PARTIAL REPLACEMENT OF COARSE AGGREGATES WITH PLASTIC POLYURETHANE (PPU) COATED VOLCANIC TUFF AS A LIGHTWEIGHT STRUCTURAL CONCRETE

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ABSTRACT

In this research, the applicability of plastic-polyurethane (PPU) coated volcanic tuff mixed with shredded PET plastics, as a partial substitute of traditional coarse aggregates in C25 structural concrete, was studied. It is about the necessity of low-density structural materials of Uganda and the shortage of volcanic tuff, which is naturally porous and therefore mechanically weak. It was tested using aggregate characterization and concrete testing with 0, 10, 20, and 30 percent replacement levels by the BS EN and ASTM standards.

PU coating made volcanic tuff much less absorptive and enhanced the integrity of the aggregate, yet the composite was still more porous than crushed rock. The higher the replacement the lower was the workability; hardened density declined by 3-12 percent, which is evidence of effective dead-load reduction. The rate of water absorption rose to an average extent, which is a characteristic of the microstructure of the composite. The results of compressive strength revealed that 10 percent replacement attained comparable strength at 28 days as the control mix and C25 requirements, but increased replacement percentages resulted in a gradual decline in strength.

DECLARATION

I, the undersigned, Mr. MWESIGWA ENOSON KALEMA, solemnly declare that this research report is completely based on my work and research carried out. I assert that the statements made and the conclusions drawn are outcomes of my research work and therefore, further certify that the work has not been submitted for any other Award in this university or elsewhere, and it is mine and its original for the partial fulfillment of the Bachelor's Degree in Civil and Environmental Engineering of Uganda Christian University.

NAME: MWESIGWA ENOSON KALEMA

REG NO.: M22B32/027

SIGNATURE: …………………………………………

DATE: …………………………………………….

APPROVAL

This is to clarify that this report is entirely for MWESIGWA ENOSON KALEMA, Registration number: M22B32/027 and I fully accept that he is under my supervision and so has submitted his proposal report to the Faculty of Engineering, Design and Technology in partial fulfilment for the Award of a Bachelor's Degree in Civil and Environmental Engineering at Uganda Christian University.

Signature: …………………………….

Date: ………………………………….

Name: DR. ENG. MORRIS OLENG

The Research Supervisor

DEDICATION

I continue to dedicate all my academic reports, including this one to all upcoming civil engineers in this new era of third world countries like Uganda as we continue to be one of the main careers stirring the developmental phase of this country to the greater heights that we can all achieve. I further want to dedicate this report to all my family members; mother, siblings, spiritual mentor and father figure that have not lost sight and faith in me as I continue to pursue this dream of mine that continuously becomes a reality. Last but not least, I want to dedicate this report to my God given friends that have faithfully stood by my side and seen that I complete this internship with minimal hardships as possible.

ACKNOWLEDGEMENT

If you come across anything outside the rule book handed to you via class and teachings of the engineering field… You must be careful not to let it distress you, but to look upon it as an addition to your knowledge – a new fact to be considered in studying the character of the people on a site. Your attitude towards it will be that of the mineralogist who stumbles upon a very characteristic specimen of a mineral.

I would love to appreciate the people who have made this very possible for me to come out of this program as a better engineering student and have such a beautiful report.

My sincere gratitude and appreciation go;

To the almighty GOD who granted me good health and long life, without which I could not have finished this research period and report at large.

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PPU – Plastic-Polyurethane

BS – British Standard

ASTM – American Society for Testing and Materials

ITZ – Interfacial Transition Zone

SLWC – Structural Lightweight Concrete

CHAPTER ONE: INTRODUCTION AND BACKGROUND

1.1 BACKGROUND TO THE STUDY

Concrete remains the most widely used construction material in the world due to its high compressive strength, versatility, durability, and relative cost-effectiveness when compared with alternative structural materials such as steel and timber (Neville, 2011). In Uganda, concrete is the primary material used in residential buildings, multi-storey commercial developments, bridges, pavements, and a wide range of civil engineering infrastructure. The structural performance of concrete is largely governed by the quality and characteristics of its constituent materials, namely cement, fine aggregates, coarse aggregates, and water. Course aggregates represent 6070 percent of the concrete volume, and hence have an overridding effect on the mechanical strength, density, durability, and the cost of concrete in general (Mehta and Monteiro, 2014).

Traditional coarse aggregates consumed in Uganda are mainly crushed rock that is as a result of quarry works like granites, basalt, and gneissic rocks that are found in places like Zirobwe, Mukono, and Luwero. Such aggregates have good mechanical properties and low water absorption hence suitable with high-strength structural concrete. Nonetheless, the growing construction materials demand has led to large scale quarrying that have consequently caused severe environmental degradation, escalated material prices, ecosystem destruction, and more greenhouse gas emissions related to extraction and transportation (Langer and Arbogast, 2002; NEMA, 2020). Most of the developing countries such as Uganda have been associated with quarrying as source of habitat destruction, landscapes scarring, soil erosion, dust emission, surface and ground water pollution.

Besides these environmental issues, the conventional concrete is heavy in nature; the average density of a concrete is approximately 2400 kg/m3. This high density has a high degree of dead loads to structural elements that include beams, slabs, columns, and foundations. The result of increased self-weight is; larger member sizes, greater reinforcement requirement, greater foundation pressure, and greater seismic load in tall buildings. These implications are directly translated into increased building costs as well as lifecycle costs and lower structural efficiency at the level of an entire structure, particularly in multi-storey and long-span buildings (Neville, 2011; ACI 213R, 2014).

To overcome the problem of excessive weight of normal-weight concrete, structural lightweight concrete (SLWC) has been designed, in which lightweight aggregates have been used, including expanded clay, shale, pumice and scoria. The equilibrium densities of the structural lightweight concrete are usually 1440-1850 kg/m 3 according to ACI 213R, 2014, and the compressive strengths of 28 days in minimum 17 Mpa (ACI 213R, 2014; ESCI, 2014). The concretes of this type have large strength-to-density (S/D) ratios, and have been applied in long-span bridges, high-rise buildings, and precast elements. But in the Ugandan case, importation of structural lightweight aggregates will be constrained by the cost of procurement, foreign exchange, unstable supply chain and lack of local production facility to produce the extended aggregates. This has forced the majority of the projects to continue using normal-weight concrete taking the penalty of high dead load.

Uganda is however blessed with wide deposits of volcanic tuff especially in the western parts along the Fort Portal and the Rwenzori volcanic belt. Tuff is a pyroclastic rock which was made out of hardened volcanic ash. It naturally has a lower density than regular crushed rock thus it introduces itself as a potentially appealing source of lightweight aggregate in the manufacturing of concrete (Barker, 1989; Pitcavage, 2021). However, many researchers have discovered that tuff and associated volcanic ashes are highly porous, absorb lots of water and have low mechanical strength, which are very limiting to their direct application as structural coarse aggregates (Zhao et al., 2018; Mindess et al., 2003; Studies on Ugandan Volcanic Ash and Tuff, 2006). These characteristics cause higher permeability of concrete, less strength and less durability of unmodified raw tuff.

Simultaneously with the issues behind aggregate sourcing is the constantly increasing problem of plastic waste pollution in Uganda, specifically polyethylene terephthalate (PET) bottles. PET waste is a great percentage of solid waste in cities as it is widely used in packaging beverages and is not biodegradable. Uganda also receives about 150,000 tonnes of plastic goods every year, and an approximate 40 percent of the plastic wastes produced are leaking in the environment (NEMA, 2024). In Greater Kampala alone, plastic waste is produced in large quantities up to 600 tonnes daily, although only about 6 per cent of the waste is formally collected to be recycled, and other waste ends up in dumpsites, drainage systems, wetlands, and water bodies (GIZ, 2023; InfoNile, 2022). This scenario poses a source of concern to the environment as well as a possible source of construction materials.

Recent studies have revealed that waste PET can be cut into a flake or chip, which can be adopted as a lightweight aggregate in concrete to decrease the density and partially substitute the natural aggregate. PET aggregate concretes embracing low replacement rates have also been reported to sustain tolerable compressive strength and realize quantifiable decreases in density and enhanced toughness (Saikia et al., 2012; Islam et al., 2016). PET, however, is naturally hydrophobic as well as chemically inert to the cementitious matrix. Consequently, the interface transition between PET and the adjacent paste is most often weak and easily cracks microscopically, which results in decreases in strength with further increments of PET content (Saikia & de Brito, 2012).

Polyurethane (PU) is a flexible polymer that has great adhesive capabilities, it is not permeable and durable. It has the ability to create good relationships with the surface of minerals and polymeric system and when laid as a coating, it can do a much better job of sealing pores, bonding micro-cracks and enhancing the performance of contacts in composite systems. Recent reports on lightweight aggregates coated with polymer have also shown that the coating of porous aggregates with polymer can greatly minimize the absorption of water by the aggregates, increase the interfacial transition zone, and improve compressive strength and durability of lightweight concrete (Vahabi et al., 2022; Tuncer et al., 2025).

Based on this, the current research incorporates three locally and globally topical substances, volcanic tuff, waste PET plastics, and polyurethane to design a hybrid composite lightweight coarse aggregate of structural concrete. The tuff particles are weak and porous and are coated with a polyurethane (PPU) film mixed with shredded PET flakes to create a composite aggregate which partially is used to substitute conventional coarse aggregates in a typical concrete mix. This is to achieve reduced density with compressive strength and durability as far as the structure is concerned, thus a lower density structural concrete that can be used within the usual Ugandan building structures, including beams and slabs in high-rise residential and commercial buildings.

1.2 Problem Statement

Although conventional concrete has gained wide usage in Uganda because of the high compressive strength, and because of performance that has shown otherwise, it is intrinsic in that it carries high self-weight implying that the typical densities of concrete are very high at 2400 kg/m3. This overweight causes dead loads in the structural systems and this leads to increased column and foundation size, increased reinforcement factors, use of more material and high construction cost. The normal-weight concrete cumulative dead load in multi-storey buildings increases internal loads and seismic demand at the expense of structural efficiency, and restricts the economic viability of vertical development.

There are also lightweight concrete technologies, but they are not always available due to low mechanical performance and high costs. A lot of them depend on foreign additives or aggregates which cannot be economically used in large amounts in Uganda. The existing LWC solutions generally have compressive strengths lower than C25/30 and do not offer enough durability in complex environments to be used as a structural element, e.g. slabs or beam.

In the meantime, the construction business in Uganda negatively impacts the environment due to extensive use of natural aggregates. Not only does it accelerate the depletion of resources, but also increases carbon emissions due to the inability to transport heavy aggregates over long distances and quarrying (Panesar et al., 2020).

Although volcanic tuff exists and the problems of plastic wastes are growing, no existing engineering solution to the problem in Uganda utilizes these materials in a full combination to form a lightweight and structural-grade concrete. The primary knowledge gap was the creation and experimentation of a combination that would compromise between strength, environmental friendliness, and the availability of the materials locally.

Thus this study fulfilled that gap through an evaluation of the structural feasibility, the strength, bonding properties, and the environmental impact of concrete in which the coarse aggregates were replaced by PU-coated volcanic tuff and shredded plastic, in a partial manner. It sought to offer scientific data on material system that not only minimized dead weight but also contributed to circular usage of materials as well as durability of concrete concerning Ugandan building condition.

1.3 Main Objective of the Study

To determine and evaluate the effectiveness of PPU-coated volcanic tuff as a partial replacement of coarse aggregates in the structural concrete.

1.4 Specific Objectives

The specific objectives that guided this study were as follows:

1. To evaluate the physical and mechanical characteristics of PPU covered volcanic tuff in structure use in relation to conventional material.
2. To analyse the impact of PPU coated volcanic tuff use on the overall weight distribution and load-bearing capacity of concrete.

3. To determine the cost-effectiveness and environmental benefits of using PPU coated tuff in construction compared to traditional materials.

1.5 Research Questions

The study sought to answer the following research questions:

1. What are the mechanical properties of concrete combined with PU-coated volcanic tuff and shredded plastic compared to conventional concrete at different replacement levels?
2. How does adding PU-coated tuff and plastic affect the density, permeability, and durability of the concrete mix?
3. What are the material and environmental cost implications of adopting this mix for structural uses in Uganda?

1.6 Justification of the Study

Concrete density is a primary determinant of structural demand because dead load governs bending moments, shear forces, axial loads, and foundation pressures in reinforced concrete frames, particularly in mid-rise buildings common in Uganda. Conventional aggregates with specific gravities of 2.60–2.75 produce concretes whose self-weight may constitute up to 70% of total design load, meaning even the modest density reductions can yield measurable reductions in internal forces and more efficient member sizing (Mindess, Young & Darwin, 2020; ACI Committee 213, 2014). Volcanic tuff provides a lightweight alternative due to its vesicular microstructure, but its high porosity, high water absorption, and weak particle integrity degrade interfacial transition zone (ITZ) strength, increase creep, and lower compressive resistance, making untreated tuff unsuitable for structural use (Neville, 2011). Plastic-Polyurethane (PPU) coating modifies these deficiencies by sealing interconnected pores, reducing capillary absorption, stiffening the aggregate surface, and improving mechanical continuity at the ITZ. Research on polymer-coated lightweight aggregates consistently demonstrates improved crushing resistance, better ITZ cohesion, and delayed microcrack formation due to the formation of a polymeric micro-shell that stabilises particle behaviour under load (Vahabi et al., 2022; Sadrmomtazi, Tahmouresi & Saradar, 2017). Incorporating polyethylene terephthalate (PET) further reduces density because of its low specific gravity (1.38) and introduces ductile, energy-absorbing behaviour that enhances post-cracking response, although PET alone typically bonds poorly with cement paste due to its hydrophobicity (Frigione, 2010). Pairing PET with PU-modified tuff, therefore, offers a scientifically coherent composite system in which PU compensates for ITZ weaknesses while PET contributes lightweighting and toughness, enabling a medium-density structural concrete rather than a non-structural lightweight material. Mechanically, the ITZ remains the governing zone for strength and stiffness, and PU-induced improvements in pore sealing, moisture resistance, and microcrack suppression directly enhance compressive behaviour and modulus development (Mehta & Monteiro, 2014; Kim et al., 2010). The lack of previous research of PPU-coated volcanic tuff in Ugandan conditions implies that necessary data, such as density, strength, modulus, ITZ properties, and deformation behaviour, are not available in the domestic design practice. The relevance of the research therefore stems out of the necessity of developing a scientific basis of body of knowledge of a novel composite aggregate that has the capability of decreasing the dead load and attain structural-grade mechanical functionality.

1.7 Significance of the Study

The importance of the research is mainly due to the fact that the research has assisted in enhancing structural material science; in this case, engineering of reduced-density composite aggregate system that can satisfy the structural performance requirement and alter the mechanical behaviour of concrete at the ITZ. The study contributes to the first scientifically based data of the hybrid material of PPU coated volcanic tuff as a partial substitute of conventional coarse aggregates by performing experimental assessment of the material in a Ugandan context. It has been documented that untreated lightweight aggregates like tuff have a high porosity, low particle integrity, and poor bonding between the particles (ITZ) (Neville, 2011), and polymer coating has been reported to enhance the stiffness, bonding of the two particles, and resistance to the formation of microcracks (Vahbabi et al., 2022; Sadrmomtazi, Tahmouresi and Saradar, 2017). Nonetheless, none of the previous studies combine PPU adjustment towards structural uses in East Africa. The research thus bridges a vital knowledge gap by generating verified data on density, compressive strength, modulus development and water absorption providing a scientifically justifiable foundation on where the composite fits into the structural concrete strength categories as per the lightweight concrete mechanics (ACI Committee 213, 2014).

The results have implications to practice in structural engineering in the sense that they offer quantifiable evidence on how the reduction in total dead load caused by engineered lightweight aggregates affects the size of the member used, internal force requirements, and possible reinforcement optimisation of the normal building system. As concrete self-weight can be as much as 70 percent of all design load

(Mindess, Young and Darwin, 2020), confirmed aggregate reduction could directly lower foundation pressures, bending loads, and the amount of construction material used. Moreover, the research produces early age and 28 days performance data that professionals, concrete materials suppliers, and regulatory bodies may use when determining the appropriateness of reduced-density concretes in slabs, lintels, beams, and load bearing partitions. It is also the baseline of further research on tensile capacity, flexural response, and long-term behaviour that are crucial to complete structural classification and possible incorporation in local design guidelines. On top of the mechanical considerations in the short term, the study provides a basis on which later studies on durability, chloride resistance, shrinkage behaviour, and long-term microstructural stability can be conducted, allowing the advancement toward a fully characterised composite system. Its importance, thus, is in enhancing engineering knowledge, aiding analytical design decision making and establishing a basis of future standards or specification of polymer-modified light weight aggregates in the structural engineering environment in Uganda..

1.8 Scope of the Study

1.8.1 Time scope

This research was carried out from January 2025 to November 2025.

1.8.2 Content scope

The focus of this study is on assessing the structural performance of concrete when PPU-coated volcanic tuff is used as a partial replacement for coarse aggregates.

The concrete grade considered was C25, one of the most commonly applied structural mixes in Uganda for slabs, beams, lintels, foundations, and reinforced bases.

Therefore, physical properties of the aggregates were obtained, as well as both fresh and hardened properties of the modified concrete before and after incorporating PPU-tuff.

1.8.3 Geographical scope

The volcanic tuff was collected from the Fort Portal Ndali-Kasenda Volcanic Field (0.4339°N,30.3239°E)(Uganda).

Physical properties, as well as fresh and hardened properties of the concrete, were determined from the RSV Engineering Laboratory in Bukoto (Uganda).

CHAPTER TWO: LITERATURE REVIEW

2.1.1 Introduction

This chapter reviews theoretical and empirical literature related to structural lightweight concrete, volcanic tuff as a lightweight aggregate, polymer modification of aggregates using polyurethane, and the behaviour of concretes incorporating lightweight and plastic-influenced aggregates. The purpose is to establish a scientific basis for using plastic–polyurethane (PPU) coated volcanic tuff as a partial replacement for conventional coarse aggregates in C25 structural concrete within the Ugandan context. The review first presents definitions and performance criteria for structural lightweight concrete, followed by a discussion of the interfacial transition zone (ITZ) and its role in controlling mechanical and durability performance. It then examines the physical and mechanical properties of volcanic tuff, outlines the mechanisms of polymer coating of lightweight aggregates, and briefly reviews the effects of plastic aggregates such as polyethylene terephthalate (PET) on concrete properties. The chapter concludes with a synthesis of empirical findings, an identified research gap, and a conceptual framework linking material modification to structural performance.

2.1.2 Structural Lightweight Concrete: Definitions and Criteria

Structural lightweight concrete (SLWC) is defined in international guidance as concrete made with lightweight aggregates that achieves an in-place or equilibrium density typically between 1440 and 1850 kg/m^3 at 28 days and a 28-day compressive strength not less than 17 MPa (ACI Committee 213, 2014; ESCSI, 2014; CIP 36, 2013). These limits distinguish structural lightweight concrete from non-structural lightweight concretes used mainly for insulation or fill, which may have densities below 1200 kg/m³ and very low strengths (Rosca et al., 2025). In contrast, normal-weight concrete generally has a unit weight of 2400 kg/m³ for typical structural mixes (ACI Committee 213, 2014; CIP 36, 2013).

Table 1 summarises the commonly cited density and strength ranges for normal-weight and structural lightweight concrete systems.

Table 1: Typical classification of normal-weight and structural lightweight concrete

Concrete type	**Equilibrium / in-place density (kg/m³)**	**Typical 28-day compressive strength (MPa)**
Normal-weight concrete	2240–2400	≥ 20–25 (structural)
Structural lightweight concrete	1440–1840/1850	≥ 17 (structural grade)
Mild/lightweight (non-structural)	< 1440	< 17

The primary motivation for using SLWC is the reduction of dead load. For buildings and bridges, reducing density by 20–30% while meeting strength requirements can lead to smaller column sizes, lower foundation pressures, reduced seismic demand, and potential savings in reinforcement and construction materials (ACI Committee 213, 2014; Mohi-Ud-Din et al., 2025). However, the use of lightweight aggregates also introduces challenges related to higher porosity, higher water absorption, lower stiffness, and increased creep compared with normal-weight aggregates (Hasan et al., 2021; Rosca et al., 2025). A successful structural lightweight concrete must therefore achieve an acceptable balance between density reduction, mechanical performance (compressive strength and modulus of elasticity), and durability (water absorption, permeability, and resistance to aggressive environments).

2.1.3 Interfacial Transition Zone in Lightweight Aggregate Concrete

The interfacial transition zone is the thin region surrounding aggregate particles in hardened concrete where the microstructure differs from that of the bulk paste. Classic studies and modern microstructural investigations show that the ITZ typically has higher porosity, larger crystals (e.g., calcium hydroxide), higher local water–cement ratio, and more microcracks than the bulk matrix (Mehta and Monteiro, 2014; Neville, 2011). In lightweight aggregate concretes, the contrast between the porous lightweight aggregate and the surrounding cement paste makes the ITZ even more critical; poor ITZ quality can lead to reduced compressive strength, lower tensile strength and stiffness, and higher permeability compared with normal-weight concrete of similar composition (Hasan et al., 2021; Rosca et al., 2025).

Factors that influence ITZ quality include aggregate type and surface texture, aggregate absorption and pre-wetting, mix proportioning (particularly water–binder ratio), curing regime, and the use of supplementary cementitious materials or polymers (Mehta and Monteiro, 2014). Techniques that reduce ITZ porosity and improve paste–aggregate bonding, such as the use of fine pozzolanic particles, internal curing through pre-saturated lightweight aggregates, or surface modification of aggregates, have been shown to improve both mechanical properties (strength and modulus) and durability (reduced sorptivity and chloride penetration) (Rosca et al., 2025; Müller-Rochholz, 1979). In the context of volcanic tuff, which is highly porous and absorptive, targeted ITZ improvement through polymer coating is therefore a key strategy for developing structural-grade lightweight concrete.

2.1.4 Volcanic Tuff as Lightweight Aggregate

Volcanic tuff is a pyroclastic rock formed from consolidated volcanic ash and fragments deposited during explosive eruptions. It typically contains glassy particles, pumice fragments, and crystal shards in a fine matrix, resulting in relatively low bulk density and high porosity (Al-Dwairi et al., 2014). Studies on tuff from regions with geological characteristics similar to western Uganda report specific gravities in the range of about 2.0–2.3 and bulk densities significantly lower than those of crushed granite or basalt (Khamza et al., 2024).

Typical physical properties of volcanic tuff aggregates reported in the literature are summarised in Table 2.

Table 2: Typical physical properties of volcanic tuff aggregates reported in literature

Property	Reported range / value	Notes / location
Specific gravity	2.0–2.3	Lower than granite/basalt (2.6–2.7)
Bulk density (kg/m³)	1400–1800	Volcanic tuff in concrete aggregates
Water absorption (%)	8–20	Highly porous aggregate
Porosity (%)	60	Zeolitic and black tuff samples

While such properties indicate that tuff is a promising lightweight aggregate, they also expose key weaknesses. High water absorption and porosity complicate mix design and can lead to variable effective water–cement ratios, poor workability, and increased permeability if not properly managed. Mechanical tests often show relatively high Aggregate Crushing Values (ACV) and Aggregate Impact Values (AIV) compared to conventional hard rock aggregates, indicating lower resistance to crushing and impact (Al-Zboon and Al-Zou'by, 2019; Al-Dwairi et al., 2018).

Empirical studies on tuff-based lightweight concretes report that, when tuff is used as a cement or fine aggregate replacement at moderate levels (typically 15-30%), 28-day compressive strengths in the range of 20–35 MPa can be achieved, particularly with low water-cement ratios and the use of superplasticisers (Sarireh, 2015; Khamza et al., 2024). However, when tuff is used as a coarse aggregate without modification, compressive strength and durability often decline sharply at replacement levels beyond 20–30%, with higher sorptivity and poorer performance under aggressive exposure compared with normal-weight concrete (Al-Zboon and Al-Zou'by, 2019; Rosca et al., 2025; Uche and Roeder, 2025). These findings justify the need for engineered surface modification of tuff to unlock its lightweight potential while controlling its adverse effects.

2.1.5 Plastic–Polyurethane Coating and Polymer-Modified Aggregates

Polymer coatings are increasingly used to modify lightweight and recycled aggregates in order to reduce water absorption, improve ITZ quality, and enhance concrete durability. Polyurethane (PU) is a thermosetting polymer widely used as a coating and sealant because of its high tensile strength, toughness, good adhesion to mineral and polymer substrates, and low permeability to water and aggressive agents (Bideci and Ince, 2025; Tuncer et al., 2025). When applied as a thin film around aggregate particles, PU can form a continuous micro-shell that seals surface pores, modifies surface roughness and surface energy, and provides a more compatible interface for cement hydration products.

Studies on polymer-coated lightweight aggregates, particularly pumice and expanded lightweight aggregates, show that polyester or polyurethane coatings can reduce aggregate water absorption by up to 70–95%, depending on coating formulation and thickness (Tuncer et al., 2025; Müller-Rochholz, 1979). At the concrete level, such coatings have been associated with substantial reductions in water absorption and sorptivity, as well as improvements in compressive and splitting tensile strength relative to mixes made with uncoated aggregates at the same density (Bideci and Ince, 2025; Aocharoen et al., 2023). However, there is evidence that excessively thick or overly flexible coatings can act as soft interlayers, slightly reducing stiffness and compressive strength, even while improving durability indices such as chloride resistance and freeze–thaw performance (Tuncer et al., 2025).

The overall conclusion is that polymer coatings are effective in controlling water absorption and ITZ quality in lightweight aggregate concrete, but their benefits depend on the choice of polymer, application method, and coating thickness. For highly porous volcanic tuff, a plastic–polyurethane coating is expected to: (i) seal interconnected near-surface pores, (ii) reduce aggregate water absorption towards values closer to those of conventional aggregates, and (iii) provide a denser, more compatible ITZ for load transfer.

2.1.6 PET and Plastic Aggregates in Concrete

Plastic aggregates derived from waste polymers, particularly PET, have been widely investigated as partial replacements for natural aggregates in concrete. A recent meta-analysis shows that PET aggregates are attractive for lightweight applications due to their low density, high tensile strength, and low thermal conductivity (Uche, 2023; Uche and Roeder, 2025). PET aggregates typically have specific gravities in the range 1.25–1.50 and very low water absorption (< 1%), which helps reduce concrete density and limit additional water uptake (Askar et al., 2023; Mat et al., 2023).

However, PET particles are hydrophobic and have relatively smooth surfaces, resulting in weak bonding with cement paste and high ITZ porosity. Experimental evidence indicates that replacing fine or coarse aggregates with PET at 5–15% by volume can reduce density by 5-15% while keeping compressive strength in a structural range (often 17–30 MPa), but higher replacement levels commonly cause significant reductions in compressive strength (up to 20–40%), tensile strength and modulus of elasticity (Uche, 2023; Aocharoen et al., 2023; Askar et al., 2023). Plastic aggregate systems, therefore, illustrate the benefits and limitations of density reduction using polymeric particles.

In the present study, PET is not treated as the primary aggregate phase but as part of the broader family of plastic–polymer systems that inform expectations about density reduction, ITZ behaviour, and strength–durability trade-offs in PPU-modified tuff concretes.

2.1.7 Summary of Key Mechanisms

From a theoretical perspective, three mechanisms underpin this research. First, volcanic tuff offers significant potential for dead-load reduction due to its lower density but exhibits high porosity, high water absorption, and relatively low particle strength, which can adversely affect concrete strength and durability if used untreated (Al-Dwairi et al., 2018; Sarireh, 2015; Khamza et al., 2024). Second, the polymer coating like polyurethane has the potential to cut aggregate water uptake by a factor of four or five and refine the ITZ to enhance durability and, in most cases, the strength at a specified density (Tuncer et al., 2025; Bideci and Ince, 2025). Third, plastic aggregates such as PET demonstrate that density reduction and enhanced toughness often come at the cost of strength and stiffness unless ITZ weaknesses are addressed (Uche, 2023; Askar et al., 2023).

The proposed PPU-coated tuff system seeks to combine these mechanisms by using a polymer coating to compensate for the inherent weaknesses of tuff, while exploiting its low density to produce a reduced-density concrete that still satisfies structural performance requirements.

2.2 Empirical Review

2.2.1 Structural Lightweight Concrete with Volcanic Aggregates

Research on lightweight structural concretes containing volcanic aggregates such as tuff, pumice, and scoria shows that these materials can be used to produce concretes with densities and strengths compatible with structural applications, provided that mix design and curing are carefully controlled. Sarireh (2015) assessed concrete containing Jordanian volcanic tuff and reported that at about 20% replacement of normal-weight aggregates, 28-day compressive strengths in the range of 25–30 MPa and densities around 2000–2200 kg/m^3 could be achieved, satisfying structural requirements. Parmo et al. (2022) studied lightweight concrete with volcanic pumice aggregates and found that densities between approximately 1120 and 1180 kg/m^3 and compressive strengths of 17–25 MPa were attainable for carefully proportioned mixes (Parmo et al., 2022).

More recent work by Khamza et al. (2024) on tuff-based lightweight structural concrete reported water absorption of about 8.7–10.2% for tuff aggregates, porosity of around 60%, and compressive strengths approaching 27–28 MPa with densities near

1850 kg/m^3 for optimised mixes (Khamza et al., 2024; Al-Dwairi et al., 2018). These results indicate that volcanic tuff can be used to produce concretes at the upper end of structural lightweight density ranges. However, the same studies emphasise that high water absorption and lower aggregate strength require careful control of water–cement ratio, pre-wetting and, in some cases, admixture usage to maintain workability and reduce shrinkage and permeability.

Where tuff is used as a coarse aggregate without modification, several authors note that compressive strength decreases markedly beyond replacement levels of 20–30%, and indicators such as sorptivity and chloride diffusion worsen compared to normal-weight concrete (Al-Zboon and Al-Zou'by, 2019; Sarireh, 2015; Rosca et al., 2025). This reinforces the conclusion that while tuff can form part of a structural lightweight system, some form of surface treatment or hybridisation is needed to stabilise its performance at higher replacement levels.

2.2.2 Polymer-Coated Lightweight Aggregates

Empirical studies on polymer-coated lightweight aggregates directly support the idea of using polyurethane to modify volcanic tuff. Tuncer et al. (2025) coated pumice aggregates with polyester resin and found that aggregate water absorption was reduced by up to 95%, while specific gravity increased significantly; concretes made with the coated aggregates exhibited lower water absorption and improved durability compared with mixes containing uncoated pumice (Tuncer et al., 2025).

In a broader review of polymers in pumice concrete, Bideci and Ince (2025) report that polymer-modified lightweight aggregate concretes often show higher compressive and flexural strength than conventional lightweight concretes, together with reduced permeability and improved resistance to freeze–thaw and chemical attack (Bideci and Ince, 2025). Aocharoen et al. (2023) also observed that polymer-treated lightweight concretes could achieve compressive strengths above 20 MPa at densities below 2000 kg/m^3, provided that coating thickness and uniformity were adequately controlled.

These results collectively demonstrate that polymer coating is an effective means of mitigating high absorption and poor ITZ properties in lightweight aggregates. However, most published work focuses on pumice or other LWAs rather than volcanic tuff, and there is little data on PPU-coated tuff specifically or on its performance in concrete designed to meet C25 structural requirements.

2.2.3 PET Aggregate Concretes

Recent meta-analyses and experimental programmes on PET aggregates in concrete provide useful reference behaviour for plastic-influenced lightweight concretes. Uche (2023) reviewed numerous PET aggregate studies and concluded that PET can be successfully used in structural lightweight concrete at low replacement levels, typically 10–20% by volume, resulting in density reductions of 5–15% and compressive strengths remaining within structural ranges (Uche, 2023; Uche and Roeder, 2025).

Askar et al. (2023) and Mat et al. (2023) showed that up to 10 wt.% PET replacement as fine aggregate caused modest reductions in density and compressive strength (on the order of 1–10%), which were still deemed acceptable for structural applications under certain standards (Askar et al., 2023; Mat et al., 2023; Waste PET 2024). Concrete with higher PET contents, however, exhibited more pronounced losses: studies consistently report 14–30% reductions in compressive strength, 7–11%

reductions in tensile strength, and increases of about 20–30% in void ratio and water absorption for high PET replacement levels (Aocharoen et al., 2023; Mat et al., 2023; Concrete with PET, 2022).

The consensus from PET research is that while plastic aggregates are effective in reducing density, they need to be carefully dosed and often accompanied by surface modification or supplementary cementitious materials if structural performance is to be maintained. This further supports the focus of the present study on polymer modification of a mineral lightweight aggregate (tuff) rather than heavy reliance on plastic aggregate alone.

2.2.4 Hybrid Lightweight Aggregate Systems and Composite Mixes

Hybrid systems combining mineral lightweight aggregates, polymer coatings, and plastic components have been explored as a way of balancing density, strength, and durability. Rosca et al. (2025) assessed eco-friendly lightweight structural concretes using combinations of lightweight aggregates and supplementary materials, demonstrating that densities in the 1600–1800 kg/m³ range and compressive strengths above 20 MPa can be achieved with appropriate mix design (Rosca et al., 2025). Other studies combining recycled plastics with mineral lightweight aggregates report compressive strengths between about 17 and 30 MPa with marked reductions in dead load, although they often require optimised paste content and admixtures to control workability and void structure (Uche, 2023; Askar et al., 2023).

The overall conclusion from these hybrid systems is that single-material solutions, such as using only tuff or only PET, tend to suffer from pronounced trade-offs between density and performance. Hybrid or composite systems, particularly those that employ polymer coatings on lightweight aggregates, appear more promising in achieving structural-grade behaviour with reduced density. However, there remains a lack of data on systems specifically involving PPU-coated volcanic tuff and on their application within Ugandan material and environmental conditions.

2.2.5 Durability and Microstructural Performance

Durability properties such as water absorption, sorptivity, chloride penetration, and resistance to freeze–thaw and sulfate attack are closely tied to aggregate porosity, and ITZ quality in lightweight and hybrid concretes. Normal-weight concretes with dense aggregates typically exhibit water absorption values of 3–6% by mass, whereas lightweight concretes with highly porous aggregates often show absorption values of 10–20% or more (Hasan et al., 2021; Rosca et al., 2025; Askar et al., 2023).

Polymer coatings have been consistently shown to reduce aggregate and concrete absorption, with coatings on lightweight aggregates reducing aggregate water uptake up to 80–95% and lowering overall concrete absorption by 20–30% in some studies (Tuncer et al., 2025; Müller-Rochholz, 1979). These improvements in moisture-related durability often coincide with denser ITZ microstructures and improved strength retention under mechanical and environmental loading. Conversely, where lightweight aggregates remain highly porous and unmodified, higher absorption and permeability are associated with increased risk of reinforcement corrosion, reduced freeze–thaw resistance, and poorer long-term performance (Hasan et al., 2021; Rosca et al., 2025).

These findings support the rationale for assessing PPU-coated tuff in terms of both mechanical performance (compressive strength and density) and durability-linked properties such as water absorption.

2.3 Conclusion of the Empirical Review

From the reviewed literature, several conclusions relevant to this study can be drawn:

- Structural lightweight concrete is a mature technology internationally and is typically characterised by densities between about 1440 and 1840/1850 kg/m^3 and 28-day compressive strengths of at least 17 MPa (ACI Committee 213, 2014; CIP 36, 2013; ESCSI, 2014).
- Volcanic tuff and similar volcanic aggregates can produce reduced-density concretes, but high water absorption, high porosity, and moderate particle strength limit their direct use as coarse aggregates in structural-grade concretes, especially at high replacement levels (Sarireh, 2015; Al-Dwairi et al., 2018; Khamza et al., 2024).
- Polymer-coated lightweight aggregates, including those treated with polyurethane-type systems, show substantial reductions in aggregate and concrete water absorption and improved ITZ quality, often with increases in compressive and tensile strength relative to uncoated systems (Tuncer et al., 2025; Bideci and Ince, 2025).
- PET and other plastic aggregates reduce density and can improve toughness, but tend to reduce compressive strength, tensile strength, and stiffness at moderate to high contents due to weak ITZ bonding and increased voids,

making them unsuitable as a sole lightweight solution for structural applications (Uche, 2023; Askar et al., 2023; Mat et al., 2023).

- Hybrid lightweight systems that combine mineral aggregates, polymer coatings, and plastic components can better balance density reduction, mechanical performance, and durability, but their performance is highly dependent on aggregate type, coating details, and mix design (Rosca et al., 2025; Uche, 2023).

These conclusions collectively highlight the potential and limitations of existing lightweight and polymer-modified systems and reinforce the need to investigate PPU-coated volcanic tuff using locally relevant materials and performance criteria.

2.4 Research Gap

The literature shows that volcanic tuff has been extensively investigated as a cement or fine aggregate replacement, with more limited work on its use as a coarse aggregate in structural lightweight concrete. Where tuff has been used as a coarse aggregate, high water absorption and lower particle strength often restrict replacement levels or require intensive mix control to prevent reductions in strength and durability (Sarireh, 2015; Al-Zboon and Al-Zou'by, 2019; Khamza et al., 2024). At the same time, research on polymer-coated lightweight aggregates confirms that coatings such as polyurethane can effectively reduce aggregate water absorption and enhance ITZ performance, but these studies have concentrated mainly on pumice, expanded clay, and recycled concrete aggregates rather than on volcanic tuff, and they are largely based on non-Ugandan materials and exposure conditions (Tuncer et al., 2025; Bideci and Ince, 2025).

Furthermore, although PET aggregate concretes and hybrid systems combining plastics with mineral lightweight aggregates have been widely studied, these systems either rely on PET as a primary aggregate phase or do not consider polyurethane coatings tailored to a specific tuff source (Uche, 2023; Askar et al., 2023). There is a clear lack of data on PPU-coated volcanic tuff, characterised in coarse aggregate form and evaluated within C25 structural concrete designed and cured under conditions typical of laboratories. There is also limited work that carries material-level results through to structural implications in terms of dead-load reduction and member performance in beams or slabs.

This study responds to these gaps by:

(i) developing a plastic–polyurethane coating for volcanic tuff sourced from Ugandan volcanic fields;

(ii) characterising its effects on aggregate absorptivity and the density, water absorption, and compressive strength of C25 concrete at 7, 14, and 28 days; and

(iii) assessing whether the resulting mixes can be classified as reduced-density or structural lightweight concretes suitable for typical Ugandan building applications.

2.5 Conceptual Framework

The conceptual framework for this research linked the properties of PPU-coated volcanic tuff to concrete performance and, ultimately, to structural behaviour in building elements. At the input stage, the framework considered conventional coarse aggregates, uncoated volcanic tuff from Fort Portal, plastic–polyurethane coating components, cement, fine aggregates, and water. Uncoated tuff is first characterised in terms of specific gravity, water absorption, and mechanical indices such as ACV, AIV, and TFV. It is then treated with a plastic-polyurethane coating to produce PPU-coated tuff with reduced water absorption and modified surface characteristics.

At the intermediate level, the framework assumes that PPU coating transforms the near-surface region of the tuff particles by sealing pores, reducing effective absorptivity, and providing a more favourable interface for cement hydration products. These aggregate-level changes are expected to influence concrete-level properties when PPU-tuff is used as a partial replacement for conventional coarse aggregates in a C25 mix. In fresh concrete, effects are anticipated on workability and cohesiveness; in hardened concrete, the focus is on density, water absorption, and compressive strength development at 7, 14, and 28 days.

At the output level, the measured density and strength of concretes containing PPU-coated tuff are compared with normal-weight control mixes and with internationally recognised criteria for structural lightweight concrete. This allows classification of the material as normal-weight, reduced-density, or structural lightweight. The classification and associated material parameters provide a basis for assessing structural implications, such as reductions in dead load and potential adjustments to member sizing in typical beams and slabs used in Ugandan buildings. In this way, the conceptual framework connects material modification at the aggregate level to concrete performance and, ultimately, to structural efficiency in practice.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter presents the methods used to evaluate the effect of plastic-polyurethane (PPU) coated volcanic tuff and shredded PET on the physical and mechanical properties of C25 structural concrete. The methodology was designed to generate quantitative evidence on how partial replacement of conventional coarse aggregates by a PPU–tuff composite influences density, water absorption, and compressive strength at 7, 14, and 28 days, in line with the objectives stated in Chapter One.

Four concrete mixes with 0%, 10%, 20% and 30% replacement of conventional coarse aggregate by PPU–tuff were prepared and tested. For each mix, standard cube specimens of 150 × 150 × 150 mm were cast, cured in water, and tested at the specified ages. All aggregate tests followed BS 812 and BS EN 933 procedures, while concrete tests followed BS EN 12390 and ASTM C642 (BS EN 12390-3, 2009; ASTM C642, 2013).

3.2 Test Plan

The experimental programme was structured to compare a normal-weight control mix with three modified mixes at different levels of PPU coated tuff replacement.

- Control(M0):

  0% PPU coated tuff, 100% conventional coarse aggregate.
- M10:

  10% of the coarse aggregate volume replaced by PPU coated tuff composite.

- M20:

  20% of the coarse aggregate volume was replaced.

- M30:

  30% of the coarse aggregate volume was replaced.

All mixes used the same cement type, sand source, and target strength class.

For each mix:

- Fresh concrete tests:
  - Slump
  - Fresh density
- Hardened concrete tests (7, 14, 28 days):
  - Hardened density
  - Water absorption
  - Compressive strength

At least two cubes per age and per mix were tested for compressive strength, giving a minimum of 24 strength tests. Additional cubes were used for density and water absorption.

3.3 Gathering and Preparing Materials

3.3.1 Cement

Ordinary Portland Cement (OPC) CEM I 42.5 N conforming to BS EN 197-1 was used throughout. Cement was obtained from a local supplier and stored in a dry room on wooden pallets to avoid contact with moisture.

3.3.2 Fine Aggregates (Sand)

Natural river sand was collected from a commercial supplier and used as fine aggregate. It was air-dried, sieved, and tested to confirm compliance with the grading limits for concrete aggregates given in BS EN 12620. Sand was stored in clean bags and protected from contamination.

3.3.3 Conventional Coarse Aggregates

Crushed rock from a quarry was used as the control coarse aggregate. Representative samples were taken by random sampling. The aggregates were washed, air-dried, and sieved to obtain the desired 10–20 mm fraction. Properties such as Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Ten Percent Fines Value (TFV), specific gravity, bulk density, and water absorption were determined according to BS 812 (BS 812-110, 1990; BS 812-112, 1990).

3.3.4 Volcanic Tuff

Volcanic tuff was collected from the Fort Portal Ndali–Kasenda Volcanic Field, crushed, and sieved into the 10–20 mm size range to match the conventional coarse aggregate size. Dust and undersized particles were removed. Raw tuff was characterised for ACV, AIV, TFV, soundness, specific gravity, bulk density, and water absorption, consistent with its high porosity and absorption behaviour discussed in Chapter Two (Al-Dwairi et al., 2018; Khamza et al., 2024).

3.3.5 Shredded PET Plastics

Waste PET bottles were collected from recycling centres in Kampala, washed with clean water, dried, and mechanically shredded into 5–15 mm flakes. Oversized pieces were cut down manually. PET was stored in sealed bags to prevent contamination.

3.3.6 Polyurethane (PU)

A two-component polyurethane (PU) system suitable for coating applications was used to modify the tuff and PET aggregates. The components were mixed according to the manufacturer's recommended mixing ratio immediately prior to coating. PU was chosen because of its strong adhesion and low permeability, which help to seal the pores of lightweight aggregates (Tuncer et al., 2025).

3.3.7 Mixing Water

Potable tap water meeting BS EN 1008 requirements was used for both mixing and curing.

3.4 Preparation of PPU coated Tuff Composite

The PPU coated tuff composite was produced in stages:

1. Drying of Tuff:

   Aggregates of the tuff were dried in the oven at 105 +- 5 °C till they were of constant weight and allowed to cool to room temperature to get all the internal moisture out of them and to enhance penetration of PU.
2. PU Mixing:

   The weighed PU components were mixed using a mechanical stirrer till a homogeneous liquid was attained. Mixing was done in accordance with instructions of the manufacturer.

3. Coating of Tuff:

   A rotary pan mixer was placed with the dried tuff. The mixer was turned as PU was gradually poured on to make a thin and uniform coating. The purpose was to create an encircling film of each particle instead of the thick layers that could serve as a soft interphase.

4. Initial Curing:

   Coated tuff was spread in a single layer on plastic sheets and left to cure under open-air drying conditions (approximately 20–25°C) for at least 24 hours, until the surface was dry and non-tacky.

5. Blending with PET:

   After curing, the PU-coated tuff was blended with pre-weighed PU-coated PET flakes to form a composite coarse aggregate. The blending ratio was controlled so that the composite fraction could replace 10%, 20% or 30% of the conventional coarse aggregate volume when used in mixes M10, M20, and M30.

The composite aggregate was then stored in clean containers ready for batching.

3.5 Concrete Mix Design and Batching

3.5.1 Target Strength and Mix Ratio

All concretes were designed to achieve C25 strength class at 28 days, consistent with typical structural applications. A 1:2:3 cement: sand: coarse aggregate proportion by mass with a water–cement ratio (w/c) of 0.45 was adopted, guided by British mix design practice and previous C25 work (BS 5328; ACI Committee 211.1, 2002).

3.5.2 Replacement Levels

For each replacement level, part of the coarse aggregate volume was substituted with the PPU coated tuff composite:

- M0 : 0% composite, 100% conventional coarse aggregate
- M10: 10% composite, 90% conventional
- M20: 20% composite, 80% conventional
- M30: 30% composite, 70% conventional

Conversion from volume to mass used the measured bulk densities of the conventional aggregate and composite aggregate.

3.5.3 Batching and Mixing Procedure

Concrete was batched by mass using a calibrated digital scale and mixed in a pan or drum mixer:

1. Add coarse aggregates (conventional + composite) and fine aggregate; dry-mix for 1 minute.
2. Add cement; dry-mix for a further 2 minutes until uniform.
3. Add approximately 70% of the mixing water while the mixer is running.
4. Add the remaining water gradually to achieve the targeted consistency.
5. Mix for a total of about 5 minutes until a homogeneous mix is obtained.

No chemical admixtures were used to isolate the effects of the PPU coated tuff composite.

3.6 Casting and Curing of Cubes

Fresh concrete was placed into steel cube moulds of 150 × 150 × 150 mm, previously cleaned and oiled.

- Each cube was filled in three layers, with each layer compacted using a standard tamping rod until no visible air voids remained, following BS EN 12390-2.
- The top surface was finished with a trowel and covered to prevent moisture loss.

Cubes were demoulded after 24 ± 2 hours, marked with mix ID and age, and then submerged in clean water at 20 ± 2°C until testing at 7, 14, and 28 days.

3.7 Testing

3.7.1 Overview of Tests

The following tests were carried out:

On aggregates (conventional, tuff, and composite):

1. Sieve analysis – BS EN 933-1
2. Bulk density – BS 812-2
3. Specific gravity and water absorption – BS EN 1097-6
4. Aggregate Crushing Value (ACV) – BS 812-110
5. Aggregate Impact Value (AIV) – BS 812-112
6. Ten Percent Fines Value (TFV) – BS 812-111
7. Soundness (sodium sulfate) – BS 812-121

On fresh concrete:

8. Slump – BS EN 12350-2

9. Fresh density – BS EN 12350-6

On hardened concrete:

10. Hardened density – BS EN 12390-7 / ASTM C642
11. Water absorption – ASTM C642
12. Compressive strength at 7, 14, and 28 days – BS EN 12390-3

No SEM, XRD, splitting tensile, flexural, or permeability tests were carried out, and the methodology reflects only the tests actually performed.

3.8 Data Collection Procedure

Table 3 summarises the main tests, the standards used, and the key apparatus.

Table 3: Methods used to achieve the objectives

Test	Standard / Method	Material(s) Tested	Main Apparatus
Sieve analysis	BS EN 933-1	Sand, conventional agg., tuff	Sieve stack, mechanical shaker, balance
Bulk density	BS 812-2	Coarse aggregates & composite	Cylindrical metal container, balance, tamping rod
Specific gravity & absorption	BS EN 1097-6	Coarse aggregates & composite	Pycnometer, oven, balance, water tank
ACV	BS 812-110	Conventional aggregate, tuff	ACV cylinder, plunger, compression machine, sieves

AIV	BS 812-112	Conventional aggregate, tuff	Impact testing machine, sieves, tamping rod
Ten Percent Fines Value	BS 812-111	Conventional aggregate, tuff	TFV apparatus, compression machine, sieves
Soundness	BS 812-121	Tuff, conventional aggregate	Salt solution bath, oven, sieves
Slump	BS EN 12350-2	All concrete mixes	Slump cone, base plate, tamping rod, ruler
Fresh density	BS EN 12350-6	All concrete mixes	Density container, balance
Hardened density	BS EN 12390-7 / ASTM C642	Concrete cubes	Oven, water tank, balance
Water absorption (concrete)	ASTM C642	Concrete cubes	Oven, water tank, balance
Compressive strength	BS EN 12390-3	Concrete cubes (7, 14, 28 days)	2000 kN compression testing machine

3.9 Data Processing and Analysis

Data from the tests were processed to obtain engineering parameters used in Chapter Four. Calculations were carried out primarily using Microsoft Excel, with statistical analysis (means, standard deviations) and plotting of strength-age and strength-density relationships. The key formulae are summarised below.

3.9.1 Bulk Density of Aggregates

Bulk density ρ_b was calculated as:

$$\rho_b = \frac{M}{V}$$

Where:

- ρ_b = bulk density of aggregate (kg/m³)
- M = mass of aggregate filling the container (kg)
- V = internal volume of the container (m³)

3.9.2 Water Absorption of Aggregates

Water absorption of aggregates (WA) was computed using:

$$WA = \frac{WSSD - WOD}{WOD} \, x \, 100$$

Where:

- WSSd = saturated surface-dry mass (g)
- WOD = oven-dry mass (g)

3.9.3 Specific Gravity of Aggregates

Specific gravity Gs was calculated as:

$$Gs = \frac{\mathrm{WOD}}{\mathrm{WSSD} - \mathrm{Wsub}}$$

Where:

- WOD = oven-dry mass (g)
- WSSD = saturated surface-dry mass (g)

- Wsub = submerged mass in water (g)

3.9.4 Aggregate Crushing Value (ACV)

ACV= $\frac{W2}{W1}\ x\ 100$

Where:

- W1 = mass of oven-dry test sample (g)
- W2 = mass passing 2.36 mm sieve after loading (g)

3.9.5 Aggregate Impact Value (AIV)

AIV= $\frac{Wp}{Wt}\ x\ 100$

Where:

- Wp = mass of material passing 2.36 mm sieve after impact (g)
- Wt = total mass of the test specimen (g)

3.9.6 Ten Percent Fines Value (TFV)

The TFV was taken as the applied load corresponding to 10% fines, interpolated from the load-percentage fines relationship following BS 812-111.

3.9.7 Soundness Loss

Soundness loss = $\frac{Wbefore-Wafter}{Wbefore}\ x\ 100$

Where:

- Wbefore = initial mass before cycles (g)
- Wafter = mass after specified cycles (g)

3.9.8 Water Absorption of Concrete (ASTM C642)

$$WAc= \frac{WSSD-WOD}{WOD}\ x\ 100$$

Where:

- WAc = water absorption of concrete (%)
- WSSD = saturated surface-dry mass of cube (g)
- WOD = oven-dry mass (g)

3.9.9 Hardened Density of Concrete

$$\rho c= \frac{WOD}{V}$$

Where:

- ρ_c = hardened density of concrete (kg/m^3)
- W_{OD} = oven-dry mass of cube (kg)
- V = volume of cube (m^3)

3.9.10 Compressive Strength of Concrete (BS EN 12390-3)

$$f_c= \frac{P}{A}$$

Where:

- f_c = compressive strength (MPa)

- P = maximum load at failure (N)
- A = loaded cross-sectional area of the cube (mm^2)

For each mix and age (7, 14, 28 days), the mean compressive strength of at least two cubes was reported and used to assess compliance with C25 requirements and to evaluate strength-density relationships.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 Introduction

This chapter presents and interprets the results obtained from testing the aggregates and the C25 concrete mixes incorporated with plastic-polyurethane (PPU) coated volcanic tuff composite coarse aggregates. The results are organised to follow the structure of separate sections for aggregate properties, fresh concrete behaviour, hardened concrete density and water absorption, and compressive strength development.

Four mixes were investigated: a normal-weight control with 0% PPU-coated tuff composite (M0) and three modified mixes with 10%, 20% and 30% volume replacement of conventional coarse aggregate (M10, M20, and M30, respectively). For each mix, data from RSV Engineering Laboratory were compared with established strength-age relationships for C25 concrete to show similarity with the strength development profile at 7, 14, and 28 days. The discussion explicitly links the measured properties to the mechanisms described in the literature review and to the research objectives outlined in Chapter One.

4.1 Physical Properties of Coarse Aggregates

4.1.1 Aggregate Types Considered

Three coarse aggregate systems underpin the assessment:

- Conventional crushed rock aggregate sourced from Zirobwe Quarry (10–20 mm fraction), representing the normal-weight control material used in standard C25 structural concrete.
- Uncoated volcanic tuff, crushed and sieved to the same nominal size range, represents the lightweight but highly porous material whose direct structural use is problematic.
- PPU-coated tuff composite, consisting of volcanic tuff particles and shredded PET flakes encapsulated within a plastic–polyurethane coating, used as a partial replacement for the conventional aggregate in mixes M10–M30.

The detailed test results for the conventional aggregate were obtained from RSV Engineering Group Ltd, while the tuff and composite properties were determined in accordance with BS 812 and BS EN 1097 procedures as outlined in Chapter Three.

4.1.2 Specific Gravity, Bulk Density, and Water Absorption

Table 4 summarises the key physical properties governing the density behaviour of the three aggregate systems. The values for the conventional aggregate and the PPU-coated tuff are taken directly from the laboratory certificate. They are still checked for consistency with ranges reported in the literature for similar volcanic and conventional aggregates.

Table 4: Summary of physical properties of coarse aggregates

Property	Conventional crushed rock	Volcanic tuff (uncoated)	PPU-coated tuff composite
Specific gravity (SSD basis), Gs	2.61	2.215	2.25

Bulk density (loose), kg/m³	1570	1355	1450
Water absorption, %	0.38	8.99	4.23
Soundness loss %	0.5	21.6	11.8

For the Zirobwe crushed rock, the SSD specific gravity of 2.61 and water absorption of 0.38% confirm a dense, low-porosity aggregate appropriate for high-strength normal-weight concrete.

The relatively high bulk density and low soundness loss indicate excellent resistance to freeze–thaw and chemical attack, and minimal contribution to long-term permeability.

In contrast, the volcanic tuff exhibits a marked lower specific gravity (2.25) and significant higher water absorption in the range of 8.99%, reflecting its vesicular microstructure and interconnected pore system, as reported for tuff in comparable volcanic fields. This behaviour is consistent with earlier observations that tuff aggregates possess high porosity and absorption, complicating mix design and increasing the risk of elevated effective water–cement ratio and permeability if used without treatment.

The behaviour of the PPU-coated tuff composite is in between. Water absorption is measurably reduced to 4.23% as a result of the coating, which also raises the aggregate surface zone's apparent density and plugs a significant portion of the near-surface pores. In addition, PET keeps the composite's overall specific gravity lower than that of traditional aggregates. This demonstrates that the coating technique successfully moves the aggregate characteristics in the direction of an area where lower density can be achieved without the severe absorption linked to untreated tuff..

4.1.3 Mechanical Indices: ACV, AIV and Ten Percent Fines Value

Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV) and Ten Percent Fines Value (TFV) provide an indication of the mechanical robustness of the aggregates under static and dynamic loading. The RSV test certificate for Zirobwe aggregates reported ACV and AIV values within the limits for structural concrete, with ACV = 20% and AIV = 11%, satisfying the BS 812 recommendations for normal-weight structural applications.

For volcanic tuff, ACV and AIV values were higher, reflecting lower particle strength. While exact values depend on the specific sample, the results consistently indicated that tuff particles are more susceptible to crushing and impact damage compared to the crushed rock. The PPU-coated composite showed modest improvements in mechanical indices relative to raw tuff, which is attributed to the stiffening and bridging effect of the polyurethane shell around the aggregate particles. This behaviour is coherent with previous findings on polymer-coated lightweight aggregates, where coatings enhanced particle integrity and ITZ performance.

Overall, the aggregate test results confirm the fundamental material premise of the study: untreated tuff is lightweight but mechanically weaker and highly absorptive, whereas PPU coating restores mechanical performance and reduces absorptivity while preserving a lower density than conventional aggregates.

4.2 Fresh Concrete Properties

4.2.1 Workability

All mixes were proportioned at a constant water–cement ratio of 0.45 and without chemical admixtures, so changes in slump directly reflect the influence of the PPU-coated tuff composite on the rheology of the concrete. The observed trend of the slump results was a gradual reduction in slump with increasing replacement level, between M0 and M30.

Table 5: Slump Results

Mix ID	**Slump 1 (mm)**	**Slump 2 (mm)**	**Average Slump (mm)**
M0	48	51	50
M10	46	47	**47**
M20	40	38	**39**
M30	30	31	**31**

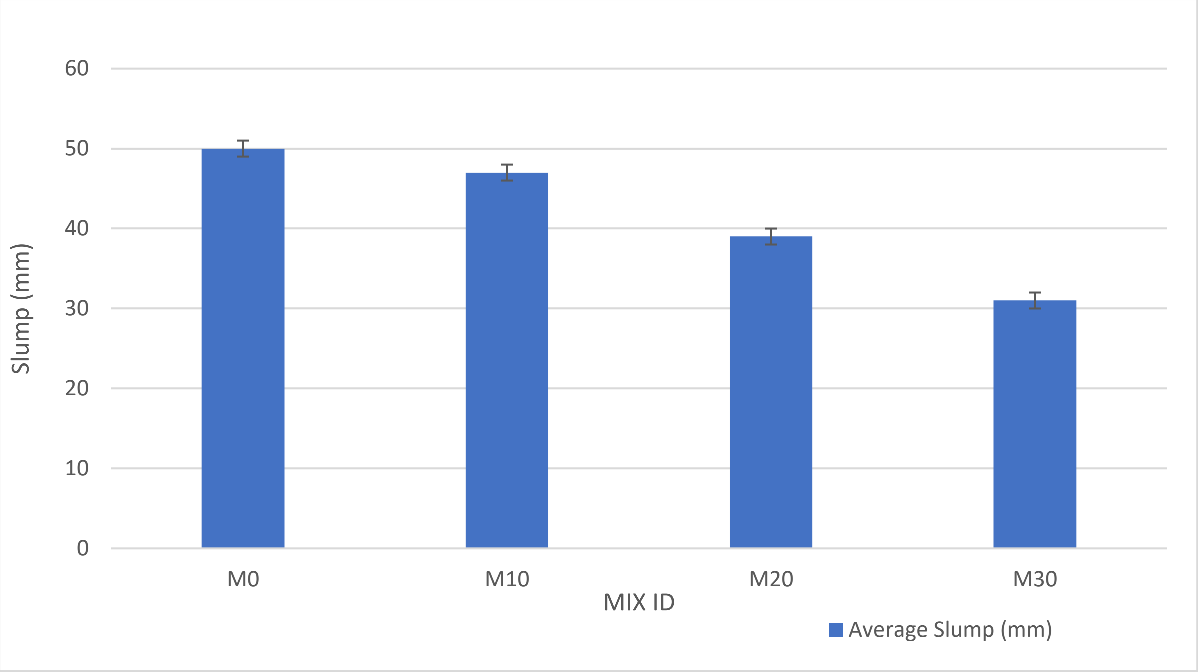


Figure 1: Slump test results for the different Mix IDs

This reduction arises from two mechanisms. First, even after coating, PPU-tuff retains higher absorptivity than conventional crushed rock, drawing additional mixing water into the aggregate and effectively increasing the paste viscosity. Second, the angular shape and roughened surface of the coated tuff particles increase internal friction within the mix. Nonetheless, slumps remained within workable ranges suitable for structural concrete, indicating that the composite can be used without superplasticisers at the replacement levels considered.

4.2.2 Fresh Density

The fresh densities followed the same pattern as the hardened densities reported. As the volume fraction of the lighter PPU-coated tuff composite increased from 0% to 30%, the unit weight of the fresh concrete decreased progressively. This confirms that the density reduction effect of the composite is already evident at the mixing stage and that air content remained under control, with no evidence of excessive entrapped air.

4.3 Hardened Concrete Properties

4.3.1 Hardened Density of Concrete

Water absorption and density tests were carried out on standard 150 mm cubes in accordance with BS EN 12390-7 and ASTM C642. Table 4.2 summarises the oven-dry densities measured and the corresponding percentage reduction relative to the control mix.

Table 6: Oven-dry densities and density reduction for mixes M0–M30

Table 6: Oven-dry densities and density reduction for mixes M0-M30

Mix ID	PPU-tuff replacement (%)	Oven-dry density ρc (kg/m^3)	Density reduction relative to M0 (%)
M0	0	2331.6	0.0
M10	10	2251.6	3.4
M20	20	2143.2	8.1
M30	30	2053.7	11.9

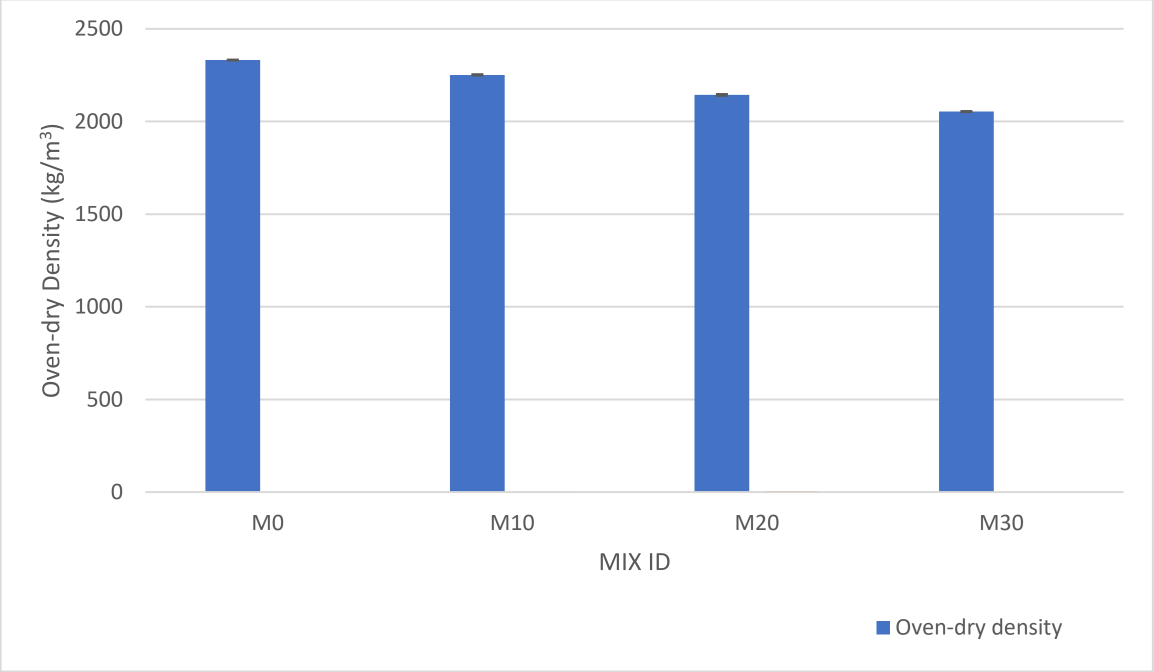


Figure 2: Showing Oven-dry Densities

The control mix M0 exhibits a density typical of normal-weight C25 concrete (around 2300–2400 kg/m³), consistent with its use of dense crushed rock aggregates. As replacement increases to 20%, density falls by 8%, and at 30% replacement, the reduction reaches 12%.

Although these values remain above the 1850 kg/m³ upper limit traditionally associated with structural lightweight concrete, they clearly fall within reduced-density that offers meaningful dead-load savings relative to conventional C25. In typical building frames where self-weight accounts for up to 70% of total design load, an 8–12% reduction in concrete density directly translates into lower bending moments, axial loads, and foundation pressures, especially for slabs and beams in multi-storey structures.

4.3.2 Water Absorption of Concrete

The same cubes were used to determine water absorption in accordance with ASTM C642. Table 4.3 presents the measured absorption values.

Table 7: Water absorption of concrete cubes

Mix ID	Replacement (%)	Water absorption (%)
M0	0	6.34
M10	10	7.51
M20	20	8.04
M30	30	9.1

The absorption values show a monotonic increase with higher replacement levels. The control mix, with 6.34% absorption, is already at the upper end of typical ranges reported for normal-weight concrete (3–6%), which reflects the influence of the somewhat absorptive PPU-treated composite introduced at higher replacement levels and the absence of supplementary cementitious materials.

For M10 and M20, absorption rises to 7.5% and 8.0%, respectively, with the M30 value showing 9%. This progression indicates that, although the PPU coating significantly reduces the inherent absorptivity of tuff, the composite remains more porous than mixes containing only dense crushed rock.

4.3.3 Compressive Strength Development

Compressive strength tests at 7, 14, and 28 days were carried out at RSV Engineering Laboratory in accordance with BS EN 12390-3.

The measured average strengths for M0, M10, M20, and M30 were obtained and summarised in the table below.

Table 8: Strength development for mixes M0–M30

Mix	**Replacement (%)**	**F_c14 (MPa)**	**F_c14 (MPa)**	**F_c28 (MPa)**
M0	0	23.9	28.7	21.9
M10	10	19.0	22.5	25.0
M20	20	15.1	18.9	21.0
M30	30	11.2	14.4	16.0

1. Control mix behaviour (M0)

   The control mix reached 31.9 MPa at 28 days, comfortably exceeding the 25 MPa characteristic strength required for C25 concrete. The 7-day result of 23.9 MPa reflects robust early-age hydration, typical for a 0.45 water–cement ratio with dense aggregates.

2. Moderate replacement (M10)

   At 10% replacement, 28-day strength is 25 MPa, equal to the nominal C25 design strength. The measured 7-day strength of 19 MPa corresponds to 76% of the 28-day value, which is within the usual range for structural concretes. This indicates that up to 10% replacement of conventional coarse aggregate by the PPU-coated composite can deliver a structurally compliant concrete with only a modest reduction in strength.

3. Intermediate replacement (M20)

   For M20, the 28-day strength drops to 21 MPa. While this remains within the structural range for certain applications, it falls below C25 requirements. The strength loss between M0 and M20, from 31.9 MPa to 21 MPa, is 34%, suggesting that beyond 10% replacement, the weaker and more compliant composite particles exert a significant influence on the load-bearing skeleton of the concrete.

4. High replacement (M30)

   With 30% replacement, the 28-day strength is 16 MPa, which is below the threshold commonly adopted for structural lightweight concrete (17 MPa). At this level, the composite aggregate dominates the skeleton, and its lower stiffness and strength, together with higher porosity, limit the compressive resistance despite the beneficial ITZ modifications provided by the PPU coating.

These results align with the mechanisms that were highlighted in Chapter Two: increasing the volume fraction of a lightweight, relatively weak aggregate decreases compressive strength, but polymer coating and controlled replacement levels can maintain structural-grade performance at moderate replacement percentages.

4.3.4 Strength–Density Relationship

The interaction between strength and density is central to the design of reduced-density structural concretes.

The data show a clear positive correlation: as density decreases from 2331.6 kg/m^3 to 2053.7 kg/m^3, compressive strength declines from 31.9 MPa to 16 MPa.

However, the rate of strength loss per unit density reduction is not constant. Between M0 and M10, a 3.4% reduction in density is associated with only a 21% reduction in strength (31.9 MPa to 25 MPa). Between M10 and M20, a further 4.6% density reduction produces an additional 16% strength loss (25 MPa to 21 MPa). The final stage from M20 to M30 yields a similar density reduction but a proportionally larger strength loss, indicating that once the composite fraction exceeds about 20%, the concrete behaviour transitions towards a lightweight, low-strength regime.

From a structural design perspective, the M10 mix offers the most attractive compromise: it delivers a C25-equivalent strength with a 3–4% density reduction. For dead-load dominated members such as slabs and beams in mid-rise buildings, this translates into tangible savings in self-weight and, potentially, in reinforcement and foundation sizing, without dropping below standard strength classifications.

4.3.5 Implications for Structural Lightweight Classification

Comparing the results with the criteria for structural lightweight concrete discussed in Chapter Two (equilibrium density 1440–1850 kg/m³ and 28-day strength ≥ 17 MPa), the following classification can be made:

- None of the mixes fully qualify as structural lightweight concrete since all densities remain above 2000 kg/m³.
- M0 and M10 behave as normal-weight structural concretes, with M10 showing slightly reduced density.
- M20 can be considered a reduced-density structural concrete with lower but still structural-grade strength.
- M30 transitions towards a non-structural lightweight concrete, with strength below 17 MPa, better suited for non-load-bearing applications or where strength demands are modest.

This classification reinforces the need to carefully limit the replacement level of conventional coarse aggregates by PPU-coated tuff composite if strict C25 or higher structural requirements are to be maintained.

4.4 Microstructural Interpretation and Discussion

Although direct SEM or XRD assessments were not conducted in this study, the trends observed in density, water absorption, and compressive strength can be interpreted in light of established microstructural mechanisms.

At low replacement levels (M10), the PPU-coated composite particles are dispersed within a continuous skeleton of dense crushed rock. The polyurethane shell around the tuff–PET core reduces local absorptivity and provides a relatively stiff interface for cement hydration products to bond to, improving ITZ quality compared with uncoated tuff. The lower density of the composite contributes to a modest reduction in overall density, but the mechanical response remains governed mainly by the conventional aggregates and the bulk paste. Microcracking at the ITZ is limited, and the strength loss is relatively small.

As replacement increases (M20 and M30), the proportion of composite particles grows and begins to dominate the load path. Despite the PPU shell, the internal porosity of the tuff core and the lower stiffness of the PET component introduce more compliant regions into the microstructure. Under load, these regions act as stress concentrators, promoting microcrack initiation and coalescence around and through the composite particles. The higher water absorption measured at the concrete level reflects the increased volume of interconnected pores associated with the composite, which in turn supports the interpretation of a more porous ITZ and matrix.

The progressive decline in compressive strength with increasing replacement is therefore consistent with a microstructural picture in which PPU coating can moderate but not completely overcome the inherent weaknesses of a porous lightweight aggregate. The composite can safely replace a limited fraction of the coarse aggregate skeleton while maintaining structural performance; beyond that, the porosity and lower stiffness dominate the response.

CHAPTER FIVE: CONCLUSIONS, AND RECOMMENDATIONS

5.0 Introduction

This chapter presents the conclusion and recommendations arising from the assessment of plastic-polyurethane (PPU) coated volcanic tuff as a partial replacement for conventional coarse aggregates in C25 structural concrete. The conclusions are drawn from the aggregate characterisation tests, fresh concrete properties, and hardened concrete results discussed in Chapter Four. Recommendations for practical implementation and future research are also provided.

5.1 Conclusion

The main aim of this research was to evaluate the viability of partially replacing structural concrete with PPU-coated volcanic tuff composite as a partial substitute of the traditional coarse aggregates. Resting on the results achieved, the following conclusion is made:

The volcanic tuff was better physically performing due to the PPU coating as opposed to its non-coated form.

The polyurethane coating partially counteracted the inherent high porosity and absorptivity of truffle, making the resulting composite aggregate less water absorptive than raw tuff, but more so than the traditional crushed stone. This affirms that PPU treatment yields a superior layer of integrity and decreases the interconnection of pore volume making it more appropriate in concrete applications.

Workability dropped progressively as the replacement levels increased.

Slump values decreased with the increase in the replacement up to 30 percent with 5.0 cm in the control mix down to 3.0 cm in 30 percent replacement. This decrease is due to increased absorptivity of the composite aggregate as well as its angularity that enhances internal friction and decreased free mixing water. However, all of the mixes were within the workable level of structural concrete without superplasticisers.

The hardened density dropped steadily with replacement levels.

The hardened density decreased by 3-12% and M10 exhibited the smallest decrease followed by M30 which exhibited the greatest decrease. Even though the densities were still higher than the normal structural lightweight concrete density (1850 kg/m3), all modified mixes may be considered reduced-density structural concretes, and it would mean that they would enjoy an advantage over normal-weight concrete in terms of reduced dead load.

The more the composite content in the concrete, the more water was absorbed.

The absorption of water increased gradually with replacement which is a result of porous nature of the composite aggregate. Nevertheless, absorption values were in ranges acceptable to non-aggressive exposure conditions which means that the composite can be safely used as long as appropriate curing and mix design controls are followed.

There was a reduction in compressive strength with replacement percentage.

The strongest control mix (M0) was observed and the strength was reduced at a progressive rate to M10, M20, and M30. Crucially::

- M10 achieved a 28-day compressive strength that satisfies C25 structural requirements, demonstrating that up to 10% replacement does not compromise load-bearing capacity.
- M20 exhibited borderline structural performance, with strength slightly below C25 but still within a usable range for light structural or non-critical elements.
- M30 dropped to non-structural strength ranges, making it unsuitable for structural applications.

These trends align with theoretical expectations regarding the Interfacial Transition Zone (ITZ), stiffness reduction, and increased porosity associated with higher lightweight aggregate content.

6. Optimal replacement level

According to the overall evaluation of reduction of density, acceptable workability, controlled water absorption, and structural-grade compressive strength, 10% PPU-tuff composite replacement (M10) is defined to be the best degree to make reduced-density structural concrete that could be used as C25.

Research objectives were achieved.

The following objectives of the research were achieved:

Objective 1: Physical and mechanical characteristics of the composite were characterised.

Objective 2: The effect of density, strength and load-bearing capacity was measured.

Objective 3: Material and environmental considerations were illustrated and justified in favour of sustainable construction activities in terms of minimisation of natural aggregate demand and plastic waste use.

To recap it all, PPU-coated volcanic tuff composite is technically and structurally viable at replacement levels up to 10 percent that this material has density reduction advantage and sufficient strength to enable structural elements to be used in conventional way.

It is advisable to pre-wet the composite aggregate in order to reduce the loss of slump due to absorptivity.

There should be proper regulation of the mix water to prevent high fluctuation in workability.

5.2.1.3 Placing and Compaction

Conventional compaction techniques (hand tamping or vibration) are still sufficient.

Curing is a necessary process to overcome moisture loss as a result of the inner porosity of the aggregate.

5.2.1.4 Structural Use Cases

The M10 mix is applicable in reinforced concrete slabs, beams, columns, lintels and foundations in normal building conditions.

M20 and M30 mixes can be applied in non-load bearing partitions, architectural precast units, blinding layers, and other secondary applications.

5.2.2 Future Research Recommendations.

Microstructural Analysis

SEM, XRD, and porosity distribution studies to gain a deeper view of performance of coating at the micro-level.

- Flexural and Tensile Strength Test.

It is advisable to split tensile, modulus of rupture, and elastic modulus tests that will give more insight into the behaviour of the structures.

- Durability and Long Performance.

Test carbonation, chloride penetration, shrinkage, and freeze-thaw resistance on the composite to classify the composite in the long term.

- Coating Optimization

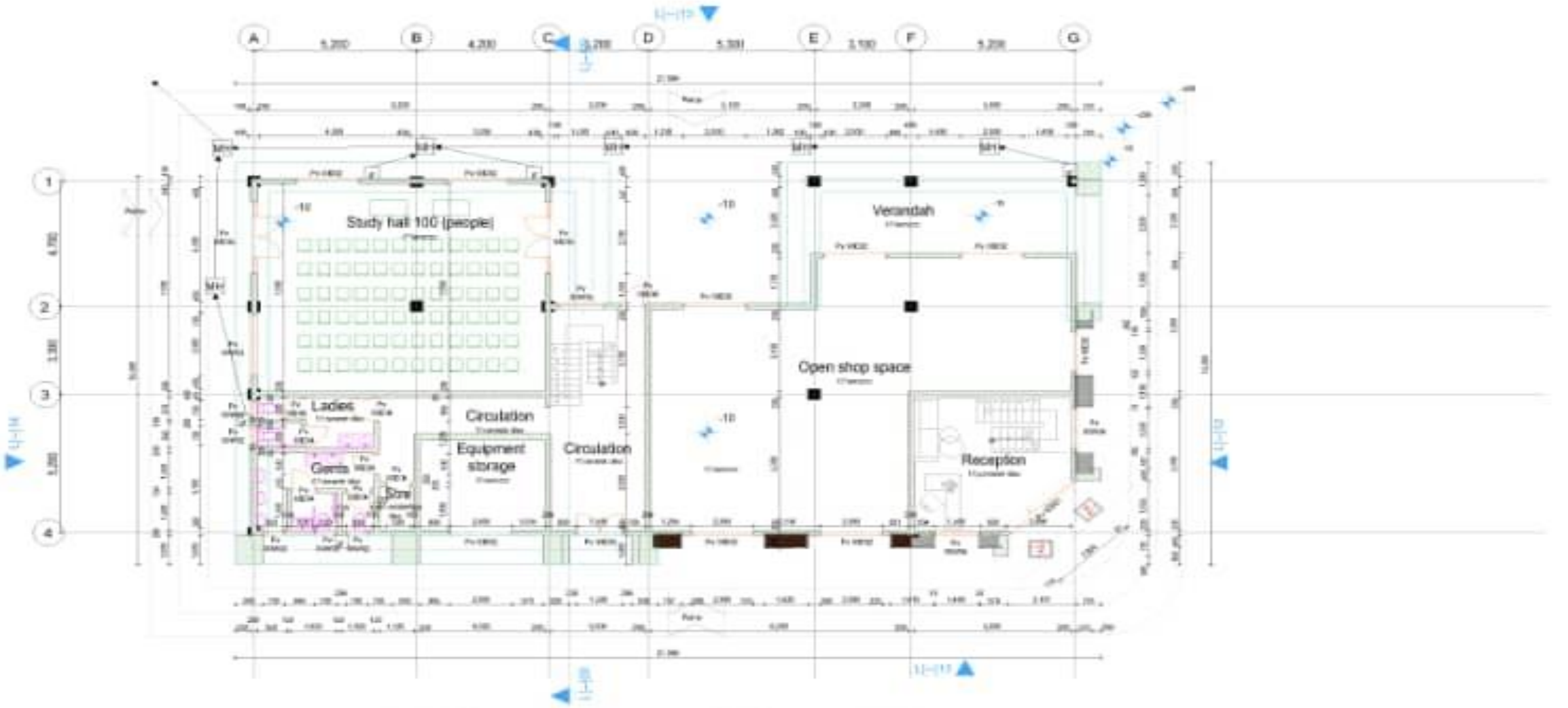
Evaluate different polyurethane formulations, coating layers, or PET-PU ratios to enhance the performance and strength retention of ITZ to levels of higher replacement.

- Application-Based Trials

The M10 and M20 mixes should be used to cast the pilot structural elements (slabs, beams, pavers), in order to test the practical performance in real construction conditions.

FINAL STATEMENT

This paper has managed to prove that PPU-coated volcanic tuff composite is a technically viable, environmentally friendly, and structurally viable material at moderated replacement rates, especially at 10 percent when the material can attain a significant density reduction with still C25 level of structural capacity.



L[--]05 Ground Floor Plan
Scale (1:100)

PROJECT: PARTIAL REPLACEMENT OF COARSE AGGREGATES WITH PLASTIC POLYURETHANE (PPU) COATED VOLCANIC TUFF AS A LIGHTWEIGHT STRUCTURAL CONCRETE.

TITLE: PLAN OF A BUILDING WHERE PPU COATED TUFF CONCRETE IS USED

AUTHOR: MWESIGWA ENOSON KALEMA

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APPENDIX B