2021).

Measures of performance assessed	Standard
Compression	ASTM D695-02a-Standard Test Method for compression Properties of Rigid Plastics
Hardness	ASTM D785-08: 2015-Standard Test Method for Rockwell Hardness of Plastics and electrical insulating materials
Flexural Strength	ASTM D790 – Flexure testing of Plastics

2.4. Performance Measurements of Pavers

In this study, the use of pavers is under investigation and therefore the relevant properties for concrete pavers as identified in IS 15658 (2006), SANS 1058 (2012) and the ASTM D570 (1998) are investigated. The properties can be categorised as either a strength or durability characteristic.

2.4.1. Durability Measures of Pavers

Durability, as defined by the Cambridge Dictionary, is "the quality of being able to last a long time without becoming damaged." Therefore, to evaluate the durability of pavers according to industry standards, various properties should be considered, including but not limited to:

- Moisture Absorption
- Resistance to Chemical Attack
- Temperature Resilience
- In Situ and Sand- clogged Permeability
- Resistance to Ultraviolet degradation
- Abrasion Resistance
- Surface Hardness
- Relative Density

Skid resistance was omitted from this list intentionally as it is only relevant for pavers which are intended for use where vehicular interaction would occur and the pavers under study are only intended for use in foot paths.

2.4.2. Strength Measures of Pavers

Strength generally refers to the ability of an element, either on its own or as part of a system, to withstand applied loads. Therefore, the properties that fall into this category are as follows:

- Flexural Strength
- Compressive Strength

These properties have been assessed in similar studies on pavers, paving blocks and other related products made of concrete, recycled material, and other composites. These results would provide a good indication of the applicability of recycled material in these products. An important observation is that there are not any defined standards for plastic pavers with glass aggregates and, therefore, an investigation into results from previous studies on pavers of alternate materials shall be conducted in tangent to an investigation targeted at studies involving concrete pavers.

2.5. Analysis of Paver Performance

2.5.1. Moisture Absorption

A moisture absorption test analyses the percentage of water absorbed by a paver after immersion (IS 15658, 2006). It is an important metric to assess as these pavers are expected to be exposed to environmental conditions. According to Ananthi (2017), the test for water absorption is necessary to assess a pavers permeability. The experimental procedure shall later be discussed in Chapter Three of this thesis.

2.5.1.1. Moisture Absorption of Concrete Pavers

Multiple standards are available to conduct this test namely ASTM C 936 (2008) and IS 15658 (2006). The standards recommend a maximum water absorption of 5 % – 6% with no individual sample below 3%. A study by Ghorbani et al. (2019) investigated the moisture absorption of a concrete paver with magnetized and non-magnetized water, both of which yielded a 10 – 11% of water absorption, above the maximum recommended standards.

2.5.1.2 Moisture Absorption of Pavers of Recycled Material

According to Robert et al. (2010), there are three distinct reasons why water can penetrate a composite material:

- Water molecules diffusing via narrow passages between polymer chains.
- Transport through matrix microcracks, which often occur after compounding.
- Capillary transport into the gaps.

Therefore, this would suggest that the method of bonding and degree of consolidation of the molecules directly affects the rate of water absorption. Sand and plastic waste were used in a study by Ingabire et al. (2018) to manufacture environmentally friendly paving stones. Following ASTM guidelines, a moisture absorption test was performed. After 24 hours, the results of the moisture absorption tests revealed a water absorption rate of 0,052%. In contrast to this, a similar study by Salvi et al. (2021) had found that a 50/50 ratio between plastic and sand yields higher water absorptions at 2%. This study, however, did not outline any standards followed or methodology adopted to assess this property therefore the outcome cannot be validated. Furthermore, a paver composed solely of recycled plastic from e-waste by Gabriel et al. (2020) had a recorded water absorption of roughly 0.085%. In comparison to recommended minimum percentage absorption, the pavers with recycled material exhibit much lower rates of absorption than their concrete counterparts.

2.5.2. Resistance to Chemical Attack

Due to their environmental exposure, the pavers may be subjected to degradation by various chemicals. To assess the extent of resistance, a mass loss experiment is conducted as it is a simple and traditional measuring factor in acid attack tests (Araghi et al., 2015; ASTM C267-20; SANS 50197-1:2014). These industry standards provide guidance on conducting acid resistance tests and determining mass loss. Further to this, observations of the surface and matrix structure enables conclusions to be drawn on the level of resistance to specific chemicals or liquids.

2.5.2.1. Resistance to Chemical Attack of Concrete Pavers

A common mass loss test to assess the chemical resistance of a concrete paver is ASTM D543 (ASTM International, 2020). Ghorbani (2019) assessed the resistance of concrete pavers to sulphuric acid (H2SO4) and found that a regular concrete paver usually experiences a mass loss of 10% after 13 weeks. This finding is consistent with the results of similar studies (Gao et al., 2021; Tataranni et al., 2019).

2.5.2.2. Resistance to Chemical Attack of Pavers of Recycled Material

Upon inspection of the available literature, it was concluded that little to no research has been conducted to assess the resistance of pavers with alternative materials to chemical attack (Beecham & Burgess, 2012; Li & Hunt, 2013). Although some studies have investigated the chemical resistance of plastic-based pavers (ASTM D543-20), very few have examined pavers made from other alternative materials, such as recycled rubber or glass. Further investigation into the behaviour of these materials under chemical attack will be conducted in Section 2.8.1 of this chapter.

2.5.3. Temperature Resilience

The temperature resilience refers to the resistance to change or deformation when subjected to extreme levels of temperature, either hot or cold. This can be measured through several different methods. The factor that requires assessment depends on the region in which the pavers are to be produced. Regions with low temperatures below 0^0C, would find an assessment into the freeze and thaw durability of the paver important. In warmer regions, investigating the behaviour of the paver at high temperatures would offer insight into its real-world behaviour. This can be done through an oven test. Furthermore, dry regions are prone to veld fires and therefore fire resistance is an important factor to consider.

2.5.4 Freeze – Thaw Durability

2.5.4.1 Freeze – Thaw Durability of Concrete Pavers

In most cases, the testing procedures incorporate procedures that may be found in either IS 15658 (2006) or ASTM C666 (2015). Sharma and Batra (2016) conducted research on the use of concrete paver blocks in rural areas. The paving stones were tested in accordance with the requirements of IS 15658:2006. It is recommended that the maximum amount of water that may be absorbed by a concrete paver block should be no more than 6% based on a sample size of three pavers. In addition, it is noted that water freezes and expands by 9%, and the freeze/thaw requirements must be specified and verified prior to the installation of concrete paver blocks. Concrete pavers have an insufficient pore structure, as was stated before in Section 2.2.1.1. of Chapter Two. Consequently, they are more prone to freezing and thawing (Ghafoori amd Mathis, 1997).

2.5.4.2 Freeze – Thaw Durability of Pavers with Recycled Material

Ryu et al. (2020) evaluated the freeze-thaw durability of a paving block made with polyethylene terephthalate (PET) waste using practices from ASTM C666 (ASTM International, 2015). According to the ASTM C666 standards, the recommended average mass loss of a concrete paver is 1% or less per 50 cycles. However, the PET block experienced a mass loss of 2% after 120 cycles, indicating a reduced freeze-thaw durability compared to concrete pavers. This finding is consistent with the results of other studies that have investigated the performance of pavers made from alternative materials under freeze-thaw conditions (Li et al., 2020; Sun et al., 2019).

2.5.5 Oven Test

To assess the effect of high temperatures on the paver, an oven test is conducted to determine the melting point (Loganayagan et al., 2020). In the study by Loganayagan et al. (2020), it was determined that a paver block made of plastic and quarry dust only experiences a change in the form of melting at temperatures exceeding 140°C. This finding is consistent with the results of other studies that have investigated the thermal properties of plastic-based pavers (Khattab et al., 2017; Li et al., 2017).

2.5.6 Permeability

Pavement surfaces can experience reduced permeability when clogged by disturbed or unstable soil (Ryu et al., 2020). ASTM C1701 (2013) contains the procedure which shall be later discussed. Other studies have also investigated the permeability of pavers, including the study by Rokhsari et al. (2017) which examined the effects of surface roughness on the permeability of pavers. Rokhsari et al. (2017) found that the permeability of pavers was affected by the roughness of the surface. Pavers with a rougher surface had a higher permeability than those with a smoother surface. This finding suggests that the texture of the paver may be an important consideration when designing permeable pavement systems.

2.5.6.1. In-situ Permeability

According to the New Jersey Stormwater Institute, the recommended infiltration rate of the permeability test is 828 mm/h, and in the Seoul Metropolitan Government, 360 mm/h (Ryu et al., 2020). The PET pavers studied by Ryu et al (2020) had an average infiltration rate of 2365.2 mm/h. Adanur et al. (2020) found that the infiltration rate of pavers was influenced by the width of the joints between the pavers. Pavers with narrower joints had a higher infiltration rate than those with wider joints.

2.5.6.2. Sand Clogged Permeability

The recommended rate for sand clogged permeability is 504 mm/h according to the Interlocking Concrete Pavement Institute (ICPI) (Ryu et al., 2020). However, Widyatmoko et al. (2018) found that the permeability of concrete pavers with high porosity was much higher, with an infiltration rate of 1200 mm/h. This suggests that the design of the paver, including its porosity, can have a significant impact on its permeability.

2.5.7 Flexural Strength

Flexural stress refers to the stress at failure at bending when subjected to a load. It is a way of measuring the tensile strength, generally of concrete. The analysis of this property is conducted either by SANS 541(2012), ASTM C67(2017), or IS 15658 (2006) standards. The recommended minimum strength as per the ASTM C67 (2017) is 1.0 – 3.8 MPa, SANS 541 (2012) is 5 MPa and IS 15658 ranges based on application. Ryu et al., (2020) observed a flexural strength of exhibited a 5.2 MPa on a polyethylene terephthalate (PET) plastic paver which is above the recommended minimum for concrete pavers.

2.5.8 Compressive Strength

Compressive strength refers to the capacity to withstand load before failure. With regards to concrete mixes, compressive strength is dependent on several factors:

- Water/cement ratio
- Coarse/fine aggregate ratio
- Compaction
- Temperature

According to the American Society for Testing and Materials (ASTM) standards, Compressive strengths of concrete paver test samples are restricted to a minimum of 55 MPa with no individual sample being less than 50 MPa. South African National Standards (SANS) 1058 (1985) requires the minimum compressive strength of the blocks to be 25 MPa – 35 MPa, depending on the grade of concrete used, with only a 5 MPa deviation allowed from these suggested values for any single sample. Further recommendations from various standards can be found in Table 2-3.

Table 2- 3: Compressive Strength requirements from various standards (Gabriel et al., 2021).

Standard		Requirements				
		Light Traffic and Pedestrians	Heavy Traffic	Bike Paths and Parking	Special Vehicles	Acceptable Limits
ABNT NBR 9781:2013	Brazil	≥35 MPa	≥50 MPa	-	-	-
ASTM C936:1996	USA	-	-	-	-	≥55 MPa
CSA A231.2-95	Canada	-	-	-	-	≥50 MPa
SANS 1058:2009	South Africa	≥25 MPa	≥50 MPa	-	-	-
AS/NZS 4456.4:2003	Australia	≥25 MPa	≥35 MPa	≥15 MPa	≥60 MPa	-
BSEM 1388:2003	Europe	No individual results <3.6 MPa and breaking load <250 N/mm				
Compression strength of the Interlocking Block made from WEEE			Room temperature (MPa) = 37–47 Saturated (MPa) = 32–60 Hot (MPa) = 15–39 Frozen (MPa) = 32–56			

2.5.8.1 Compressive strength of Pavers with Recycled Material

The incorporation of glass in concrete pavers has also been tested by Ling and Poon (2014). The samples assessed incorporated varying compositions of glass in the concrete mixture to provide the finished product. Tests of these samples yielded compressive strengths ranging between 58 MPa and 70 MPa at 28 days. They also reported a loss of 30-40% of compressive strength in comparison to concrete pavers with 0% glass. Upon inspection of the microstructure of the crushed samples, loss of bonding was noticeable, and Ling and Poon (2014) concluded that this is due to the smooth surface of the glass particles.

An assessment of the effect that the amount of plastic has on a recycled paver was conducted by Salvi et al. (2021). The pavers under study consisted primarily of sand and plastic. As seen in Table 2-4, It was observed that as the percentage composition of plastic increased in the pavers, the compressive strength decreased. The data in Table 2-4. was achieved by Salvi et al. (2021) and it indicates that the compressive strength falls substantially below the minimum acceptable criteria.

Table 2- 4: Compressive strength test results on pavers made of plastic and sand *(Salvi et al., 2021)*

Plastic (%)	Load (KN)	Compressive strength (MPa)
40	79	24.49
50	68	21.08

60	53	16.43

A similar study by Thiam and Fall (2021) on a mortar with plastic (High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE)) and sand aggregates has also been conducted. The study by Thiam and Fall (2021) achieved a maximum compressive strength of 15 MPa for the sample with 40% plastic waste whilst achieving 14 MPa for the sample with 50%. The authors concluded that the compressive strength is influenced by the compactness of the plastic when pouring and the effect of the interfacial behaviour of the transition zone between the two materials. This refers to the region of the bulk paste that is disturbed by the aggregate, in the case of Thiam and Fall (2021), it refers to the zone between plastic paste and sand aggregate.

Both Salvi et al. (2021) and Thiam and Fall (2021) arrive at compressive strength characteristics that are below the standard recommended compressive strength for a paver. It is further suggested by Salvi et al. (2020) that these pavers are not suitable for application in heavily trafficked areas.

A study assessing the compressive strength of pavers made of recycled plastic (Acrylonitrile Butadiene Styrene (ABS), polystyrene (PS)), metallic residues, sawdust, discarded toys and cigarettes was conducted by Gabriel et al. (2021). The compressive strength for this paver was assessed under different conditions and is presented in Table 2-5. It was determined that a material comprised solely of plastic exhibits compressive strengths that are acceptable to the requirements of SANS 1058 (1985) but not ASTM standards for testing.

Table 2- 5: Average Compressive strength test results on pavers made of plastic only (Gabriel et al., 2021).

Condition	Strength (MPa)
Room temperature	42
Saturated	46
High temperature	27
Frozen	44

2.5.9 Abrasion Resistance

The pavers may be subjected to trafficked areas and therefore would experience surface wear. Therefore, to simulate this wear, an abrasive resistance test can be conducted. The IS 15658 (2006) standards contains the exact methods of testing for abrasion resistance. Other relevant standards that detail the exact procedure to follow to assess micro-abrasion can be found in Table 2-6.

Table 2- 6: Micro-Abrasion requirements from standards (Gabriel et al., 2021).

Standard		Requirement
ABNT NBR 12042:1992	Brazil	Group A: floor with high traffic demand ≤0.8 mm Group B: heavy pedestrian traffic between 0.8 mm and 1.6 mm Group C: light traffic between 1.6 mm and 2.4 mm
ASTM C936:1996	USA	Volume loss: ≤15 cm^3/50 cm^2
BSEM 1388:2003	Europe	<23 mm
Interlocking block made from WEEE		*K* with load 1 N (m^3/Nm) = 0.0008 to 0.0012 *K* with load 3 N (m^3/Nm) = 0 to 0.0004

An experiment assessing the micro-abrasive wear of a plastic paver was conducted by Gabriel et al. (2021). After being subjected to abrasive wear by a rotating sphere, a Scanning Electron Microscopy (SEM) analysis was conducted to study the wear mechanism. It was noted that the micro-abrasive wear coefficients were 0.001 m^3/Nm for a 1N load and 0.0002 m^3/Nm for the 3N load. These were deemed acceptable and within the required standards. Micropores were also observed to be generated during the experiment and this is suggested to cause further degradation by allowing contaminants to enter the structure (Gabriel et al., 2021).

2.5.10 Surface Hardness

An assessment of the mechanical properties of plastic pavers made from recycled electronic waste by Gabriel et al. (2021), investigated the surface hardness at room temperature of these products using the Rockwell hardness test. The results indicated an average roughness of roughly 51.1 HRC, which Gabriel et al. (2021) suggest could be attributed to the Acrylonitrile Butadiene Styrene (ABS) content. ABS is a type of plastic that the paver was partially composed of. The study highlighted the inconsistency that may arise when conducting multiple hardness tests on a single point on a paver and attributed it to micro-deformations on the surface of the pavers. It was also found that direct comparisons to hardness assessments on concrete could not be made due to a different metric system used to determine hardness of Portland concrete. However, Winslow (1981) determined the surface hardness of concrete to range from 45 to 52 HRC. This can therefore be used to draw comparisons against surface hardness of concrete and plastic. Since the plastic and the glass used for the Eco-pavers are waste materials the process of generating them as well as waste management practices are investigated in the next Section.

2.6. Waste Management

2.6.1. Statistics Related to General Waste and Recycling

Waste generation has become a growing challenge worldwide, with global waste volumes increasing rapidly in recent decades. It is estimated that 7 to 9 billion tonnes of waste are produced annually (Wilson and Velis, 2015; Hoornweg et al., 2013). Municipal Solid Waste (MSW) alone accounted for roughly 2.1 billion tonnes of the total global waste in 2019 (Nichols and Smith, 2019; World Bank, 2018).

Developing countries, although not the largest contributors to waste generation, do also display high levels of waste generation in places. It is noted according to SAWIC that not all waste that is disposed of is deposited in engineered landfills. This has implications for the environment as it is unsustainable and regarded as poor waste management. Table 2-7 presents South Africa's (SA) waste statistics for the years 2019 and 2020. Of particular interest to this study is the recycling of plastic and glass waste. The comparison between 2019 and 2020 tonnage reports in Table 2-7 shows a large discrepancy between recycling amounts. This could be due to the lockdowns imposed by the Covid-19 pandemic which consequently resulted in a lot of disruptions to different sectors of the world. Therefore, the 2019 statistics will be considered as a baseline average.

Table 2- 7: South African Waste statistics comparison between 2019 and 2020 (Source: http //sawic.environment.gov.za/index.php?menu=15)

Description	2019 Total (tonnes)	2020 Total (tonnes)
Waste disposal (landfill and dumping)	25,763,066.6	19,292,627.2
Waste recovery or recycling	26,919,238.2	4,356,636.9

2.6.2. Waste Statistics, Management and Recycling for Plastic and Glass

2.6.2.1. Plastic waste

Table 2-8 presents the South African plastic waste recovery and recycling statistics for the years 2019 and 2020. It was observed that there are large amounts of polyethylene and polypropylene-based plastic waste that are recycled.

Table 2- 8: South African plastic waste recovery and recycling statistics for 2019 and 2020 (Source: http //sawic.environment.gov.za/index.php?menu=15)

Waste type	Recycled or recovered (tonnes)	
	2019	**2020**
General Plastic	10 214 787.4	65 264.5
High-density Polyethylene (HDPE)	167 105.5	48 331.5
Low-density Polyethylene (LDPE)	581 817.7	31 173.6
Other	1 122 881.9	191 823.1
Polyethylene terephthalate (PET)	238 033.5	98 088.3
Polypropylene (PP)	858 737.3	32 164.7
Polystyrene (PS)	47 853.7	494.6
Polyvinylchloride	27 259.9	6 403.4

According to Thomas (2020), most plastics have an identification code known as a resin code written on the product, indicating the type of plastic it is. This makes it easier to classify the different plastics. Table 2-9 lists the origins of various plastic waste. Different plastic polymers can be separated using a range of separation processes. According to Thomas (2020), understanding the density of polypropylene might help identify the material. Another straightforward method uses near-infrared methods, which, because light-coloured polymers don't absorb radiation, can only be utilized with those materials.

Table 2- 9: Sources of recycled plastic waste (Ghuge et al., 2018).

Plastic waste	**Source**
Low-Density Polyethylene	Carry bags, sacks, milk pouches, cosmetic and detergent bottles
High Density Polyethylene	Carry bags, bottle caps, household articles etc.
Polyethylene Terephthalate	Drinking water bottles etc.
Polypropylene	Detergent, biscuit packets, microwave trays for readymade meal etc.
Polystyrene	Bottle caps. Foamed polystyrene: food trays, egg boxes, disposable

Polypropylene is a recyclable thermoplastic that may be reused, recycled, and upcycled (Ghuge et al., 2019). Another thermoplastic that is recycled on a worldwide scale is high-density polyethylene (HDPE) (AZoCleanTech, 2012). Additionally, it was discovered that HDPE can be recycled 10 times without losing any of its original characteristics (AZoCleanTech, 2012). To recycle this waste, the plastics are put into an extruder where they are melted at a temperature of 2400^{0}C, then cut into granules, cooled into pellets, and made suitable for use in other applications (Leblanc, 2019). In a 2012 study, Yao et al. compared the characteristics of plastic at the point of manufacturing to plastic after use. The findings imply that the recycled material is more brittle, although it does show equal UV exposure resistance to the manufacture sample (Yao et al., 2012).

2.6.2.2. Glass Waste

The main constituent of glass is sand, which is a natural resource. Glass is used in various applications. Some of which are presented in Table 2-10. The composition of these many types of glass varies, and as a result, the different varieties can typically be distinguished from one another based on the colour or stain of the glass. Since there is a lack of consistency because of this, recycling waste glass is made more difficult as a result. This makes it more challenging to separate the waste glass into its many components.

Table 2- 10: Types of glasses and possible sources (McLellan and Shand, 1984)

Glass	Source
Soda-Lime glasses	Bottles, Containers, Floats, Sheet, Light bulbs, Tempered ovenware
Borosilicate	Chemical apparatus, Pharmaceutical, Tungsten sealing
Lead glasses	Colour TV funnel, Neon tubing, Electronic parts, Optical dense flint
Barium glasses	Colour TV panel, Optical dense barium crown
Aluminosilicate glasses	Combustion tubes, Fiberglass, Resistor substrates

2.7. Application of Waste Materials in Civil Engineering

2.7.1. General Overview

The use of alternative construction materials has grown in popularity for a variety of reasons. Some of these contributors include the fact that there are less raw materials accessible, waste generation is on the rise, and construction projects have been noticed to negatively impact the environment (Abukhettala, 2016). The types of waste material that is used varies, and includes everyday waste like plastic, rubber, and glass as well as construction waste like brick and waste concrete from demolitions (Wong et al., 2018). Adoption of these substitute materials could lead to products that are more durable.

Wong et al. (2018) conducted research to determine whether brick waste might be used as a substitute for cement in the construction sector. By substituting 20% of the cement with brick waste, it was observed that the finished product had enhanced strength and performed better in durability tests compared to the control sample, which comprised only of cement. However, waste material does not always appear to be beneficial. Sormunen and Kärki (2019) conducted a study assessing the use of recycled material in the manufacture of composites where the waste was utilized to replace fillers in the composite. It was observed that the inclusion of waste material resulted in a composite with inferior mechanical properties in comparison to a control composite (Sormunen and Kärki, 2019).

2.7.2. Plastic Waste in Engineering

The global increase in plastic waste generation has resulted in the investigation of alternative uses for the waste material. One of the sectors which are of interest to this study is the engineering industry and in particular, the built environment. Arulrajah et al. (2017) proposed that the low rate of use of waste plastic materials in construction was owing to a lack of knowledge of their qualities; nevertheless, in recent research, recycled waste material samples were shown to be equivalent to those created from virgin material. Therefore, it is vital to analyse the qualities of the material in the environment so that the durability and resistance to environmental degradation of recycled plastic materials may be identified.

2.7.3. Glass Waste in Engineering

Mohajerani et al. (2017) state that glass waste may be utilized as a replacement for aggregate in cement. In terms of geotechnical behaviour, glass waste is equivalent to conventional aggregate, based on the results of tests and a review of the relevant literature (Disfani et al., 2011). In most cases, recycled glass is crushed and sorted. Through testing, Disfani et al. (2011) established that only small and medium-sized glass particles are appropriate for engineering applications. In addition, Disfani et al. (2011) showed that the usage of recycled glass waste has minor environmental consequences during its entire service life, hence bolstering its attractiveness as a viable alternative to conventional aggregate material.

2.8. Plastic Material

2.8.1. Polypropylene

As mentioned in Section 2.6.2.1. of Chapter Two, polypropylene is categorised as a thermoplastic. According to Maddah (2016), it further can be classed as a semi-crystalline commodity thermoplastic. This implies that the resins macromolecules are nearly ordered since they are embedded with crystalline phases (Maddah, 2016). Other examples of commodity thermoplastics include polyethylene, polypropylene, polystyrene, and polyvinyl chloride. The chemical structure of polypropylene can be seen in Figure 2-3.

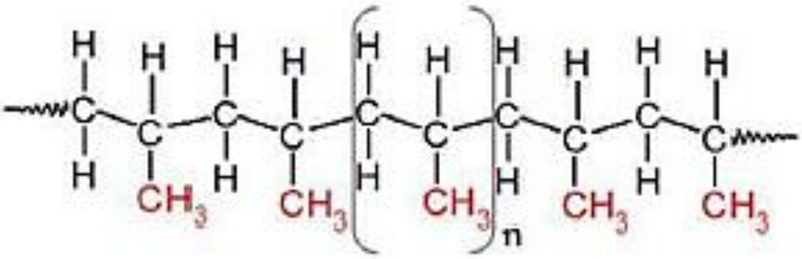

Figure 2- 3: Chemical structure of polypropylene material (Maddah, 2016).

Maddah (2016) also states that polypropylene has the lowest density among commodity plastics. A key trait of polypropylene is its high resistance to high temperatures and chemical attack. Homo-polymer polypropylene (HPP) is the most commonly used type of polypropylene in industry. While HPP is very rigid and has a high melting point at room temperature, it is less transparent and has a lower impact strength (Maddah, 2016). Because HPP has both crystalline and amorphous (non-crystalline) regions, this is the case. The amorphous portions include polypropylene that is both isotactic and atactic. In amorphous areas, isotactic PP may crystallize gradually over time. Table 2-11 provides further HPP material characteristics.

Table 2- 11: Properties of Isotactic Homo-polypropylene (Maddah, 2016)

Property	**Unit**	**Value**
Density	g/cm^3	0.91 – 0.94

Water absorption	%	0.01
Melting point	ºC	160-166
Thermal expansion	10-5in/in. ºC	5.8 - 10
Specific volume	cm^3/lb	30.4 – 30.8

A comparison between the advantages and disadvantages of the material was offered by Maddah (2016) and are summarized in Table 2-12. It is noted to be degraded by Ultraviolet (UV) radiation, which is not ideal as the paver under study comprises, in part, of polypropylene and pavers are subjected to outdoor use which consequently would result in UV exposure.

Table 2- 12: Advantages and disadvantages of polypropylene (Maddah, 2016)

Advantages of PP		**Disadvantages of PP**
Homopolymer	Copolymer	Degraded by UV
Process ability: Good	Process ability: High	Flammable, but retarded grades available
Impact resistance: Good	Impact resistance: High	Attacked by chlorinated solvents and aromatics
Stiffness: Good	Stiffness: High	Difficult to bond
		Several metals accelerate oxidative degrading
		Low temperature impact strength is poor

Additionally, polypropylene is known to be resistant to the following liquids that are pertinent to the investigation, according to Curbell Plastics' chemical resistance of plastic (2020).

- Acetone
- Gas Oil
- Water

2.8.2. Polyethylene

Polyethylene (PE) is a polyolefin type of thermoplastic, having a chemical structure shown in Figure 2-4. According to IUPAC, olefins are unsaturated hydrocarbons that contain at least one carbon-carbon double bond (International Union of Pure and Applied Chemistry, 2014). The density of different varieties of polyethylene is used to classify them. Maddah (2016) states that all varieties of polyethylene are semicrystalline, with crystallinity determined by chain branching. Within the polymer, the ordered crystalline parts have a higher density than the disordered, amorphous regions. When compared to LDPE, HDPE has less chain branching, higher crystallinity, higher density, and hence higher modulus and strength. Because HDPE and LDPE are the two most common forms of polyethylene utilized in commercial applications, they are the most relevant to this thesis. The mechanical properties for HDPE and LDPE are shown in Table 2-13. It is observed that HDPE has greater mechanical qualities compared to LDPE.

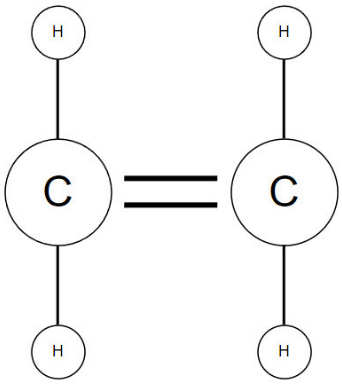

Figure 2- 4: Chemical structure of ethylene

Table 2- 13: Mechanical and Thermal properties of polypropylene (Maddah, 2016)

Property	HDPE	LDPE
Melt flow index	0.01-6	0.01-6
Tensile Strength (MPa)	20 - 30	6 - 17
Flexural modulus of elasticity	200000	30000
Modulus (GPa)	1.1	0.14 – 0.185
Density (g/cm^3)	> 0.940	0.910 – 0.925
Rockwell hardness (R-scale)	69	55

Similar to polypropylene, HDPE has a characteristic rate of moisture absorption of 0.1% (AC Plastics inc. n.d.). In addition, it is known to be resistant to temperatures up to 1200^{O}C and is also UV-resistant. Furthermore, the plastic has excellent chemical resistance qualities, particularly against sulfuric acid and diesel (Curbell Plastics n.d.). However, when submerged in acetone for extended periods of time, the material has only a moderate resistance to the solvent and may sustain damage.

2.8.3. Degradation Mechanisms of Plastics

Zhang et al. (2021) states that traditional plastic materials are highly resistant to degradation, generally exhibiting resistance for a long period of time, ranging from decades to centuries. However, this long-term durability also raises concerns about potential environmental impacts, as plastic may eventually break down and release harmful chemicals. Therefore, investigating the degradation mechanisms of plastics is critical for determining the true environmental impact of plastic pavers. This understanding can inform the experimental procedure and ensure accurate assessment of the long-term sustainability of plastic pavers. Despite the rate of degradation being slow, one of the primary factors resulting in degradation is environmental weathering. This causes plastic to breakdown and results in changes to the polymers properties. This can occur due to two processes, biotic or abiotic degradation. An outline of the mechanisms surrounding the degradation of plastic are illustrated in Figure 2-5. It depicts the contribution that both biotic and abiotic have towards the degradation of plastics and the subsequent production of microplastics and these result in environmental problems (Zhang et al., 2021).

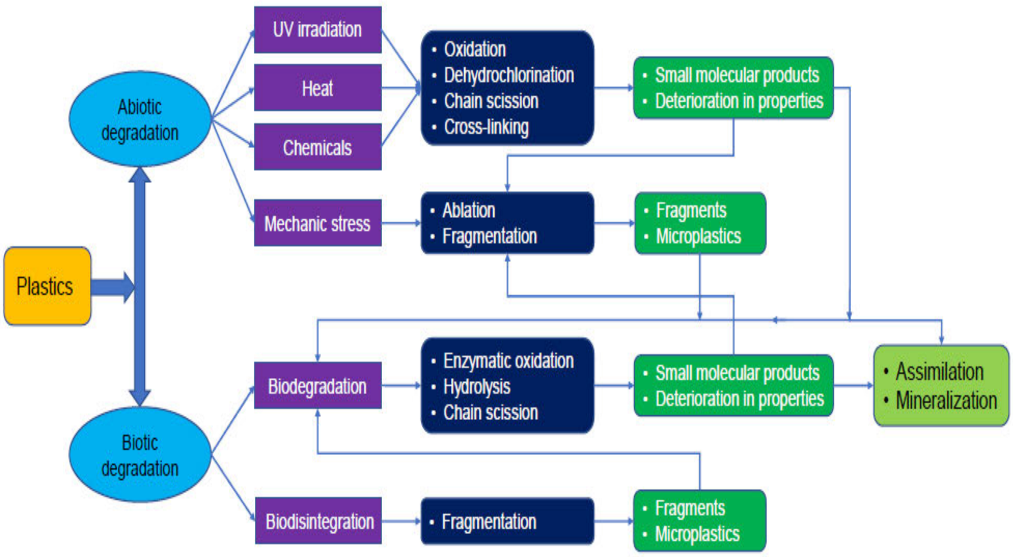

Figure 2- 5: General processes of plastic degradation (Zhang et al., 2021).

2.8.3.1. Biotic Degradation

Biotic degradation is a process through which plastic is degraded due to organisms. Bacteria, fungi, and insects are some of the most common organisms responsible for the biodegradation of plastics (Crawford and Quinn, 2016). The microorganisms degrade plastics either physically, through biting, chewing or digestive fragmentation, or biologically through biochemical processes (Dando et al., 2019; Zhang et al., 2021). Plastics generally have a small portion of polymer exposed to environmental degradation and are, therefore, considered to have low bioavailability, implying that the impact of microorganisms would not be as aggressive. This is further enforced by the fact that microorganisms require macromolecular polymers to first breakdown into smaller molecular products before the cellular uptake can occur (Chen et al., 2019). However, abiotic degradation, which will be covered in the subsequent section, could allow for biotic degradation to speed up since it usually results in cracks which create pores on the polymer which can be exploited by microorganisms to accelerate the degradation process (Wu et al., 2019).

2.8.3.2. Abiotic Degradation

Abiotic degradation is the process through which plastics experience a change in physical or chemical properties because of abiotic factors which include light, air, water, temperature, chemical attack, and mechanical forces. As illustrated in Figure 2-5, exposing the plastic to these factors over time can result in the breakdown of the macromolecular polymer structure, producing smaller polymer molecules which are then further broken down by biotic processes. Zhang et al. (2021) suggest that abiotic degradation can occur in tangent with biotic degradation, whilst abiotic degradation occurs first.

2.8.3.2.(a) Photodegradation

Photodegradation of plastics is caused by solar radiation which is usually attributed to exposure to Ultraviolet (UV) rays. According to Zhang et al. (2021), High-energy UV and medium-energy UV are the main causes of Photodegradation. Their respective wavelengths can be found in Table 2-14. Zhang et al. (2021) also stated that photodegradation is the most prevalent degradation mechanism of plastics.

Table 2- 14: Wavelength of different types of UV that degrade plastics (Zhang et al., 2021)

UV-Type	Wavelength
High energy irradiation (UVB)	290e315 nm
Medium energy irradiation (UV-A)	315e400 nm

One of the traits of polyethylene is that it lacks chromophores. This is significant as chromophores are atoms or molecules whose presence is responsible for the colour of a compound and the absorption of electromagnetic radiation (Zhang et al., 2021). This electromagnetic radiation is responsible for direct decomposition when exposed to ultraviolet because of bond dissociation. This, therefore, implies that PE is essentially resistant to photodegradation. However, impurities or structural flaws in polymers because of inadequate quality assurance or weathering might function as chromophores and hence induce photodegradation. Weber et al. (2011) states that photodegradation causes a reaction which results in the production of aldehydes, ketones, carboxylic acids, esters, and alcohols which are harmful to humans and the environment.).

2.8.3.2.(b) Thermal Degradation

The breakdown of plastics due to an increase in temperature is referred to as thermal degradation. The degradation is due to the plastics undergoing a thermo-oxidative reaction at these elevated temperatures, as suggested by Zhang et al. (2021). The process of thermal degradation is like photodegradation due to the production of hydroperoxide. Hydroperoxide is produced because of the reaction between oxygen and the free radicals when the long polymer chains of the plastic are broken with the energy from the elevated temperatures.

Common plastics containing hydrogen undergo exothermic oxidation in the presence of oxygen at temperatures close to $200^{O}C$, while higher temperatures are often required for polymers with a higher melting point (Kotoyori, 1972). Considering this, Zhang et al. (2021) propose that exothermic oxidation is unlikely to take place in the environment due to the high temperature that is necessary for it to take place. Additionally, it has been hypothesized that progressive thermal oxidation of plastics may take place in combination with photodegradation, on sun-exposed pavements and beaches. Kamweru et al. (2011) reinforced the findings of Andrady et al. (2003) indicating that oxidative and thermal degradation both appear to coexist as there exists a linear relationship between the temperature and degree of oxidative reactions inducing plastic degradation. In addition to this, Kotoyori (1972) discovered that increased humidity resulted in a reduction in the required thermal energy for which degradation would occur.

2.8.3.2.(c) Chemical Degradation

Pollutants in the atmosphere such as ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs) can either damage plastics directly or stimulate the creation of radicals through photochemical reactions, resulting in plastic degradation (Crawford and Quinn, 2016). UV and lightning can produce O_3, which is naturally present in low quantities in the atmosphere, however ozone levels at ground level are higher due to air pollution (Placet et al., 2000). NO_2 experiences a photochemical reaction with O_2 that produce ozone.

2.8.3.2.(d) Mechanical Degradation

Mechanical degradation is the action of the application of force which results in the breakdown of plastic. Zhang et al. (2021) suggests that plastics can be subjected to external forces in the environment through different contributors which including collision and abrasion of plastics with surrounding areas due to natural causes. The extent to which the plastics are affected by the external forces is dependent on the characteristics of the plastic and its subsequent resistance to these forces. Persistent stress on plastics inevitably causes polymer chain scission (Zhang et al., 2021).

2.8.3.3 Degradation of Plastics in Different Environments

Studies that have investigated the degradation of plastics under natural or simulated environments can be found in Table 2-15. From the results of the experiments in air by Ojeda et al. (2011), its observed that the plastics experienced photodegradation in the air, which changed their appearance and texture, lowered their mechanical characteristics, and altered their physicochemical properties. Pastorelli et al. (2014) noted that plastics which air exposed to air, but no UV experience a change in surface colour as a result of visible light and NO_2 degrading the plastic, with secondary degradation from O_3. It is observed that most studies were unable to determine the long-term degradation effects due to the plastics requiring a long time to reach full degradation. In addition to this, only a select few studies have included findings on the formation of microplastics through degradation mechanisms (Garnai et al., 2019).

2.8.4. Characterization of Degraded Plastics

Tracking the properties associated with degradation can assist in determining the degree of plastic degradation by monitoring any observable or quantifiable changes. These quantifiable changes also include any changes in mass, i.e., weight loss, or the release of gasses (Wu et al., 2019). It is through degradation that fragmentation occurs, which results in the formation of microplastics (Andrady, 2003).

2.8.4.1. Chemical Composition

Polymers, which are big molecules generated by the polymerization of monomers, make up plastics. The chemical make-up of plastics is determined by the monomer's chemical make-up and the degree of polymerization, however it’s important to note that many chemical additives are generally added to plastic mixes. (Zhang et al., 2021). During deterioration, reactions can occur in the polymer chain as well as among the plastic additives, altering the chemical makeup of the plastic. Degradation produces polymer chain scission and cross-linking, resulting in changes in their molecular weight. Because no two polymer chains have the same mass, an average molecular weight is commonly utilized. Table 2-16 illustrates the different methodologies used for assessing the degradation mechanisms of plastics.

Table 2- 15: Degradation of plastics in different environments (Zhang et al., 2021)

Plastic	Exposure	Characterization	Consequences	Mechanisms	Reference
LDPE, PP, PS	24 hours in a rotating laboratory mixer with sediment added	Visual inspection, fluorescence microscope, balance,	As the grain of the sediments increased, so does the generation rate of microplastics	Mechanical fragmentation	Chubarenko et al. (2020)
PE, PP, EPS	UV exposure for up to 12 months followed by Mechanical abrasion for 2 months	Scanning electron microscopy (SEM), microscope	Observation of cracks on surface; Surface colour changing to yellow; Fragmentation and formation of microplastics	Biodegradation and mechanical oxidation	Wu (2017)
PA, PVC, PS, PE, PP, PC, PUR	2 years in air sheltered from UV and precipitation	Colorimeter	Yellowing and changes in lightness	Chemical degradation and photodegradation	Pastorelli et al. (2014)

Table 2- 16: Assessment of degradation mechanisms (Zhang et al., 2021)

Characterization of plastic degradation	Methodology for assessment
Chemical composition	Visual inspection, Fourier-transform infrared spectroscopy (FTIR)
Appearance and texture	Visual inspection, Spectrophotometer, Colorimeter, SEM
Mechanical properties	Instron universal materials testing machine
Microplastics	SEM, Microscopes

2.8.4.2. Mechanical Properties

Mechanical characteristics are often determined with a universal materials testing machine utilizing ASTM and ISO standard techniques (McKeen, 2014). A stress-strain experiment can be used to determine tensile parameters such as elongation at break and tensile modulus. Shear strength and shear modulus are the two primary measures of shear characteristics, both of which can be obtained in a stress-strain experiment. The mechanical properties of plastics are dependent on their chemical composition and physicochemical properties, such as molecular weight, crystallinity, cross-linking, and additives (Zhang et al., 2021). The mechanical properties of a plastic generally deteriorate because of degradation on the plastics' chemical and physiochemical properties (Arhant et al., 2019). When applied forces exceed the plastic materials mechanical strength, highly deteriorated plastics begin fragmenting and generating microplastics (Andrady, 2003).

2.8.4.3. Weight Loss and Gas Release

The total mass of a plastic can completely diminish during deterioration and be converted to either CO_2 or CH_4, depending on the environment in which the degradation occurs. Weight loss is a common sign of plastic degradation, which can be measured with a high-precision balance. Additionally, weight loss can be indirectly represented by total organic carbon (TOC) measurement with a TOC analyser, which calculates the organic carbon concentration of a sample by measuring CO_2 produced by burning (Zhang et al., 2021). The reduction in mass can be attributed to the mineralization of plastics and the subsequent release of additives. As a result, simply losing weight may not be enough to show mineralization (Oberbeckmann and Labrenz, 2020).

2.9. Characteristic Properties of Glass

Glass is a very durable material as it has a strong resistance to chemical attack and is also stated to hypothetically require thousands of years before fully degrading (Cairoli, 2019). Its resistance to high temperatures varies with composition however usually have melting points exceeding 1200^{O}C. As a result, high temperatures are unlikely to have a harmful impact on this material in the natural environment as it is unlikely that temperatures would elevate to these levels. An important characteristic of interest are the mechanical properties of the materials used, as the properties of individual material, affect and influence the compound formed. The general mechanical properties of typical glass are presented in Table 2-17.

Table 2- 17: Mechanical properties of glass (Structural Glass Design n.d.)

Property	Magnitude
Density	2500 kg/m^3
Compressive Strength	1000 MPa
Tensile Strength	40 MPa for annealed glass
Elasticity	Material is plastic
Youngs Modulus	70 GPa
Poissons Ratio	0.22
Linear Expansion	9 x 10-6 m/mk at a temperature of 20^{0}C to 300^{0}C

2.10. Chapter Summary

Concrete pavers are required to satisfy an array of requirements as identified in the various standards. These requirements touch on both strength and durability characteristics as the pavers are likely going to be applied in different environments which would likely subject it to different types of loading. This chapter identified that some standards outline some requirements that others don't, and this implies that various methods of testing from different standards would be required to get a comprehensive overview of the pavers. Since the materials for the paver are plastic and glass, it was identified that standard methods of testing plastics also need to be considered.

The most important durability and strength characteristics of a paver were found. It was observed that with regards to durability, pavers made of plastic may exhibit significantly lower rates of absorption than traditional pavers due to the tightly packed molecular structure reducing the number and size of pores in the material. Another characteristic, permeability, is dependent on the pores and ability of the material to absorb or restrict water absorption. Furthermore, depending on application, the pavers may require resistance to different temperatures.

The findings on the compressive strength of pavers incorporating plastic indicate that a plastic incorporating aggregate may suffer from poor bonding and subsequently fail at lower loads. This is also reinforced when considering the use of sand as an aggregate in a plastic paver. In all studies, the flexural strength, of pavers made with alternative materials, is comparable to that of a regular paver, and in some instances they test better.

The characteristics identified in the chapter are also significant when assessing the pavers environmental impact. Plastic has the potential to release harmful chemicals and material (i.e., microplastics) into the environment and this can occur through either biotic or abiotic processes. The characteristics discusses in this chapter align with abiotic mechanisms of degradation and observations based on the behaviour of the plastics during testing would offer insight into how it would behave in the environment.

From the review undertaken it should be noted that in the literature there was no study investigating pavers made of plastic and glass similar to the ones produced locally. Therefore, this gap in knowledge needs to be filled and the current study attempts that. In the next chapter the methodology associated with this research will be presented.

CHAPTER THREE: METHODOLOGY

3.1. Introduction

This chapter outlines the experimental program followed to meet the aims and objectives outlined in Chapter One of this thesis. A brief overview and history of the pavers under study are included, providing insight into the manufacturing process as well as the composition of the constituent materials. The qualitative approach adopted in determining the relevant parameters of a paver as identified in Chapter Two is then discussed in detail. Raw data was acquired through laboratory testing and thereafter analysed. The appropriate information and testing standards, if applicable, have been supplied and utilised in a South African context since this waste-reuse project happens in a capacity that applies to it. The limitations and uncertainties associated with this study are also included.

3.2. Methodological Approach

The research endeavours to discover the characteristics of the composite material that the paver is made of, and as such, research related to the study is undertaken to develop a strategy that will match the stated goals and objectives in Chapter One as accurately as possible. The methodologies used were both quantitative and qualitative. The selected theoretical approach is found in Chapter Two of the thesis and is comprised of the literature review. The research offered in the literature review provided a wide comprehension of the topics investigated in this study; nevertheless, the information gathered from the literature review is insufficient, by itself, to accomplish the stated goals and objectives. Therefore, an evaluation of the paver's production process is included and a qualitative approach that permitted comparisons. Figure 3-1 illustrates the overall methodological approach.

3.3. Qualitative Approach

As seen in Figure 3-1, a qualitative approach is taken in defining the methodology. This leans on the information obtained from the literature review and informed the relevant properties that were investigated, and the standards used. The google scholar and science direct search engines were used to obtain relevant literature. Reputable sources were prioritised such as articles, journals, and peer reviewed publications. Where no published sources were found, websites were consulted to fill in any gaps in knowledge. Key words such as "Pavers", "Recycled plastic pavers", "Glass aggregate", "Pavers with recycled waste" were used.

3.3.1. Properties to Investigate

One of the key aspects of this thesis is identifying which parameters are relevant to investigate. The literature review outlines some of the key properties associated with a paver with respect to durability and strength. These two aspects align with the aims and objectives of this thesis and therefore upon comparison of all the various properties that could be considered, the following were considered:

- Water absorption – It was observed that the water absorption rate of a paver was investigated in various studies and proved to be a key component in determining the suitability of paver. The experimental procedure which outlines the method of testing this property is also identified in multiple standards and as such this property was considered necessary to determine the durability of the paver.
- Resistance to chemical attack – Since the material for the paver is plastic and would likely be subjected to exposure to an array of different chemicals during its life span, it would be crucial to determine the effect of these chemicals. Although no prior research surrounding this paver exists, similar studies observe the effect of chemicals on the pavers. To also determine the environmental impact of the pavers, determining their degree of resistance to chemicals would clarify the possible degradation mechanisms of the pavers as Section 2.8.3.2.(c) highlights the impact that chemical attack has on abiotic degradation. Furthermore, resistance to chemical attack was also found to be a large factor when assessing durability.
- Permeability – It was found that the permeability informs the type of pavement system that would be most appropriate with the pavers. A few studies were identified to have investigated the rate of infiltration and it was useful to this study to determine the possible applications of the pavers.

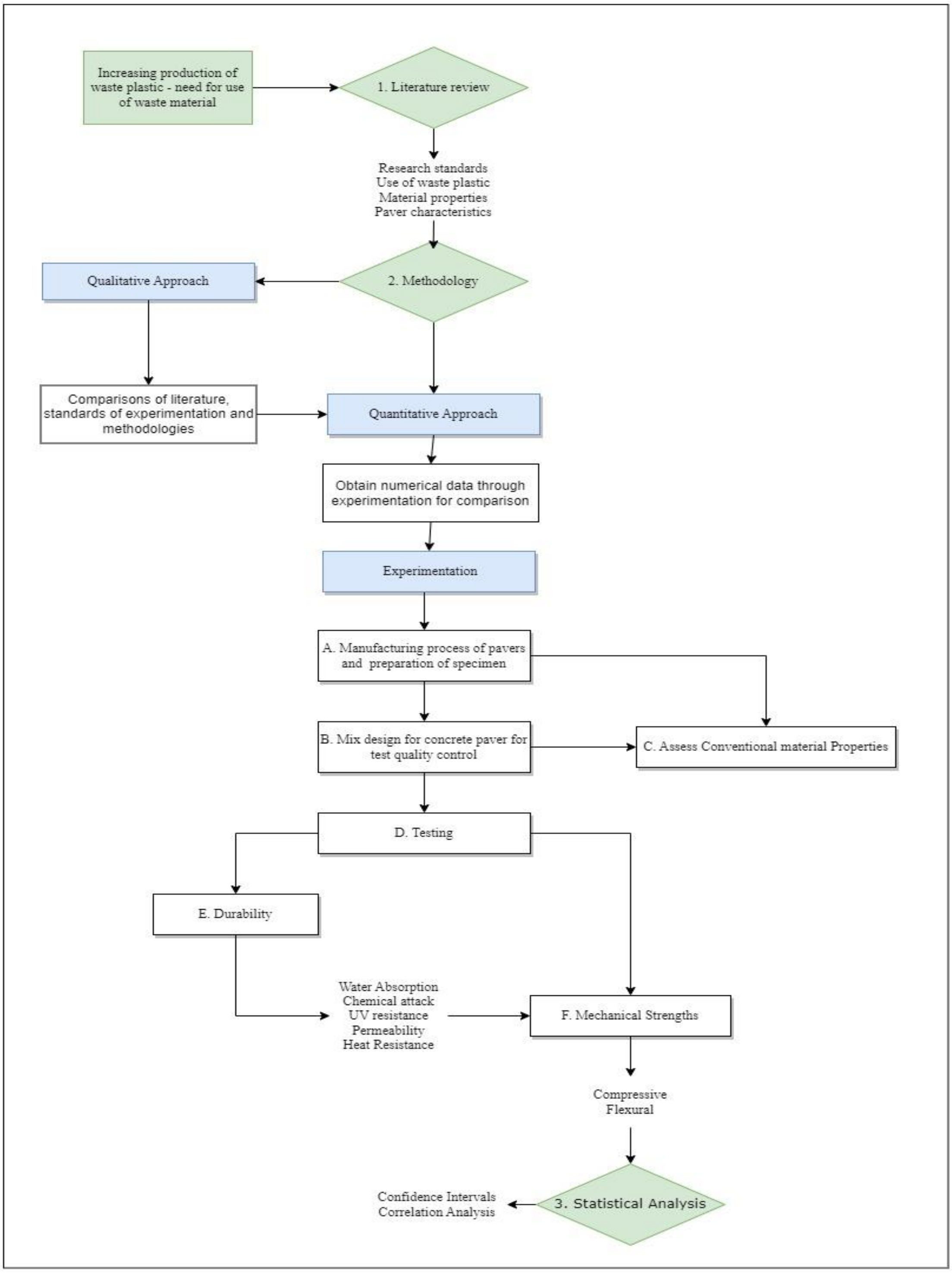

Figure 3- 1: Schematic of the fundamental research methodology

- UV resistance – It was found that no set standards exist for pavers resistance to UV exposure, however UV exposure plays an important role in the degradation of plastics and the release of microplastics. It was noted that UV degradation tends to start occurring after several years of exposure and to replicate this in a laboratory setting would require expensive equipment to simulate the effects of years of exposure in a short period of time, which may not be feasible in this study. Therefore, this attribute was not tested.
- Heat resistance – Since the pavers would be exposed to a variety of temperatures, it would be useful to observe its behaviour at higher temperatures that may be experienced in the environment.
- Flexural and compressive strength – These two strength characteristics were found to appear most frequently in each study and in addition, every standard provides a procedure to follow to determine these characteristic values. Therefore, they were considered instrumental to compare the suitability of the pavers.

The water absorption, resistance to chemical attack, permeability and heat resistance will be assessed in order to assess the durability of t he pavement whilst the compressive and flexural strengths will be used to determine the mechanical strength of the pavers. These attributes were found to be the most applicable as the pavers' intended use is outdoors as footpaths/walkways. This would therefore subject the pavers to loads that would cause either compression and/or flexure. They will also experience rain, possible flooding, surface blockage through debris or sand, as well as high temperatures due to direct sunlight causing heating of the surface. It was also found that these characteristics are types of abiotic degradation mechanisms of plastic. Therefore, understanding these characteristics of the pavers would help to inform how the paver would behave when placed in the environment, and wether it would be likely to release microplastics or other forms of pollutants into the environment when in use.

3.3.2. Comparison of Standards

Since the pavers are made of plastic, the literature explored the standards relevant to testing pavers as well as those relevant to testing plastic material. The initial assumption was that the standards for testing plastics could be used as a substitute for testing the plastic pavers if a standard was unable to be found. For the properties mentioned above, a comparison of the different standards revealed that the best approach would be use the SANS standards for testing pavers where possible, as this would allow for direct comparisons between the plastic pavers and concrete pavers and it was also found that the methods of testing in the Indian standards and American standard testing methods are similar, which would allow for the results obtained in this experiment to be directly compared with those from other studies. In the event a procedure of testing is not found in SANS, ASTM or IS will be followed as they also contain experiments that are relevant to this study that may not be found in SANS.

3.4 Paver Manufacturing Process

To fulfil the objectives outlined in Chapter One, it was determined that both plastic and concrete pavers were required. This allowed for testing on both types of pavers and comparisons to be drawn between them. However, the plastic pavers were subjected to all the experiments as the composite material that they consist of were the primary focus of the study, whilst the concrete pavers were used as a validation mechanism in paver specific experiments. The design and manufacturing process of each paver is outlined in the next sections.

3.4.1 Plastic Composite Pavers

Since this thesis investigates a pilot initiative, the manufacturing process of the plastic composite (Eco-pavers) was conducted in an artisanal manner as there are no predefined methods of manufacturing. The process that was followed involved a trial-and-error approach in casting them initially and the steps outlined represent the procedure which appeared to yield a mix that was fluid enough to cast into a mould to cool. The materials used in the paver are recycled materials and as such, were obtained at a local recycling depot. Using a crusher, the glass was broken down into a cullet, as shown in Figure 3-2, which was then kept in plastic containers until needed. The glass cullet had been used as aggregate and the size ranged from 8-12 mm. The main plastic used in the paver was polyethylene and polypropylene. The waste plastic had been shredded (see Figure 3-3) so that when heated, it would melt evenly and quickly. Due to the high energy required to break the carbon and hydrogen bonds in plastics, this was essential to lower the cost of melting it down.

Figure 3- 2: Crushed glass (Cullet) (Maharaj, 2020)

Figure 3- 3: Shredded polypropylene waste (Maharaj, 2020)

The Eco-paver manufacturing takes place at the recycling facility due to the convenience and availability of equipment. The mix proportions (see Figure 3-4) were weighed out and thereafter the plastic waste was inserted into the blast furnace (see Figure 3-5), which melted the plastic at a temperature of approximately 400^0 C. The glass aggregate was thereafter added, and the mix was continuously stirred to incorporate it adequately and ensure even distribution. On an eight-hour cycle, the electric-powered furnace consumes 25 litres of fuel. In a period of 8 hours, sixty Eco-paver blocks were created.

Figure 3- 4: Chosen mix proportions (Maharaj, 2020)

Figure 3- 5: Blast furnace used to melt plastic (Maharaj, 2020)

This mix was then allowed to flow into a mould which had been set aside to cool down. The mould size and the proportion of glass and plastic might vary depending on the operator's requirements. The blast furnace uses an alkaline chemical scrubber to control the emissions released from the melting process. The finished product can be seen in Figure 3-6. The composition of the pavers is presented in Table 3-1.

Table 3- 1: Composition of Eco-pavers

Sample	**Composition (%)**		
	Polypropylene	HDPE	Glass
Composite Pavers	25	25	50

Figure 3- 6: Eco-paver finished product (Maharaj, 2020)

3.4.2. Concrete Paver Mix Design

Concrete pavers were cast to serve as quality control samples for the experiment to ensure that the experiments yielded values in line with standards for concrete pavers. This is primarily done to ensure that direct comparisons can be made between the plastic pavers and concrete pavers as well as the standards and other studies. These pavers will be cast in accordance to the relevant standards as referenced below.

3.4.2.1. Mixture Proportions

A 20 MPa concrete paver was designed using the Cement and Concrete Institute (C & CI) design method in accordance with the Concrete Institute (South Africa) as well as the SANS standards for pavers. The coarse aggregate used in the mix was tillite stone of 19mm in size. Since SANS 541 (2012) requires concrete paving slabs to have a minimum flexural strength of 5 MPa, this was the targeted flexural strength. Table 3-2 contains the design mix required to cast the concrete pavers.

Table 3- 2: Design mix required for casting concrete pavers

Material	**Mix**		
	Per m^3	Required	Units
Water	210	11,50	l
Cement	467	25,58	kg
Umgeni sand	581	31,82	kg
Stone (G2)	1113	60,96	kg

The various materials were inserted into a mechanical concrete mixer to prepare the concrete samples in accordance with SANS 5861-1:2006. These materials were mixed for roughly 4 minutes to create the mixture. Water is then added incrementally until the desired consistency is achieved.

3.4.2.3. Specimen Sampling and Curing

For the compression testing, a sample of the specimens consisted of four cubes measuring 150x150x150(mm), and for the flexure tests, three samples were cast using custom moulds measuring 500x500x45(mm). A vibrating table was used to obtain the desired level of compaction for each specimen. All moulds were removed twenty-four hours after casting, and specimens were immersed in a water curing chamber for 28 days as this experiment only focused on the comparison of the hardened concrete at 28 days to the Eco-pavers. The temperature range for curing was (22 - 25) °C.

3.5. Experimental Procedure of Testing

To evaluate the properties of the eco-pavers as identified in Section 3.3.1. of this thesis, the experimentation was conducted in accordance with relevant standards and recommendations reviewed in Chapter Two of the Thesis. The primary objective is to assess the plastic pavers, and therefore some of the experiments are specific to the plastic pavers, in particular the chemical attack, permeability, and heat resistance experiments.

3.5.1. Sample Preparation

Eco-pavers

Eco-paver samples were obtained at the recycling depot. These samples were subsequently taken to the University of KwaZulu-Civil Natal's Civil Engineering laboratory for storage, processing, and testing. Due to the size and scarcity of these samples, it was decided to reduce their size to properly perform the tests and meet the goals outlined in Chapter One. To cut the pavers, a table saw was used, which cooled the blade with water to prevent the blade from overheating and fracturing and to avoid any damage to the pavers that may have resulted from high temperatures. The use of the table saw resulted in blocks with exposed interior structures. This was useful during immersion testing to determine the true extent of saturation and chemical penetration. It is also noted however, that cutting the pavers may introduce marginal errors as some glass aggregate may loosen during the cutting process, and these factors were considered when analysing and discussing the results.

Concrete Pavers

Since the concrete pavers were only required for the moisture absorption, flexural strength, and compressive strength tests, they were cast as required and therefore no further preparation of these samples was needed.

3.5.2. Sample Selection

Since the number of pavers cast were low and they were subsequently cut, the specific ratios of plastic to glass varying in the cut samples used in this study. Therefore, simple random sampling methods were implemented when choosing samples for each experiment from both the concrete and plastic pavers. The method of random sampling ensures that every sample in the set has an equal and fair chance of being chosen (Acharya et al., 2013). After preparation, each paver in the set had been allocated a number which refers to that specific paver. A random number generator was used in the range of the entire set to choose samples for each test. These samples were then used in the experiments that follow. This process also ensured that every single sample available was used in an experiment and reduced the level of bias in the study.

3.5.3. Chemical Attack

Several mass loss experiments were undertaken to measure the chemical resistance of the eco-pavers. These tests were conducted in compliance with ASTM D543 standards. From the literature in Chapter Two, it was identified that the pavers will likely be exposed to vehicular and relevant industrial fluids. Therefore, the following chemicals were chosen:

- Diesel
- Gasoline (Petroleum)
- Engine oil
- Acetone

Given the potential for the pavers to be utilized in industrial settings, where they would be subjected to leaks of diesel, gasoline, and engine oil, these fluids were selected for testing. In addition, acetone occurs naturally in the environment and is also created by industrial activities, thus exposure is probable. The procedure begins with weighing the samples as seen in Figure 3-7 and recording their respective dimensions and surface finish. A microscope attachment was used to capture detailed images of the surface at the different faces of the samples as in Figure 3-8. Immersion testing was selected as the testing technique. The container used to house the samples required to be able to hold the chemical and samples for an extended period without degrading itself.

The chosen durations are as follows: 1 day, 7 days, 30 days, 60 days, and 90 days. These durations were chosen as it would provide insight into both the short- and medium-term effects of the chemical on the pavers. However longer-term effects will be difficult to ascertain due to the degradation of plastics requiring decades before it takes effect.

The equation used to determine mass loss is as follows:

$$\%\ \text{Mass loss} = \frac{(\text{Mass before immersion} - \text{Mass after immersion}) * 100}{\text{Mass before immersion}}$$

Figure 3- 7 Weighing of samples

Figure 3- 8: Carson Microscope

When handling the substances, safety procedures were implemented with the use of latex gloves and goggles. The samples were measured and then submerged in the chemical solutions. Following the required intervals, the samples were allowed to dry before being weighed. Notable observations were also made on the appearance of the material following immersion.

3.5.4. Water Absorption Test

A water absorption test was carried out in accordance with SANS 1058 to determine the rate of absorption. The testing technique, according to the standard, starts with drying the samples and then weighing. Following that, the samples were immersed in water for a certain duration before being weighed again. The following equation was used to compute the percentage of water absorption:

$$\% \text{ Water absorption} = \left(\frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}}\right) \text{x } 100$$

The chosen durations are as follows: 1 day, 7 days, 30 days, 60 days, and 90 days. These durations were chosen as it provided insight into both the short and medium-term effects of the chemical on the pavers. Three samples were immersed for each stipulated period as required in SANS 1058. Further to the weight, the dimension of each sample was recorded before immersion and any swelling was noted.

3.5.5. Flexural Strength Testing

The flexural strength testing was executed as per SANS 5864:2006 since it addresses the flexural strength required of concrete in general and the equipment available would allow for this approach to be followed. Accordingly, the flexural strength is determined as per the equation below:

$$f_{cf} = \frac{F_f \, I}{bd^2}$$

Where, f_{cf} = flexural strength (MPa)

- F_f = maximum two-point compressive load at failure (N)
- l = length between axes of supporting rollers (mm)
- b = width of sample (mm)
- d = depth of sample (mm)

The pavers under study have a length and width of 500m and a depth of 50mm. A universal testing machine was used to conduct the experiment as it was the only suitable, available piece of equipment. According to Figure 3-9, the distance between the rollers needed to be at minimum three times the depth of the sample, which would imply 150mm apart for this sample. However, this would have resulted in the rollers being spaced too closely together and would risk the load being concentrated in a small area and may lead to early failure. Therefore, a distance greater than that was required. In addition, raised rolling supports were required as the pavers are not thick enough for the machine to fully load it on the standard rollers. As such, the supports seen in Figure 3-10 were used in the only possible position. The effect of their position was closely monitored, and the plane of failure was noted for each sample and will be discussed in the results section of the thesis.

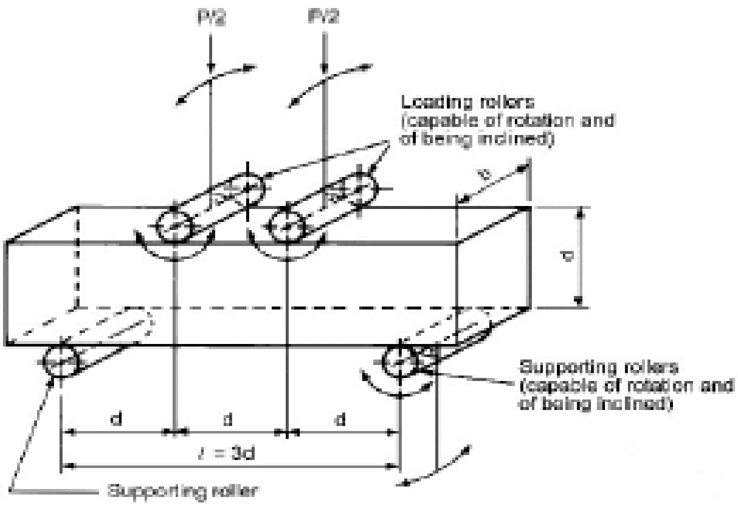

Figure 3- 9: Arrangement of the flexural (SANS 5864, 2006)

The load was applied through rollers on the top face, at the middle of the sample. The rate of loading was 6kN/min. The load was increased at a constant rate until the specimen failed, as seen in Figure 3-11. Thereafter, the maximum load was recorded.

Figure 3- 10: Eco-paver on Universal testing machine

Figure 3- 11: Eco-paver after failure in flexure

The relevant measurements and loads will be recorded and inputted to this formula to obtain the flexural strength. Further to the test on the standard paver, the flexural strength of pavers exposed to chemicals as in the chemical attack mentioned in Section 4.4.3 were tested. The method of testing was repeated for these samples after they had dried.

3.5.6. Compressive Strength Test

The Compressive Strength test is conducted as per IS 15658 (2006). This test was conducted on a cube cut from the paver. A compression testing machine (Figure 3-12) was used to conduct the experiment. Following the Indian standards, four samples were used, and the compressive strength were taken as the average of this. The dimensions of the samples were also recorded. The samples were placed in the machine and subjected to an applied load without shock which shall increase at a rate of 15 N/mm^2/min until failure was reached. Failure was considered as collapse or delamination of the sample. The maximum load was recorded.

Figure 3- 12: Universal UCS machine

To obtain the compressive strength from this load, the following calculation was used:

$$F_c = \frac{\text{Load (N)}}{\text{Plan area (mm}^2\text{)}}$$

Where:

- F_c = Compressive strength in N/mm^2
- Load = Maximum load in N
- Plan area = Area of face in contact with load

A correction factor was applied to the calculated compressive strength of the traditional pavers in accordance with the thickness of the paver. The relevant correction factors are presented in Table 3-3.

Table 3-3 Correlation factor for thickness of traditional paving block (IS 15658, 2006)

Paver thickness (mm)	Correction factor
50	0.96
60	1.0
70	1.12

The relevant measurements and loads were recorded and inputted to this formula to obtain the compressive strength. Further to the test on the standard paver, the compressive strength of pavers exposed to chemicals as in the chemical attack mentioned in Section 4.4.3 were determined. The method of testing was repeated once the samples were dried.

3.5.7. Permeability Testing

In-situ permeability was assessed following ASTM C1701 requirements. The paver was pre wet and thereafter had a single ring infiltrometer placed on it which was then filled with 1.2kg of water as in Figure 3-13. The penetration time was measured at 1 second intervals for 2 minutes by assessing the drop in water level inside the infiltrometer. The Infiltration rate was taken as the average of three samples.

Figure 3- 13: Single-ring Infiltrometer on paver

To obtain the infiltration, rate the following calculation was used:

$$I\ \left(\frac{mm}{h}\right) = \frac{K * M}{D^2 * T}$$

Where:

- I = Infiltration rate in mm/h
- M = Mass of infiltrated water
- D = inner diameter of the infiltration ring
- T = time in seconds
- K = Conversion coefficient (4,583,666,000 mm^3.s/(kg.h))

3.5.8. Heat Resistance

To assess the effect of temperature, an oven test was conducted. Samples were inserted into an oven which is set at a temperature of 40^{O}C and increased in increments of 20^{O}C up to a maximum temperature of 120^{O}C. The changes in surface conditions were noted at each increment as well as observations surrounding any melting that had occurred.

3.6. Statistical Analysis

The confidence interval statistical analysis approach was used for this research in order to handle and analyse the data received via the processes indicated above in a suitable way. The confidence interval, according to Newman & Choo (2003), is the interval within which the population value may lie with a certain probability, which they refer to as the confidence level. It was found that a 95% confidence criterion is generally used, even in the field of concrete technology as mentioned by Matalkah et al. (2018). This study used a 95% degree of confidence due to these considerations. A t-distribution analysis was employed for estimating the confidence interval since the sample size in this study is less than 30. Assuming X1, X2, X3…Xn are the results of a sample for a particular experiment, the confidence interval for the population mean, is given by the following expression:

$$\bar{x} \pm t(v;\, a) = \frac{S}{\sqrt{n}}$$

Where, $\bar{x}$ = Sample mean

- S = Sample standard deviation
- n = Number of samples
- v = Degrees of freedom; given as n – 1
- a = Significance level
- t (v; a) = Critical value

3.7. Limitations and Uncertainties

The limitations of the study are mainly due to the artisanal pilot case-study approach and were as follows:

- The study does not investigate the effect of different ratios of plastic to glass in the paver as the focus of the study was primarily to determine if the mix would produce a favourable composite material. This was because they were cast in an artisanal manner and the mix proportions that yielded a mixture fluid enough to pour into a mould were used. In addition, since the pavers were cast at an external facility which had the equipment to cast it, i.e., a blast furnace for the plastic, only a few samples were able to be cast during the period of access to the facility. This subsequently resulted in the ratio used to be fixed and kept consistent.
- The number of pavers were limited as the recycling depot was only able to manufacture a small quantity.
- The long-term effects of ultra-violet exposure was not investigated due to the unavailability of testing equipment and extensive cost of outsourcing to external labs.
- Limited time to conduct experiments due to the constraints of a deadline to submit the thesis. As a result, the long-term effects of the chemical attack could not be measured.

3.8. Chapter Summary

This chapter explored the methodological approach adopted by the author to achieve the outcomes. The qualitative approach followed to determine the types of parameters that require investigation and the standards to follow started the study. The identified properties to investigate were the moisture absorption, chemical resistance, temperature influence resistance, permeability, flexural strength, and compressive strength. Thereafter, the quantitative approach outlined the specific steps of assessing the pavers from the manufacturing process, through the sampling and experimental procedure, up till the analysis of the numerical and visual data. The manufacturing process outlines the fact that the study introduces a new concept and as such follows no specific standards for manufacturing. Following the methodology presented was deemed to be sufficient to meet the aims, objective and answer the research question as the procedure will provide insight on the strength, durability and environmental impact of the paver whilst simultaneously focusing on possible applications of the pavers.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Introduction

This chapter outlines the results achieved by following the methodology presented. The eco-pavers will be compared to concrete pavers where applicable. They will also be compared against the relevant standards and other pavers from past studies as identified in the literature. The results obtained will provide insight regarding the behaviour of the plastic pavers in the environment and any subsequent consequences. Based on their characteristics, areas of possible applications are identified and discussed.

4.2. Material Properties

The paver formed from the manufacturing process developed a black colour. This is likely a result of the heating and cooling process. The eco-pavers are heated and cooled within a chamber and as a result, the volatiles and additives that are present in the plastic, get released within the chamber and although the blast furnace from the manufacturing machines allows some of the particles to exit the chamber when they get excited through the increase in temperature, some may condense into the mixture during cooling, resulting in a change in appearance. The other contributor is the dye from the various plastics releasing and mixing upon heating and cooling.

The average density of the plastic paver was calculated to be 1450 kg/m3. The concrete paver samples have an average density of 2242 kg/m^3. Therefore, the plastic pavers are less dense than the concrete pavers. This difference is due to the difference in aggregate used in both pavers, the concrete pavers make use of stone aggregate which is significantly heavier than glass aggregate. Furthermore, plastics have less mass than concrete constituents and result in the eco-pavers being lighter than the concrete pavers. Although greater density usually implies greater strength and less voids/porosity, it is unlikely that this difference implies that the plastic pavers are more porous than concrete pavers. Figure 4-1 presents a microscopic image of the paver surface and illustrates the consolidation of the glass aggregate and plastic.

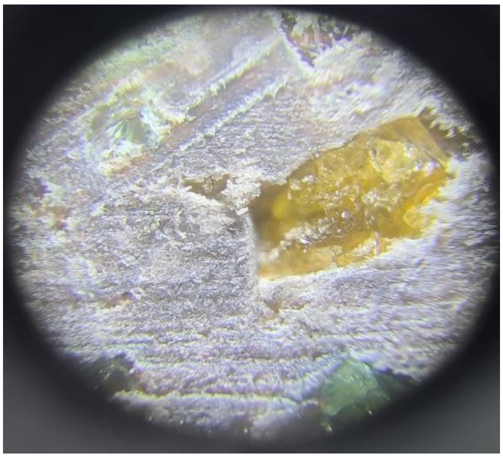

Figure 4- 1: Microscopic image of Eco-paver

4.3. Durability Assessment

4.3.1. Water Absorption

The average results of the moisture absorption tests yield an average absorption rate of 0,28%, with an upper interval of 0,35% and a lower interval of 0,21% with a 95% level of confidence. In comparison to the recommendation of the maximum rate of 6,5% according to SANS, and 5% in IS and ASTM standards, the plastic pavers are considerably lower. Furthermore, to ensure the validity of these results, the concrete paver samples that were immersed yielded a 4% rate of absorption over the same period which is generally the observed rate for traditional pavers. The results also indicate that the uptake primarily occurs within the first 24 hours and no further absorption takes place. The pavers also do not experience any swelling or surface defects from the immersion.

The findings of this experiment align well with those of Ingabire et al. (2018) and Gabriel et al. (2021) whose experiments both yielded water absorption below 0,01%. Robert et al. (2010) suggested that composite materials are affected directly by the degree of bonding and consolidation of molecules, and since the material in question is largely made of plastic, the properties of this material would directly affect the results. The literature also indicates that that HDPE and PP both have an average rate of absorption of 0.1%, and further to this, when the polymer chains bond, the molecules tend to consolidate closely, resulting in the overall low rate of absorption.

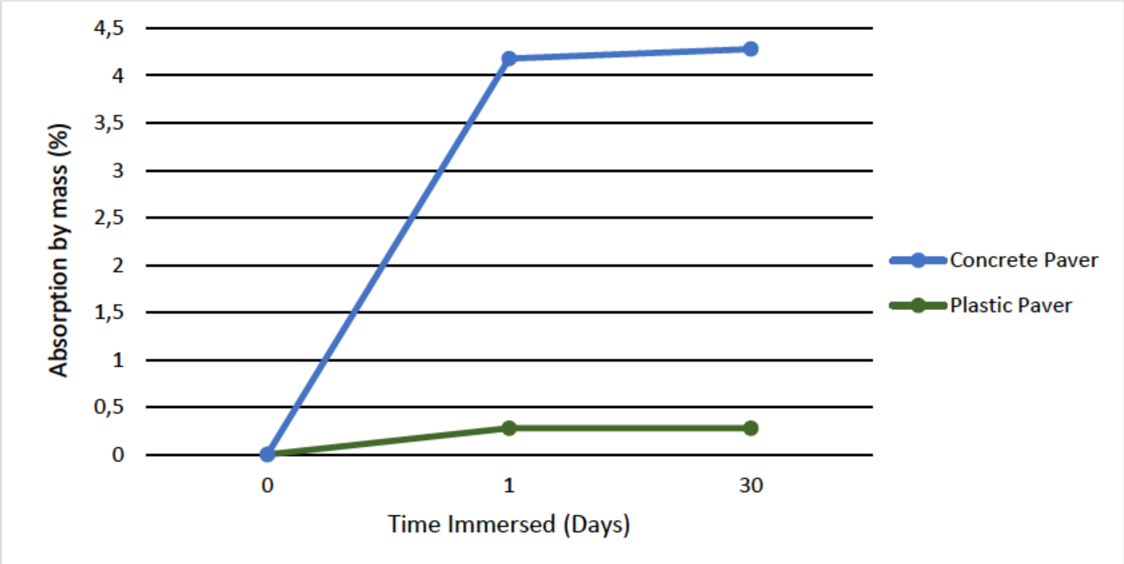

Figure 4- 2: Moisture absorption of eco-paver

4.3.2. Chemical Attack

The results of the immersion in various chemicals are found in Figure 4-3. Like the observations from the moisture absorption experiment, most of the absorption takes place within the first day of immersion. Over the 90-day period, the maximum absorption experienced by the pavers in each of the chemicals is as follows:

- Diesel - 0.35%
- Petrol - 0.36%
- Engine oil - 0.37%
- Acetone - 0.37%

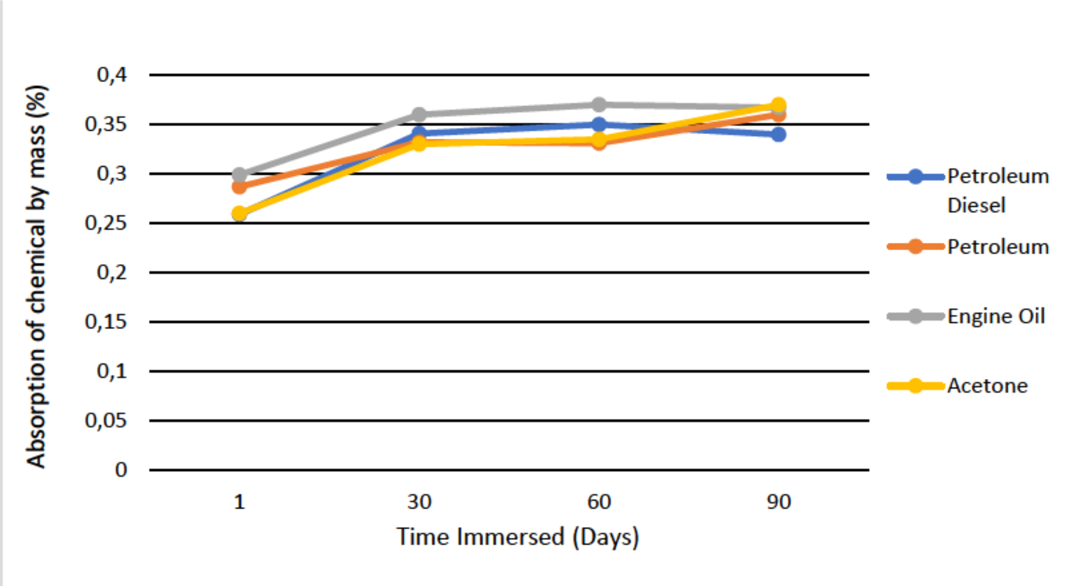

Figure 4- 3: Absorption of chemical during immersion tests

From observing the trend of the absorption rate over time, no definitive time related pattern is identifiable. The samples immersed in petrol shows an uptake up to day 30, thereafter the absorption rate drops at day 60 before increasing again. This likely can be attributed to the fact that the percentage absorption equates to roughly one gram of the average weight of the samples and could result from residual chemical on the surface at some point during weighing. This follows for the decrease observed in the Diesel sample at day 90 as well.

Upon inspection of all the samples after immersion at different periods, no visible effects were noticeable on either the surface finish or the exposed planes. This, therefore, suggests that the pavers exhibited strong resistance to the chemicals. Since plastic is known to take years before degradation occurs, the lack of mass loss or visible degradation may suggest that the pavers require a longer duration of immersion before it is degraded. In reality, the pavers are unlikely to be subjected to full immersion. Partial spills are more likely to occur and as such, degradation would likely be even slower. Therefore, they would likely be suitable in industrial environments in which they would be exposed to these chemicals.

4.3.3. Permeability

The experiment revealed that no infiltration occurred for the plastic paver, which aligns with the low rate of water absorption noted in Section 4.3.1. This falls below the ASTM C1701 standard of 868 mm/h required for classification as a permeable paver, confirming its impermeable nature. As a result, the paver's environmental applications are somewhat restricted. To mitigate potential surface runoff issues, the paver system may need to incorporate strategically designed joints or be combined with permeable materials or drainage solutions. In larger areas with high runoff, conventional drainage and attenuation systems might be necessary to manage surface runoff effectively, depending on the specific location. These pavers are best suited for pedestrian areas, such as footpaths and residential driveways.

4.3.4. Heat Resistance

The paver observed no changes in appearance or mass when heated to 40^{O}C, 60^{O}C, 80^{O}C, 100^{O}C and 120^{O}C. The melting temperature was not found to fall within the range of temperatures assessed during the experiment. The primary reason that greater temperatures were not considered was that the most probable maximum temperature to which the pavers would be exposed to is 120^{O}C. Temperatures in the environment are unlikely to surpass the considered range unless there is a fire, in which case temperatures would likely be considerably higher. However, the application of these pavers is for outdoor use and as such, would be unlikely to be subjected to degradation through fire exposure. The behaviour of the paver aligns with the information found in the literature pertaining to the melting point of plastics which can be expected to be greater than 200^{O}C. Therefore, the manufacturing process does not noticeably impact the plastics known melting point.

4.4. Mechanical Strength

4.4.1. Flexural Strength

The results from the flexural strength test of the paver are first discussed and thereafter used as a control to compare the flexural strengths of samples that had undergone chemical attack.

4.4.1.1. Control

The Eco-Pavers are observed to have an average flexural strength of 7,9 MPa with a lower confidence interval of 7,74 MPa. The recommended minimum according to SANS 541 (2012) is 5 MPa. It is, therefore, determined that these pavers surpass the minimum criterion by 54.8% when considering SANS. When assessing the plane of failure, it was observed that all of the pavers failed at the middle of the sample, which is an indication that the load was uniformly applied, and edge effects may not have influenced the results. If edge effect did influence the results, since the entire paver is made of a uniform material, edge effects would generally decrease the observed results. This would still indicate that the pavers compare favourably to the concrete pavers and other literature.

When working with the flexural strength, the load at failure is referred to as the breaking load, measured in kN. According to IS 15658 (2006), the minimum criterion for the breaking load varies according to application and a comparison of the breaking load of the Eco-pavers (11,89 kN) to the IS 15658 (2006) are illustrated in Figure 4-4. In conformance with these standards, the pavers are suitable in any application.

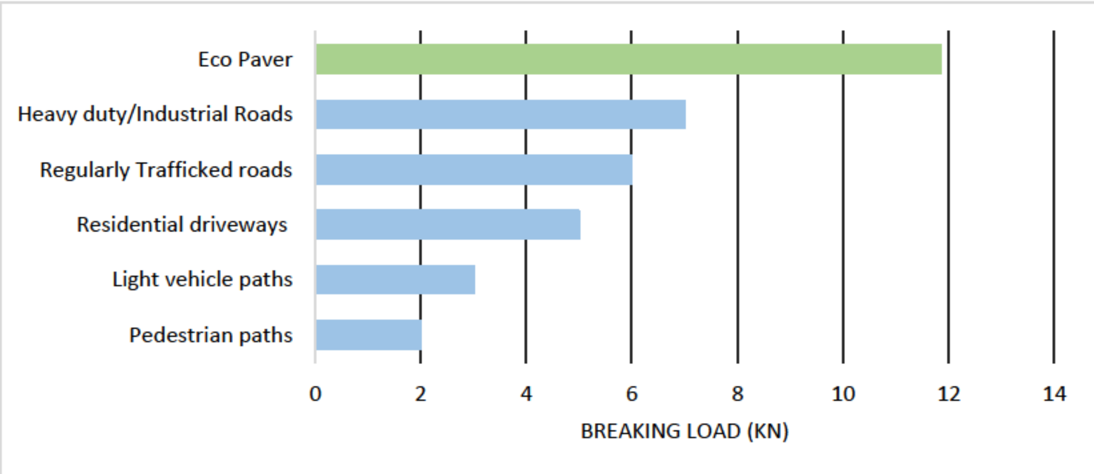

Figure 4- 4: Comparison of minimum breaking load requirements to eco-paver (IS 15658, 2006)

The concrete paver exhibited an average Flexural Strength of 8,04 MPa with a lower confidence interval of 7,91 MPa to which the Eco paver compares favourably. Comparing the

Eco-paver to the PET paver assessed by Ryu et al. (2020), it exhibits greater potential as the average strength is 54,6% greater. However, these pavers were assessed using different standards and methods and this could be the reason for the large difference. Another contributing factor is likely the difference in aggregates used and quantity thereof. The PET paver contained a 7.5% PET to aggregate mass ratio whilst the Eco-pavers used a 50/50 composition of HDPE/PP to glass aggregate ratio. However, due to the variance in testing methods, no definitive conclusions can be made. It is noted that during the application of load, no visible deformation occurred prior to failure. The paver, therefore, exhibited high levels of stiffness which is in line with the high modulus of elasticity of HDPE.

Additional samples which had not undergone adequate mixing during the manufacturing process were also assessed to determine if the degree of distribution of the aggregate would influence the results. These samples, after failure, were observed to have lower flexural strengths with an average of 3,04 MPa, showing a 61,52% decrease from the control. The cross-section along the plane of failure of these samples also indicates that the aggregate consolidates primarily on the lower half of the paver. Therefore, the mixing process is vital in ensuring the even distribution of the aggregate and adequate performance of the Eco-paver in flexure. This also suggests that the arrangement of the glass aggregate contributes to the mechanical properties of the composite.

4.4.1.2. Chemical Influence on Flexural Strength

The results obtained from testing the samples immersed in various chemicals can be found in Table 4-1. The immersed samples displayed no considerable loss in flexural strength. The delta value (**Δ**) indicates the variance of the result in comparison to the control sample and, in this experiment, indicates that the samples do not vary to a large extent from the control sample. Although the immersed samples do appear to have slightly lower flexural strengths than the control sample, this can be attributed to minor differences in the glass arrangement within the pavers from the manufacturing process as opposed to degradation through chemical immersion. The confidence interval also offers insight into the accuracy of the results and represents the range within which the average flexural strength of the population likely resides in and is stated with a 95% confidence. From these results, it is observed that the ranges are relatively small indicating that the averages obtained are a true reflection of the population.

These results align with those in Section 4.3.2 regarding the effect of chemicals on the Eco-paver.

Table 4- 1: Results obtained from flexural tests.

			Confidence interval	
Substance	Average Flexural strength (MPa)	Δ(MPa)	Lower (MPa)	Upper (MPa)
Control	7,90	-	7,74	8,06
Concrete	8,04	0,13	7,91	8,16
Engine oil	7,85	-0,06	7,65	8,04
Diesel	7,80	-0,1	7,24	8,37

4.4.2. Compressive Strength

The results from the compressive strength test of the paver are first discussed and thereafter used as a control to compare the compressive strengths of samples that had undergone chemical attack.

4.4.2.1. Control

The Eco-paver observed an average compressive strength of 12,47 MPa, with a confidence interval of 4 MPa as seen in Figure 4-4 below. The large confidence interval suggests that the results obtained may not represent the population mean for the paver samples. The large variance stems from the process of preparing and sampling the pavers. The samples used for this experiment were extracted from a whole paver. This consequently results in varying amounts of glass aggregate per sample and, therefore, additional samples were tested to account for this.

It was observed that the samples which failed at lower strengths appeared to contain significantly more glass aggregate than those that failed under higher loads. Therefore, the samples' strength dependency on the glass aggregate is acknowledged and it is noted that higher quantities of glass possibly reduce the compressive resistance of the material. A possible reason for this likely resides in a study by Ling and Poon (2014) as the authors noticed a decline in compressive strength as the glass quantity was increased in the cement-glass composite pavers. Their analysis of the crushed samples indicated that loss of bonding was the cause, and it was due to the smooth surface of the glass aggregate. Due to the bonding being a limiting factor, the glass properties and compressive resistance thereof likely have little to no positive contribution to the compressive resistance of the paver. The limitation of the degree of bonding is also common in concrete pavers when considering the interfacial transition zone (ITZ), which is generally considered the weak point in a concrete mix, however since the composite plastic paver is non-porous, the effect of the ITZ does not factor in.

The results obtained in this study also suggest that the addition of glass aggregates hinders the potential strength of the plastic. This suggestion is supported by the results obtained by Gabriel et al. (2021), as the author noted significantly higher compressive strengths (42 MPa) under the same environmental conditions for a paver comprising solely of plastic. However, it would be useful to control the proportion of plastic and glass in each specific sample and determine what the optimum ratio is to get an accurate depiction of the relationship between their proportions and the resulting strengths.

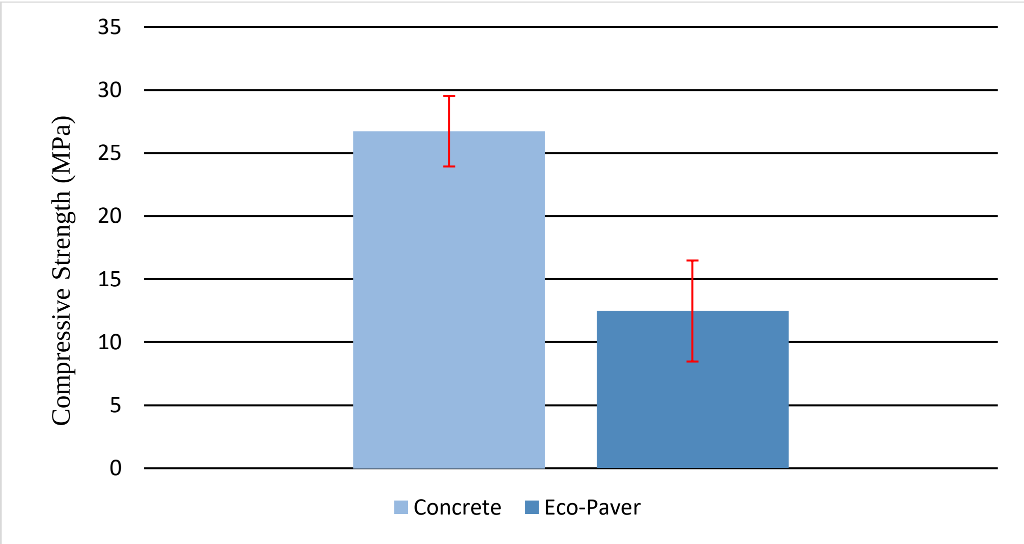

Figure 4- 5: Comparison of compressive strengths

The compressive strength of the Eco-pavers is subpar as they do not meet the minimum recommended strength from SANS 1058:2009 of 25 MPa. It is important to note that results from both Salvi et al. (2020) and Thiam and Fall (2021) observed compressive strengths that were also below the recommended standards when plastics are included in the mix design. Although the samples in their studies contained a mix of plastic and sand, the results in this study correlate well with their findings.

4.4.2.2. Chemical Influence on Compressive Strength

The immersed samples displayed the same compressive strengths as the control, with no notable changes as seen in Table 4-2. Therefore, it is noted that the chemicals have little to no effect on the pavers and have no induced any degradation during the period of immersion. It is likely because the degradation of plastic generally takes many years before occurring.

Table 4- 2: Results obtained from compression tests

			Confidence interval	
Substance	Average Compressive strength (MPa)	Δ (MPa)	Lower (MPa)	Upper (MPa)
Control	12,85	-	9,98	15,73
Petrol	13,11	0,26	10,97	15,26
Engine oil	13,53	0,68	9,12	17,95
Diesel	12,90	0,04	9,47	16,33

4.5. Possible Applications Based on Properties

The suitability of the pavers for various applications depends on the properties discussed in this chapter. Given their low moisture absorption rate and inability to infiltrate water, these pavers should be considered impermeable rather than permeable. As a result, they may not directly contribute to drainage improvements in areas with high volumes of run-off. However, Eco-pavers can still be employed to direct run-off by utilizing strategic placement along cracks, joints, or slopes towards drains. Although the Eco-pavers themselves are impermeable, they could be integrated into a larger permeable pavement system by combining them with permeable materials or strategically designing the layout to direct runoff to permeable areas or drainage systems. This could help address stormwater management concerns in urban environments.

Impermeable pavers are typically appropriate for footpaths, residential driveways, and bicycle tracks, but not for high traffic or heavy load traffic areas. This is supported by the compressive strength tests, where the pavers failed under 12.85 MPa of stress, despite exhibiting acceptable performance in flexure. The Eco-pavers may also find applications outside of South Africa, particularly in warmer climates, as their high thermal resistivity suggests that increased temperatures will likely have no significant impact on their performance.

4.6. Environmental Implications

A large concern of using plastic composites in the environment is the possible release of microplastics. As identified in Chapter 2, the degradation of plastics is the primary reason for this occurrence. For the purposes of this thesis, assessing the different mechanisms of abiotic degradation assists in understanding the environmental implications of it its use. From the results obtained, the following observations are made:

- With respect to thermal degradation, the temperatures under which the samples were tested reflected no change in appearance or mass. As Kotoyori (1972) suggested, the pavers may only observe changes at temperatures over 200^0C. Since these temperatures are unlikely to occur naturally in the intended environment of application, the pavers will likely not release microplastics as a direct result of this mechanism. According to the literature, it is possible that pavers subjected to adverse temperatures over a long period of time in conjunction with UV exposure could degrade. However, no conclusions surrounding this can be made as the effect of photodegradation was unable to be determined in this thesis.
- Mechanical degradation is another important mechanism to consider. The results from the mechanical strength tests indicate that under loads that induce flexure, the pavers

will not be compromised as they are able to withstand adequate loading before failure and therefore are unlikely to release microplastics. However, the compressive resistance is not adequate, and the pavers would fragment under loads greater than 12 MPa. This would result in plastic material releasing into the environment and the creation of microplastics.

- Chemical degradation, as suggested by the literature, influences the preceding mechanisms. During the chemical immersion, the pavers exhibited no signs of degradation. Furthermore, during the strength assessment of the samples exposed to various chemicals, no change in strength was observed when compared to the control sample. Therefore, exposure to these chemicals is unlikely to cause degradation in the short term, however the long-term effects are yet to be determined. Therefore, microplastics are unlikely to be released because of the chemicals to which the pavers are likely to be exposed to.

4.7. Summary of Results

The Eco-paver's properties conformed with the relevant standards to which concrete pavers must adhere in most instances except for compressive strength. This was observed to be due to the amount of glass aggregate in the pavers. The findings from the results of each experiment are presented in the sections below.

4.7.1. Moisture Absorption

- The results indicate that the rate of moisture absorption of the recycled pavers was significantly lower than maximum set standards, with an average rate of 0.28%.
- Concrete pavers exhibited an absorption rate of 4%, which aligns with the general concrete paver rate of absorption identified in Section 2.5.1. of the thesis.
- This aligns with the general absorption rate of plastic and suggests that the formation of the composite material contains minimal voids.
- No visible swelling occurred.

4.7.2. Permeability

- The results of an infiltration test suggest that no infiltration takes place.
- The pavers would be more suitable for use in applications that require impermeable surfaces, while being strategically combined with permeable materials or drainage designs to support stormwater management.
- These results are supported by the low rate of water absorption.

4.7.3. Heat Resistance

- Plastic pavers did not experience any deformation or degradation during heat exposure up to temperatures of 120^{O}C.
- It is unlikely for environmental temperatures to surpass this.

4.7.4. Flexural Strength

- The recycled concrete pavers exhibit a flexural strength of 7.9 MPa which surpasses the minimum standards set by SANS by 58%.
- The flexural strength may be influenced by the degree of mixing during the manufacturing process as the glass aggregate from pavers with poor mixing methods consolidated at the lower half of the paver and resulted in average strengths of 3.04 MPa.
- This also suggests that the paver derives some of its strength from the inclusion of the glass aggregate, or that the glass aggregate is the limiting variable.

4.7.5. Compressive Strength

- The results of the experiment reflect an average compressive strength of 12,47 MPa, however presents a large confidence interval of 4 MPa. This suggests that the experiment would benefit from a larger sample size. The amount of variability observed in the compression tests on the eco-pavers in a small sample suggests that there is a large variation in the material properties of this type of paver.

- This was perhaps a result of the varying quantity of glass in each paver since the samples were parts of a whole paver.
- The samples which exhibited lower strengths were observed to have higher quantities of glass present in comparison to others. This decrease in strength was suggested to be a result of loss of bonding between the plastic and glass aggregate and was identified in other studies from the literature.
- The samples did not meet the minimum recommended standards of 25 MPa and were also weaker than the concrete pavers which had average strengths of 27 MPa.

4.7.6. Resistance to Chemical Attack

- The pavers experienced similar mechanism of absorption when immersed in chemicals as when immersed in water. The rates of absorption were 0.35%, 0.36%, 0,37% and 0,37% for the samples immersed in diesel, petrol, engine oil and acetone respectively.
- This suggests that the degree of penetration through voids is limited and that the most susceptible plane on the paver is the surface.
- No loss of mass is reported after drying for a period of 7 days in direct sunlight.
- A visual inspection indicated no defects or surface degradation.
- This aligned with known characteristics of plastic and its subsequent resistance to these chemicals.
- The chemicals also had no effect on the flexural or compressive strengths of the pavers.

CHAPTER FIVE: CONCLUSION

5.1. Introduction

This chapter concludes the study by providing a summary of the key research findings in relation to the aims and objectives outlined in Chapter One. Further to this, the value and contribution of the work found in this thesis will be stated. It will lastly propose opportunities for further research and provide an overall conclusion of the thesis.

5.2. Overall Findings and Conclusions

This study aimed to investigate the implications of using recycled plastic and glass material as a full replacement for concrete in pavements. Samples of pavers were cast from a mix of plastic and crushed glass and subjected to experimentation in accordance with the methods outlined in Chapter Three. A concrete mix design was conducted to cast concrete pavers in accordance with standards such that comparisons can be drawn between traditional and recycled pavers, along with the reference to relevant research.

The Eco-pavers, made of glass and plastics, exhibited significantly lower rates of water absorption than the concrete pavers and conformed with the standards. They also displayed no infiltration during experimentation and this, in conjunction with the low rate of water absorption, indicated that the plastic consolidates closely with the glass aggregate, resulting in minimal pores within the structure. This was further observed during the chemical immersion tests where the chemical absorption rate was low and in line with the rate of water absorption. This indicated that there was minimal penetration of the chemical. The immersed samples did not display any signs of degradation either through mass loss or surface distortion in this study.

The Eco-pavers did not display any change in surface condition when exposed to temperatures up to 120^{O}C which suggest that the pavers would be suitable in most regions with warm – high temperatures. The flexural strength of the Eco-pavers was 58% higher than that of the concrete pavers, however, the compressive strength averaged at 12 MPa, which is less than 50% of the recommended minimum, which suggests that these pavers are not suitable for areas with heavy traffic. However, the results for the compressive strength may not fully represent the population average due to the large variance and as such further investigation into this property would be required.

The results indicate that the Eco-pavers are theoretically durable enough not to degrade in the environment unless subjected to compressive forces of 12 MPa or greater. Since most of the degradation mechanisms investigated in this study indicate that the pavers will not degrade or release microplastics, it is assumed that these pavers would likely not be harmful to the environment if used in footpaths or light traffic areas.

5.3. Research Outputs

5.3.1. Completion of Objectives

The objectives, as stated in Section 1.4.2, were met as follows:

(A) "As part of a comprehensive literature review, document the relevant properties and characteristics of pavers as well as plastic and glass material and identify any environmental concerns surrounding the use of plastic in the environment"

Chapter Two presents a literature which investigates the various characteristics of pavers (Section 2.4). In addition to this, Section 2.5 outlines the findings from other studies in relation to the relevant performance measures. Plastic is discussed extensively in Sections 2.8.1 and 2.8.2 with the possible degradation mechanisms discussed in Section 2.8.3 which investigates environmental impacts. The properties associated with glass material is outlined in Section 2.9.

(B) Investigate the strength and durability properties of the pavers.

Chapter Three contains the methodology which was followed to achieve this objective. The results in Section 4.3 outline the durability properties of the pavers and Section 4.4 present the results of the strength assessments. It was found that the pavers have adequate durability properties with respect to water absorption, chemical resistance temperature resilience and permeability. The flexural strength is considerably higher than its concrete counterpart, however, the pavers exhibit poor compressive strengths.

(C) Use knowledge gained from the literature review to analyse all sets of results and compare them with the control (conventional) paver to explain its viability and environmental consequences.

Sections 4.2 to 4.4. delve into the results obtained and compare them to findings from the literature which include past studies and relevant standards. Concrete pavers were cast to ensure the results obtained were accurate and to draw comparisons. The environmental consequences were derived through analysing the different degradation mechanisms that were assessed and determining the impact they have on the paver. It was found that the pavers would likely only pose a threat to the environment when subjected to compressive loads. This would result in failure and subsequently the possible release of microplastics.

5.3.2. Response to Research Questions

The findings from this thesis allow for the following points to be made:

- In this study, the plastic pavers demonstrated impressive durability characteristics, making them well-suited for a range of applications. Although they have a low rate of moisture absorption and are impermeable, their properties can be leveraged through strategic integration with permeable materials or drainage designs. This approach allows the pavers to contribute to stormwater management while providing a durable and sustainable solution for various construction projects, such as footpaths, residential driveways, and bicycle tracks..
- They are unlikely to be degraded by chemical attack in the short term which would ensure that they would not harm the environment if used.
- Under loads that induce flexure, they perform better in comparison to concrete pavers and surpass the required minimum standards for any application.

- They fail to meet the minimum requirement in terms of compressive strength and would require further research into this property and the surrounding factors before the paver can be deemed feasible as a whole.
- The paver is likely to release microplastics if subjected to compressive loads greater than 12 MPa as the material would fail and degrade.

5.4 Recommendations for Further Research

The thesis could be enhanced in the following ways:

- Due to budget and time constraints, the resistance to UV exposure was unable to be determined. Investigation into this would be beneficial in assessing whether UV would illicit degradation and subsequently impact other mechanisms of degradation.
- Since the number of pavers was limited for this thesis, it might be advisable to cast additional Eco-pavers with controlled portions of glass aggregate for additional compression tests to be conducted. This would provide better insight into the compressive strength of the Eco-pavers.
- Conducting the study over a longer period to assess the long-term effects of chemical attack on the Eco-pavers. In addition, a microscopic analysis can be conducted to assess any microscopic signs of degradation.

The following related topics may warrant potential avenues of research:

- An investigation into the relationship between glass aggregate content and plastic in a recycled plastic-glass composite paver.
- An investigation into the influence of varying recycled plastic material on a plastic paver.
- The development of a sustainability model which must include a life-cycle assessment and an economic analysis.
- The development of SANS-approved specifications for the manufacturing and testing of plastic and crushed glass composites for application in construction

5.5. Conclusion

Managing plastic and glass waste is an increasingly important environmental concern. It was observed that there are several studies published surrounding the implementation of waste material in the engineering space and this thesis contributes to that pool of knowledge, filling in the gap of information surrounding a composite material comprising of waste plastic and crushed glass aggregates. The results in this thesis indicate the strong possibility that these materials have good potential for use as pavers. They may even offer properties superior to that of concrete in some instances and further research is required to recognize its full potential and limitations.

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APPENDICES

Appendix A: Moisture Absorption

	Mass (g)		
Eco-paver Samples	Before immersion	1 day	30 days
1	624	625	625
2	612	613,1	613,1
3	589,7	590,97	590,97
4	606,4	608,5	608,5
5	541,2	543,5	543,5
6	615,5	616,6	616,6
7	606,1	607,2	607,2
8	614,8	615,9	615,9
9	538,4	540,2	540,2
10	568,1	570,5	570,5
11	568,8	570,6	570,6
12	580,7	583	583
Avg	588,8083333	590,4225	590,4225

		Mass (g)	
Concrete Sample	Before immersion	1 day	30 days
1	624	648,96	675,57
2	612	635,26	660,67
3	650	675,35	701,69
Average	628,67	3,9	4

	% Mass change		
Eco -paver Sample Number	Before immersion	1 day	30 days
1	0	0,160256	0,160256
2	0	0,179739	0,179739
3	0	0,215364	0,215364
4	0	0,346306	0,346306
5	0	0,424982	0,424982
6	0	0,178716	0,178716
7	0	0,181488	0,181488
8	0	0,17892	0,17892
9	0	0,334324	0,334324
10	0	0,422461	0,422461
12	0	0,396074	0,396074
Avg	0	0,277924	0,277924

		% Mass change	
Concrete Sample	Before immersion	1 day	30 days
1	0	4	4,1
2	0	3,8	4
3	0	3,9	3,9
	0	3,9	4

Appendix B: Chemical Attack

Raw data

Diesel			Mass (g)			
Sample	Before immersion	1 day	30 days	60 days	90 days	After drying
1	552,2	553,80	554,08	554,41	554,08	552,52
2	558,6	559,66	560,47	560,16	560,78	559,10
3	624	625,87	626,18	625,56	625,93	624,83
4	596,7	598,31	598,85	599,21	598,37	596,85
5	598,9	600,40	600,94	600,58	601,00	599,79
6	618,6	620,20	620,78	620,77	621,38	619,10
7	654,4	656,17	656,64	657,15	656,36	654,49
8	588,5	590,02	590,21	590,74	590,38	589,82
9	580,3	582,10	582,45	582,33	582,62	582,07
10	541,7	543,22	543,55	543,43	543,43	543,65
11	520,4	521,75	522,14	523,42	521,86	522,72
12	586,9	588,07	588,89	588,19	588,90	587,22

Petrol			Mass (g)			
Sample	Before immersion	1 day	30 days	60 days	90 days	After Drying
1	606,10	607,74	608,18	608,65	607,80	606,19
2	614,80	616,39	616,58	617,14	617,01	616,12
3	538,40	540,07	540,39	540,28	540,55	540,17
4	568,10	569,69	570,04	569,92	570,32	570,05
5	568,80	570,27	570,71	572,10	570,79	571,12
6	580,70	581,86	582,67	581,98	583,14	581,02
7	624,00	625,81	626,13	626,50	626,37	624,32
8	612,00	613,16	614,05	613,71	614,39	612,5
9	589,70	591,47	591,76	591,17	591,53	590,53
10	606,40	608,04	608,58	608,95	608,28	606,55
11	541,20	542,55	543,05	542,72	542,82	542,09
12	615,50	617,09	617,67	617,65	618,09	616

Engine oil			**Mass (g)**			
Sample	Before immersion	1 day	30 days	60 days	90 days	After drying
1	644	645,87	646,20	645,61	646,58	645,30
2	558,4	560,35	560,27	559,96	559,96	559,70
3	526,1	527,68	527,99	527,31	527,31	527,35
4	554,7	556,20	556,70	556,86	557,03	556,00
5	554,9	556,51	556,79	556,45	556,45	556,70
6	600,8	602,36	602,91	602,78	602,90	602,10
7	572,5	574,50	574,49	575,13	574,90	574,40
8	533,7	535,14	535,25	535,73	535,73	535,30
9	524,5	526,13	526,60	526,97	526,55	525,80
10	544,5	546,02	546,95	546,30	546,41	545,80
11	556,5	557,94	558,36	559,73	559,73	557,80
12	591,1	592,87	593,41	593,17	593,46	593,00

Acetone			**Mass (g)**			
Sample	Before immersion	1 day	30 days	60 days	90 days	After drying
1	570	571,54	571,94	572,00	571,94	570,32
2	536,3	537,48	537,91	537,80	538,39	536,93
3	612,5	614,34	614,52	614,03	614,89	614,33
4	578,6	579,93	580,68	581,03	580,22	578,82
5	601,3	602,92	603,35	602,80	603,40	602,19
6	599,6	601,10	601,58	601,70	602,30	600,95
7	518,7	520,52	520,48	520,88	520,26	518,79
8	608,6	610,12	610,36	610,43	610,85	609,92
9	590,6	592,31	592,67	592,67	593,26	592,37
10	558,6	559,88	560,50	560,28	560,39	560,55
11	540,23	541,42	542,04	543,36	542,50	542,15
12	582,6	583,77	584,58	583,88	584,58	582,92

Calculated Values

Diesel	% Mass change					
Sample	Before immersion	1 day	30 days	60 days	90 days	After drying
1	0	0,29	0,341	0,4	0,34	0,057782
2	0	0,19	0,335	0,28	0,39	0,08934
3	0	0,3	0,35	0,25	0,31	0,132615
4	0	0,27	0,36	0,42	0,28	0,025071
5	0	0,25	0,341	0,28	0,35	0,148235
6	0	0,259	0,352	0,35	0,45	0,080619
7	0	0,27	0,343	0,42	0,3	0,013716
8	0	0,259	0,29	0,38	0,32	0,22372
9	0	0,31	0,37	0,35	0,4	0,304072
10	0	0,28	0,341	0,32	0,32	0,358973
11	0	0,259	0,335	0,58	0,28	0,444659
12	0	0,2	0,339	0,22	0,34	0,054415
Avg	0,00	0,26	0,34	0,35	0,34	0,16

Petrol	% Mass change					
Sample	Before immersion	1 day	30 days	60 days	90 days	After Drying
1	0	0,27	0,34	0,42	0,28	0,01
2	0	0,26	0,29	0,38	0,36	0,21
3	0	0,31	0,37	0,35	0,40	0,33
4	0	0,28	0,34	0,32	0,39	0,34
5	0	0,26	0,34	0,58	0,35	0,41
6	0	0,20	0,34	0,22	0,42	0,41
7	0	0,29	0,34	0,40	0,38	0,05
8	0	0,19	0,34	0,28	0,39	0,08
9	0	0,30	0,35	0,25	0,31	0,14
10	0	0,27	0,36	0,42	0,31	0,02
11	0	0,25	0,34	0,28	0,30	0,16
12	0	0,26	0,35	0,35	0,42	0,08
Avg	0	0,26	0,34	0,35	0,35	0,19

Engine oil	% Mass change					
Sample	Before immersion	1 day	30 days	60 days	90 days	After drying
1	0	0,29	0,34	0,25	0,40	0,20
2	0	0,35	0,33	0,28	0,28	0,23
3	0	0,30	0,36	0,23	0,23	0,24
4	0	0,27	0,36	0,39	0,42	0,23
5	0	0,29	0,34	0,28	0,28	0,32
6	0	0,26	0,35	0,33	0,35	0,32
7	0	0,35	0,35	0,46	0,42	0,33
8	0	0,27	0,29	0,38	0,38	0,30
9	0	0,31	0,40	0,47	0,39	0,25
10	0	0,28	0,45	0,33	0,35	0,24
11	0	0,26	0,34	0,58	0,58	0,23
12	0	0,30	0,39	0,35	0,40	0,32
Avg	0	0,29	0,36	0,36	0,37	0,27

Acetone	% Mass change					
Sample	Before immersion	1 day	30 days	60 days	90 days	After drying
1	0	0,27	0,341	0,35	0,34	0,06
2	0	0,22	0,3	0,28	0,39	0,12
3	0	0,3	0,33	0,25	0,39	0,30
4	0	0,23	0,36	0,42	0,28	0,04
5	0	0,27	0,341	0,25	0,35	0,15
6	0	0,25	0,33	0,35	0,45	0,22
7	0	0,35	0,343	0,42	0,3	0,02
8	0	0,25	0,29	0,3	0,37	0,22
9	0	0,29	0,35	0,35	0,45	0,30
10	0	0,23	0,341	0,3	0,32	0,35
11	0	0,22	0,335	0,58	0,42	0,35
12	0	0,2	0,339	0,22	0,34	0,05
Avg	0,00	0,26	0,33	0,34	0,37	0,18

Appendix C: Flexural Strength Test

Raw Data

Sample Type	Sample Number	Breaking Load (N)	Length (cm)	Breadth (cm)	Depth (cm)
Control	1	12000	450	500	45
	2	11700	450	500	45
	3	11980	450	500	45
	4	11740	450	500	45
Concrete	1	19470	500	500	60
	2	19020	500	500	60
	3	19410	500	500	60
	4	19240	500	500	60
Engine oil	1	11740	450	500	45
	2	11840	450	500	45
	3	11620	450	500	45
	4	11880	450	500	45
Diesel	1	11540	450	500	45
	2	11770	450	500	45
	3	11970	450	500	45
	4	11540	450	500	45

Calculated Values

Sample Type	Sample Number	Fb (MPa)	Mean (MPa)	(fb-mean)^2		SD	SE	Confidence interval	Lower (MPa)	Upper (MPa)
Control	1	8,00		0,0093						
	2	7,80		0,0107						
	3	7,99		0,0069						
	4	7,83	7,903333	0,0059	0,0641	0,0227	0,067916	0,160622	7,742711808	8,063955
Concrete	1	8,11		0,0059						
	2	7,93		0,0122						
	3	8,09		0,0027						
	4	8,02	8,035417	0,0004	0,0515	0,0182	0,054562	0,129039	7,906378146	8,164455
Engine oil	1	7,83		0,0004						
	2	7,89		0,0022						
	3	7,75		0,0100						
	4	7,92	7,846667	0,0054	0,0474	0,0274	0,082002	0,193935	7,652731496	8,040602
Diesel	1	7,69		0,0121						
	2	7,85		0,0019						
	3	7,98		0,0312						
	4	7,69	7,803333	0,0121	0,1382	0,0798	0,239191	0,565688	7,237645656	8,369021

Appendix D: Compressive Strength Test

Raw Data

Sample type	Sample Number	Load at Break (KN)	Length (cm)	Width (cm)	Height (cm)
Control	1	114,6	13,6	6,5	4,6
	2	85	14	7	4
	3	127	14	6,6	3,6
	4	132	14	6,5	4,5
Petrol	1	114,6	14	6,5	4,2
	2	100	13,5	6,5	5,2
	3	127	14	6,5	3,7
	4	132	14	6,5	5
Engine oil	1	114,6	13,5	6	4,2
	2	100	14	6,5	5
	3	127	14	6,5	3
	4	132	13,5	6,5	4,4
Diesel	1	114,6	14	7	4,5
	2	132	14	7	5
	3	127	14	7	5,5
	4	132	14	7	4
Concrete	1	592,36	15	15	15
	2	588,95	15	15	15
	3	623,19	15	15	15

Calculated values

	Sample Number	Fb (MPa)	Mean (MPa)	(fb-mean)^2		SD	SE	Confidence interval	Lower (MPa)	Upper (Mpa)
Eco-Paver	1	12,96		0,24						
	2	8,67		14,43						
	3	13,74		1,62						
	4	14,51	12,47	4,14	1,60	0,56	1,69	4,01	8,47	16,48
Petrol	1	12,59		0,27						
	2	11,40		2,95						
	3	13,96		0,71						
	4	14,51	13,11	1,94	0,86	0,30	0,91	2,15	10,97	15,26
Engine oil	1	14,15		0,38						
	2	10,99		6,48						
	3	13,96		0,18						
	4	15,04	13,53	2,28	1,08	0,62	1,87	4,42	9,12	17,95
Diesel	1	11,69		1,45						
	2	13,47		0,33						
	3	12,96		0,00						
	4	13,47	12,90	0,33	0,84	0,48	1,45	3,43	9,47	16,33
Concrete	1	26,33		0,17						
	2	26,18		0,31						
	3	27,70	26,73	0,93	0,68	0,40	1,18	2,80	23,93	29,54