Upcycling Agricultural and Plastic Waste for Sustainable Construction: A review

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HIGHLIGHTS

- Mechanical strength initially increases with waste content but decreases after a threshold
- Waste content inhibits bonding in cement or soil-based materials.
- Waste integrated components are suitable for non-structural elements.
- Integrating waste results in construction materials for light weight applications.
- Agricultural and plastic waste improves thermal insulation properties.

Abbreviations

AR: Alkali Resistant

ASTM: American Society for Testing and Materials

BIS: Bureau of Indian Standards

CO_2: Carbon dioxide

FRC: Fibre-Reinforced Concrete

OPC: Ordinary Portland cement

PE: Polyethylene

PET: polyethylene terephthalate

POFA: Palm Oil Fuel Ash

PP: Polypropylene

PS: Polystyrene

PVC: Polyvinyl Chloride

PUR: Polyurethane

RPETFRC: Recycled PET Fibre-Reinforced Concrete

WPET :Waste PET

WPLA: Waste Plastic Lightweight Aggregates

WMP: Waste Metalized Plastic

ABSTRACT

The production of conventional construction materials such as concrete, cement, and bricks, has contributed significantly to the high environmental footprint associated with the construction industry. Moreover, there is a global push to deviate from the linear take-use-dispose model to a circular economy model, which incorporates upcycling and reuse of materials. This paper reviews the application of agricultural and plastic wastes, in construction, exploring the performance of the resulting component using five key parameters: compressive strength, tensile strength, flexural strength, density, and thermal conductivity. The study showed that the compressive, tensile, and flexural strengths can be increased slightly by increasing waste content, however, this only occurs in a narrow range after which an increase in waste content reduces the mechanical strength. This reduced strength can be attributed to a weaker bond resulting from the increased waste content. It also suggests that components may not directly benefit from the mechanical properties of waste materials. The waste materials resulted in a lower density which has implications for lightweight applications. Similarly, both waste materials were observed to improve the thermal insulation properties which is an advantage for improving thermal comfort in buildings. Despite the reduction in mechanical strength, it was observed that components with waste materials can be used for non-structural elements, thereby reducing the quantity and cost of new materials to be used. The application of these wastes in construction offers a pathway to reducing the environmental impact of construction, avoiding reliance on landfills for waste disposal, and reducing construction costs.

KEYWORDS

Waste materials; plastic waste; Agricultural waste; sustainable construction; circular Economy; Sustainability

1 Introduction

Global waste production has increased in recent years due to a myriad of factors. According to Tiseo (2022) [1], worldwide municipal solid waste production will increase to 3.4 billion metric tons by 2050 from 2.02 billion metric tons in 2016. Likewise, developing countries such as India produce significant quantities of agricultural waste which has led to serious disposal problems. The reuse of these wastes as sustainable construction materials could contribute to solving the waste management crisis [2]. Furthermore, the energy consumption of buildings can be observed across their entire lifecycle from construction up to the demolition stage. Energy consumption in buildings can be direct or indirect (i.e. operating or embodied) within the phase of its lifecycle from cradle to grave [3]. It is estimated that around 60% of the world's extracted raw materials from the earth's crust are used in the construction sector, and therefore, embodied energy is used in the material extraction process [4].

In the building sector, concrete, bricks and steel are among the most used construction materials. The main issues associated with bricks are their production, material acquisition and transportation. Clay is one of the main components of bricks, its extraction from quarries causes long-term impacts on the landscape. The firing of clay has high embodied energy and produces high levels of carbon dioxide, moreover, it produces pollutants such as chlorides, sulphur, nitrogen oxides and fluorides [5]. It is estimated that the brick construction sector produces around 80 tons of particulate matter, 30 tons of carbon, 7 tons of nitrogen oxides and 5 tons of sulphur oxides [6].

Additionally, the production of cement and steel causes serious damage to the environment. Their production relies on the heavy depletion of natural resources and produces harmful pollutants to both the environment and human beings. The process is also very energy demanding. Concrete is composed of three basic components: water, cement and aggregates (such as sand and rock). Like the firing of clay, the manufacturing of cement and steel also produces CO_2 emissions. It is believed that the building industry produces between 5-7% of the global CO_2 emissions [7]. The impact of CO_2 emissions on the environment is disastrous and can lead to adverse effects such as ozone depletion, acid rain and global warming [8]. These emissions not only affect the environment but also deteriorate human health. Studies such as Skinder et al. (2015) [6] have shown a clear link between CO_2 emissions and health problems. The negative effects of CO_2 emissions, health problems and the threat of climate change, have made more than 170 countries sign the historic Paris Agreement, including the largest emissions producers in the world (U.S. and China). This alone is a testament to the seriousness of the current environmental conditions (Committee for Climate change, CCC, 2019) [9].

Nevertheless, one approach to tackling the negative effects mentioned above is by utilizing waste materials for developing alternative sustainable building materials. Several scholars have investigated the suitability of upcycling materials for construction. For example, Choi et al. (2009) [9] investigated the use of Polyethylene terephthalate (PET) bottles as fine aggregate to produce lightweight aggregate concrete. While Segetin et al. (2007) [10] investigated the compressive strength of the soil cement composites after the Harakeke fibres were coated with enamel paint to improve bonding between the cement and fibre matrix. Oyinlola et al. (2018) [11] explored upcycling PET bottles for low-cost construction. The growing interest in waste material for construction is further demonstrated by the quantity of review papers in recent times [12–14].

This article contributes to the discourse of utilising waste materials for sustainable construction by providing insights on five key parameters of building materials incorporating Agricultural waste or Plastic waste. These five parameters: compressive strength, tensile strength, flexural strength, density, and thermal conductivity, are important considerations when determining the suitability of alternate building materials [15,16]. Waste materials are usually integrated into construction either as fibres for reinforcement or as granules for bulking or improving performance. Therefore, this study further explores the influence of the method of integration on the performance.

2 Review of Agricultural waste in Construction

Agricultural Waste (Agro-waste) refers to waste generated from various agricultural operations [17]. Examples of agro-wastes include palm kernel shells, palm kernel ash, wood saw dust, rice husk ash, rice straw, peanut shells, coconut shells, cassava peels, sugarcane bagasse, oat straw, flax boon, barley straw, wheat straw, rye straw, plant stalks, etc. [18]. Agricultural waste has been considered as a promising replacement/addition to traditional construction materials due to the geometric increase in the amount of agro-waste produced in countries [18], and also because of the large demand in construction materials from the increased population in recent times [19,20].

Consequently, various researchers have investigated the application of different types of agro-waste in construction. For example, Sathiparan and De Zoysa, (2018) [21] investigated the effects of partially replacing sand with agricultural-wastes like sawdust, rice straw, rice husk, peanut shells and coconut shells. Bakatovich et al. (2018) [22] manufactured thermal plates made from agricultural waste comprising of wheat straw, barley straw, oat straw, rice straw, rye straw, rice husk and flax boon bonded together with PVA emulsions, liquid glass, or latex. Other researchers have also investigated the application of agricultural waste in panels/plates [23,24].

Agro-waste has been widely used as fibres from time immemorial, for example, in ancient Egypt, bricks were reinforced with straw fibres. Agro-waste used as fibres in sustainable construction include basalt fibre, coir fibre, cellulose fibre, coconut fibre jute fibre. The advantages of these natural fibres over traditional materials include lower costs, lower density, good thermal properties, non-abrasive, non-toxic, renewable and biodegradable [25]. Various scholars have investigated the application of these fibres in building components such as roofing tiles, insulation, soil blocks, cement stabilized soil and concrete.

Coir fibre was used by Darsana et al. 2016 [26], to replace 10% cement of the roofing tiles. The aim was to reduce the weight of the roof tiles and strengthen them. The result of the experiment showed that the addition of coir fibres reduced the self-weight, cost, and improved the breaking load and ductility of the tiles. Lopez et al. (2016) [27] investigated the use of flax, jute and hemp to replace traditional insulating materials like fibre glass and polyurethane. The investigation showed promising results as plant-based fibres required lower energy to process the materials when compared with traditional insulating materials. Buratti et al. (2015) [23], Lopez et al. (2016) [27] and Hansen et al. (2001) [28] all agree that the use of fibres such as flax, jute and hemp as an insulating material is cheaper than traditional insulating materials, because of the low energy demand. Table *1* presents the mechanical properties of some of the agro- waste reviewed in this paper.

Table 1: Mechanical Properties of some Agro-Waste

Agro-Waste	Ultimate Tensile Strength (MPa)	Flexural modulus of elasticity (MPa)	Density (Kg/m^3)	Thermal conductivity (W/mK)
Sugarcane Bagasse	25 -62 [33]	500-1300 [33]	560 [33]	0.08 [75]
Coconut	83-222 [33]	230-280 [33]	810 [33]	0.048[76]
Oil Palm	65-141 [33]	700-1100 [33]	770 [33]	0.2688 [77]

This section uses the five key parameters (compressive strength, tensile strength, flexural strength, density, and thermal conductivity) to examine the performance of construction materials that have been made with upcycled agricultural wastes.

2.1 Compressive strength

The compressive strength of a material is defined as the capacity of the material to withstand loads tending to push it together [29]. The compressive strength of a material is therefore considered a key parameter for construction purposes. For example, bricks at the base of a wall will be under compression and its capacity to withstand the weight of the wall is its compressive strength. It is important to understand the compressive strength of the resulting combination from agro-waste inclusions as this will indicate its suitability as a construction material. Several scholars have investigated the effect of introducing different types of Agro-waste in construction on the compressive strength.

2.1.1 Agro-waste Fibres

Khedari et al. (2005) [30], produced 18 samples of cement stabilized soil with varying mix ratios of soil, cement, sand and coconut fibres. They observed that the inclusion of fibre content reduced the compressive strength. The compressive strength decreased by up to 82% with the mix ratio of 4.5:1.5:2:0.8 respectively. The results also indicate that the compressive strength of the samples with mix ratios up to 4.75:1.25:2:0.8 respectively meet the minimum requirements of the (ASTM C 129. 2006) for non-load bearing walls. For these samples the compressive strength ranged from 3.05 MPa – 5.79 MPa. It was also observed that the low soil ratios to high cement ratios decreased compressive strength.

Bentchikou et al. (2012) [31] utilized cellulose fibres as cement replacement for lightweight cement composite. The cellulose fibres content in the composite ranged from 0% to 16% by mass of cement. They report that the compressive strength decreases when the fibre content increases due to voids that weaken the material.

Furthermore, Taallah et al. (2014) [32], studied the behaviour of date palm fibres in soil blocks stabilized with cement. The fibres' lengths and content ranged from 20mm-35mm and 0%-0.2% respectively. The study investigated the samples under both wet and dry conditions (submerged and unsubmerged in water) with cement content of 5%,6.5% and 8%. As expected, the samples which were dry and contained higher cement content yielded higher compressive strength results. It was also observed that the compressive strength decreased with the increase of fibre content. The sample containing 0.05% fibre and 8% cement content was the only one to experience an increase in strength (6%) compared to the control sample. The decrease in strength of the soil cement sample could be explained by the increase in pores and lower bond strength of the specimens caused by the inclusion of fibres. Similarly, Danso et al. (2015) [33], tested two soil block samples, soil B (brown) and R (red) which had a higher clay content. Sugarcane, oil palm fruit and coconut husk fibres were used as reinforcement in soil blocks with fibre content ranging from 0.25% to 1% by weight. The study showed that the inclusion of fibres increases the compressive strength. It was found that the optimum fibre content was 0.5% for the sugarcane and coconut husk, alongside 0.25% for the oil palm fruit. An increase in compressive strength for the sugarcane, coconut and oil palm fibres was observed to be 18%, 57% and 53% in soil B and 21%, 41% and 42% for soil R respectively. The higher increase in compressive strength of soil R compared to soil B was associated with the higher clay content present, thus improving the adhesion between the matrix and fibres.

Wei et al. (2018) [34] also investigated the effect of soil blocks stabilised with lime and reinforced with rice straw, wheat straw at different content levels and lengths. The fibre lengths and content ranged from 6mm-36mm and 0.1%-0.3%. The results show that the inclusion of fibre increases the compressive strength however, once the fibre content exceeds an optimum proportion, the compressive strength decreases. Likewise, Sujatha and Selsia Devi (2018) [35] researched the use of jute fibre and banana fibre amongst others in soil blocks. The fibre content used ranged from 0.25% to 1% and the lengths of the natural were 60mm-70mm. The inclusion of fibre greatly impacted the compressive strength. The compressive strength increased with the increase of fibre content which was observed to have gained a minimum of around 50% strength compared to the control sample at 0.75% fibre content. The highest recorded compressive strength values were for the jute fibre followed by the banana fibre.

Islam et al. (2018) [36] investigated the use of jute fibres as reinforcement in concrete blocks. The samples with the jute fibres varied in length and content ranging from 10mm and 20mm and 0%-1% respectively for each of the lengths. The compressive strength increased with the inclusion of 0.25% fibres (20mm) and 0.5% (10mm). However, at 1% content inclusion the compressive strength decreased. Similarly, Kammoun and Trabelsi,(2019) [37], investigated the use of prickly pear fibres in concrete blocks. Samples were produced with hot water treated fibre, with content and length ranging from 0 kg/m^3 - 15 kg/m^3 and 2cm-5cm. The results show the usual trend of concrete compressive strength increasing over time and decreasing with the increase of fibre content. The compressive strength of the control sample was 32 MPa and the lowest decrease in compressive strength was observed for the sample containing 15 kg/m3 of fibre content after 28 days of curing by 29%. The study also showed that as the length of the fibres increase, the compressive strength decreases accordingly.

It is clear from the studies above those integrating fibres has an effect on the compressive strength of the component regardless of if they are soil blocks, cement stabilized soil or concrete. For soil block samples, research by [33], [34]and [35] show an increase in compressive strength when fibre waste is introduced. Similarly, the concrete sample study [36] agrees that there is a corresponding increase in compressive strength when fibre is introduced. This increase in compressive strength was observed at fibre contents below 5%, however, studies by [32] [30] and [37] show that at fibre contents above 10%, the compressive strength in concrete and cement stabilized soil begins to decrease, which was also highlighted by [38]

2.1.2 Agro-waste Granules

Turgut et al. (2007) [39] studied the effect of combining wood sawdust and concrete on the compressive strength of concrete, using three different mix proportions (10% to 30% wood sawdust replacement) to manufacture the samples. The samples were cured in a lime saturated water tank for 28 days. The compressive strength of the 10% , 20% and 30% were 16.6 MPa, 11 MPa and 7.2 MPa respectively. The data shows that the increase in wood sawdust drastically reduces the compressive strength by up to 71% compared to the control sample.

In the same vein, Muntohar (2011) [40] investigated the use of rice husk ash and lime for soil stabilization. Several samples with varying rice husk ash and lime content were made. Some samples were submerged in water before testing, whereas others were moist cured at room temperature. It was observed that the samples submerged in water displayed lower compressive strength than those moist cured at air temperature. The compressive strength was observed to increase with the addition of lime and rice husk ash. The optimum lime to rice husk ash ratio (5% by weight each) which yielded the highest compressive strength value was 1:1. Samples containing clay-sand showed lower compressive strength than the clay samples. This result is due to the clay particles being finer and thus the highest recorded compressive strength value was 20.7MPa for the clay sample.

Villamizar et al. (2012) [41] investigated the addition of fly ash and cassava peels in soil block. Five samples with different percentages of clayed soil, fly ash and cassava peels were made. The result showed that the highest average recorded strength value was 3.31 MPa and was for the sample containing 95% clayed soil and 5% fly ash. The sample containing 90% clayed soil, 7.5% fly ash and 2.5% cassava peels had the second highest average compressive strength value of 2.53 MPa followed by the sample containing 95% clayed soil and 5% cassava peels at around 2.25 MPa. The lowest average recorded compressive strength values were for the samples containing 90% clayed soil, 10% fly ash and 100% clayed soil at 1.97 MPa and 1.06 MPa respectively. The results showed that the samples containing cassava peels and fly ash experienced an increase in compressive strength. The study indicates that the cassava peels should be combined with fly ash to obtain the best results. On the other hand, the data shows that the fly ash content should not exceed 5% as this has an adverse effect on the compressive strength.

Rahman et al. (2014) [42] examined the introduction of oil palm kernel shells in a lightweight masonry block. Samples were produced using three different oil palm kernel shells sizes (size A up to 2.36mm, size B up to 4.75mm and size C up to 9.5mm) and cement: sand: shell mix ratios (1:1:1, 1:1:2 and 1:1:3). All samples exceeded the compressive strength value of the control sample (around 11 MPa) except those with the mix ratio of 1:1:3 and the sample with size A shells and mix ratio 1:1:2. This shows that an increase in oil palm kernel shells reduces the compressive strength. The highest recorded compressive strength value was 23 MPa for the sample with size A and mix ratio 1:1:1. In general, the sample with lower sized shell particles displayed higher compressive strength values. However, this was not the case for the samples with mix ratios of 1:1:2 where the trend was reversed. Alsalami et al. (2018) [43], likewise, investigated the addition of dates palm kernel shells, crushed palm kernel and palm kernel ash as a concrete replacement with contents ranging from 0% - 40%. The compressive strength of the samples was measured after 7,28 and 56 days of curing. Findings from his study show that the compressive strength of the dates palm kernel shells, crushed dates palm kernel and dates palm kernel ash after 28 days curing ranged from (46 MPa-63 MPa), (49 MPa-67 MPa) and (51 MPa-71 MPa) respectively. The higher compressive strength values of the kernel ash and crushed kernel could be linked with the kernel shells lower surface area and higher number of pores (on the shells surface) which reduced the adhesion between the shells and cement. The kernel ash experienced the least reduction in strength which can be explained by the small particles filling the small gaps. Hence, there is an increase in compressive strength with the addition of date palm kernel ash.

Sathiparan et al. (2018) [21] prepared samples with three different mix ratios (1:5:1, 1:4:2, 1:3:3 - cement: sand: agro-waste). Peanut shells, sawdust, rice husk, coconut shells and rice straw were selected as potential sand substitute materials. In general, the samples with the mix ratio of 1:5:1 displayed the highest compressive strength value. However, this was not the case for the peanut shell samples as the mix ratio of 1:4:2 showed the lowers compressive strength. The coconut shell sample achieved the highest compressive strength with a value around 7.8 MPa followed by the rice husk, sawdust, peanut shell, and straw samples with values around 5.7 MPa, 5.6 MPa, 4.3 MPa and 3.1 MPa respectively. The control sample compressive strength was around 9.2 MPa. All samples with the mix ratio of 1:5:1 and 1:4:2 met the (ASTM 2006) requirements (minimum of 4.14 MPa) except for the straw samples where no mix ratios met the requirements.

Likewise, Kazmi et al. (2018) [44] incorporated sugarcane bagasse ash and rice husk ash at different ratios (5,10 and 15%) as aggregate replacement in burnt clay bricks. The results indicated that the samples with sugarcane bagasse ash and rice husk ash by up to 15% content met the compressive strength minimum requirements of several standards such as the (AS/NZS4455 2008) and (Bureau of Indian Standards (BIS) 1992) for sustainable construction. At 5% waste content both the sugarcane bagasse ash and rice husk ash samples exhibited their highest and similar compressive strength with values around 7MPa. At 10% and above, the rice husk ash exhibited higher compressive strength compared to the sugarcane bagasse ash sample. The lowest recorded compressive strength value was 5.01MPa for the sugarcane bagasse ash sample.

Ozturk et al. (2019) [45] investigated the application of waste tea in clay brick samples with content ranging from 2.5% to 12.5%. The results of the study follow the trend mentioned in other studies of showing a decrease in compressive strength with the increase of waste content. The compressive strength values obtained ranged from 6.6 MPa to 34.2 MPa. The samples with 12.5% tea waste content displayed the lowest compressive strength values with reductions of up to 79% compared to the control sample. The reduction in compressive strength was attributed to the tea waste burning during the firing process which increased the porosity of the bricks. The increase in porosity has been linked with a decrease in compressive strength by other studies.

2.2 Tensile strength

The tensile strength of a material is defined as the capacity of the material to withstand being stretched or pulled [29]. This property is a measure of the resistance to tension and is therefore significant in materials used for construction, especially those required as structural elements. The tensile strength predicts how well a building component will behave when external forces such as wind and gravity act on it.

2.2.1 Agro-waste Fibres

Taallah et al. 2014 [32] further investigated the effect of date palm fibres in soil blocks stabilized with cement to observe changes in the tensile strength. It was reported that an increase in fibre content resulted in a decrease in tensile strength. The highest recorded decrease in tensile strength was seen in the sample containing 0.2% fibre content. The decrease in tensile strength were 14%, 18.5% and 23.5% for the samples containing 8%, 6.5%, 5% cement and 0.2% of fibre content. The decrease in tensile strength was linked to the weak strength and distribution of the fibres which could cause the formation of clusters which increases the porosity of the sample and thus reduces the strength.

Danso et al’s. 2015 [33] results showed that fibre content between 0.25% and 0.5% by weight yielded the highest tensile strength. The tensile strength increase for the sugarcane, coconut, and oil palm fibres at optimum content in soil B was 21%, 29% and 38% and 16%,23% and

35% for soil R respectively. The cracks observed in the reinforced samples were fine whereas the control sample produced one large crack. Similarly, Sujatha and Selsia Devi (2018) [35] observed that the inclusion of fibres in soil blocks increases the tensile strength. The tensile strength of the samples with jute and banana fibre ranged from 5.61 MPa-9.89 MPa and 2.28 MPa-7.46 MPa respectively. The highest improvement in tensile strength compared to the control sample was 81% and 74% respectively.

Islam et al. (2018) [36] tested the relationship between fibre content and length with tensile strength. The samples in the tensile strength were cylindrical and results were obtained on the 28th and 90th day. The results show that the effect of fibre inclusion on tensile strength was negligible. However, this was not the case for the samples containing 0.5% fibre content which saw an increase of 24% (20mm) and 15% (10mm) in tensile splitting strength on the 90th day compared to the control sample.

2.2.2 Agro-waste Granules

Yang et al's. (2005) [46] experiment introduced oyster shells in concrete. The result showed that the 28th day tensile strength obtained was higher, with a smaller replacement value than the control concrete. Also, as the replacement value increases, the tensile strength reduces. Similarly Modani and Vyawahare (2013) [2] investigated the tensile strength of concrete mixed with agro-waste in accordance with IS 5816: 1999 (Indian Standard, 1999) and found that the addition of sugarcane bagasse ash to concrete decreased tensile strength. However, Shafana and Venkatasubramani (2014) [47]observed an increase in tensile strength when up to 10% of bagasse ash was introduced and then a decrease in tensile strength beyond 10% replacement value.

2.3 Flexural strength

Before a new material can be used in construction, it is necessary that the flexural strength is determined to ascertain its suitability as a construction material. The flexural strength of a material is defined as the capacity of the material to withstand an amount of force without rupture, breaking or permanent deformation [29]. The flexural strength will be the same as the tensile strength if the material is homogenous, however, flexural strength is an important parameter to understand when integrating waste into construction materials. Even though most studies report on compressive and tensile strength, a few studies have reported on the flexural strength.

2.3.1 Agro-waste Fibres

Bentchikou et al. (2012) [31] utilized cellulose fibres as cement replacement for lightweight cement composite. The Cellulose fibres content in the composite ranged from 0% to 16% by mass of cement. They report that the flexural strength increases between 0% and 4% fibre content, due to bridging effect of fibres in the matrix. In contrast, Islam et al 2018 [36] study shows that the inclusion of jute fibres reduces the flexural strength of concrete beams. However, there was an exception to this trend where the sample containing 0.5% fibre content with 10mm lengths achieved an increase in flexural strength of around 6%.

Sujatha et al (2018) [35], observed that the use of fibre increased the flexural strength. The highest increase in flexural strength was for the jute fibre sample by around 36%. In the same vein, Kammoun and Trabelsi, (2019) [37] reported very high-level increases in flexural strength with the inclusion of prickly pear fibres in the concrete. The results indicate flexural strength increases between 135%-156% after 28 days compared to the control sample. The study also noticed that fibre lengths affect flexural strength positively. The data portrays the effect of fibre lengths on flexural strengths as more prominent in samples with lower fibre content.

2.3.2 Agro-waste Granules

The findings from Turgut and Murat Algin (2007) [39], conformed with the BS 6073 1981 standards which state that the minimum allowed flexural strength value for materials to be used in structural applications is 0.65 MPa. Consequently, the introduction of wood sawdust in concrete increased flexural strength and satisfies the flexural strength requirement for building construction.

Muntohar (2011) [40] studied the combination of rice husk ash and lime stabilised soil for its effect on flexural strength. Results of the research showed that samples with lime and rice husk ash ratio of 1:1 attain the highest flexural load. The sample had the highest absorption rate meaning that more energy is required for the sample to crack. The energy absorption capacity was obtained from the area under the load and deflection curve. The sample had a modulus of rupture (flexural strength) of around 57kPa. The lowest flexural strength was obtained by the sample with lime: rice husk ash ratio of 3:1 and the untreated sample both with values around 22 kPa.

Villamizar et al. (2012) [41] results showed that the highest recorded average flexural strength value was 0.76 MPa for the sample containing 95% clayed soil and 5% fly ash. Unlike in the compressive strength tests, the sample containing 100% clayed soil exhibited better average flexural strengths values of 0.64 MPa compared to the other three samples. However, although it exhibited better flexural strength it also had the most fractures. The lowest recorded average flexural strength values were for the sample containing 95% clayed soil and 5% cassava peels followed by the sample containing 90% clayed soil and 10% fly ash with values of 0.48 MPa and 0.38 MPa respectively. The inclusion of fly ash improves the strength and durability of the samples but should not exceed 5% as this will have an adverse effect.

The flexural strength observed by Rahman et al. (2014) [42] when introducing oil palm kernel shell in lightweight masonry block shows that the flexural strength decreased with an increase in palm kernel shell. Also, the sample with mix ratio of 1:1:1 had the highest value. The trend showing a decrease in flexural strength with the increase of waste material content was also observed in this experiment. The results indicated that the dry samples had higher flexural strengths than the wet samples (submerged in water 24 hours prior and dried) by 17%, 33% and 36% for the mix ratios 1:1:1, 1:1:2 and 1:1:3 respectively. The highest and lowest flexural strength value obtained for the dry samples were 2.22 MPa (1:1:1 mix ratio) and 0.11 MPa (1:1:3 mix ratio) respectively.

Sathiparan et al. (2018) [21] findings showed flexural strength decreasing with the increase of agro-waste content. The results show that the only samples to achieve at least 50% of the control samples flexural strength (0.85 MPa) were the coconut shells and rice husk with values of around 1.15 MPa and 0.95 MPa respectively.

2.4 Density

The density of a material is referred to as the amount of mass per unit volume. It is the degree of compactness of a given material. Materials whose particles are more closely packed will have a higher density when compared to materials with sparsely packed particles. Materials with low density are particularly suitable for specific types of construction such as light weight floating concrete for the construction of dwellings on water [48].

Khedari et al. (2005) [30] observed a decrease in bulk density with the inclusion of fibres when compacted at 1.0 M N/m^2 pressure. The bulk density of the control sample was 1913.17 kg/m^3 whereas the densities of the samples with fibres ranged from 1344.60 kg/m^3 – 1754.94

kg/m^3. Similarly, Bentchikou et al. (2012) [31] utilized cellulose fibres as cement replacement for lightweight cement composite. The cellulose fibres content in the composite ranged from 0% to 16% by mass of cement. They report that as the fibre content increases, the bulk density decreases thereby providing a light-weight construction material.

Also, Rahman et al. (2014) [42] showed that samples with palm kernel shells recorded a lower density. This can be attributed to the increased amount of packed void observed when the palm kernel shell is introduced. With this increased void, the density of the masonry block fall between 1680 – 2000kg/m^3 as indicated in the ASTM standard C55. They observed that using a mix of 1:1:3 can result in the density of the masonry block being as low as 1400kg/m^3. However, the mix proportion can only produce lightweight materials for non-structural section (non-load bearing).

Sathiparan and De Zoysa (2018) [21] observed that in every case, the density decreased with an increased introduction of agro-waste. The reason for the decrease in density can be linked to the low specific gravity of agro-waste. Likewise, Sujatha and Selsia Devi (2018) [35] reported a density reduction in their study, ranging from 2.7% to 16.2%. The banana fibres showed the lowest reduction in density ranging from 2.7% to 7.2% followed by the jute fibre. The recorded density of the control sample was 2040.6 kg/m^3.

Kammoun and Trabelsi (2019) [37] tested samples that were produced with hot water treated fibre, with content and length ranging from 0 kg/m^3 - 15 kg/m^3 and 2cm-5cm. The results indicate that even though fibre content reduces density, the fibre length had no effect.

2.5 Thermal conductivity

Thermal conductivity is another important material property to consider in the development of sustainable construction materials. It indicates the material's ability to conduct heat [31]. This property is particularly important as materials with low thermal conductivity would improve thermal comfort within buildings.

Several scholars have investigated the effect incorporating agro-waste on the thermal conductivity of the resulting material. Bentchikou et al. (2012) [31], experimentally investigated the effect of replacing cement with cellulose fibre in lightweight composite. After 28 days of curing the specimen, thermal conductivity test was carried out using Neuman's dynamic method. The result of the test showed that thermal conductivity decreases with fibre waste inclusion. This can be attributed firstly to porosity that occurs from packing the fibres as they induce air bubbles during mixing operation, and secondly to the self-insulating property of fibres which has a thermal conductivity of 0.035 W/mK.

Similarly, Kazmi et al. (2018) [44] reported that the inclusion of sugarcane bagasse ash and rice husk ash decreased the thermal conductivity of the bricks. The thermal conductivity of the control sample was 0.52 W/mK. The samples containing 5%, 10% and 15% content of sugarcane bagasse ash content experienced a decrease in thermal conductivity by 14%,19% and 31% respectively and 6%, 9%, 29% respectively for the rice husk ash samples. The study also showed a linear relationship between the thermal conductivity and weight per unit area of the bricks. This trend was also observed by Modani and Vyawahare, (2013) [2].

Furthermore, Ozturk et al. (2019) [45] observed that the thermal conductivity of the samples ranged from 0.410 W/mK to 0.764 W/mK. The lowest thermal conductivity value belonged to the sample with the highest amount of tea waste content and vice versa. The trend was in accordance with what was reported in other studies. The study also demonstrated the relationship between thermal conductivity, porosity and bulk density of the clay bricks. As apparent porosity increases, thermal conductivity decreases whereas when bulk density increases, thermal conductivity also increases. Hence the introduction of waste tea decreases thermal conductivity.

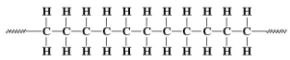
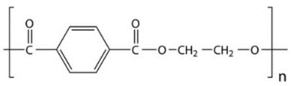
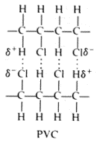
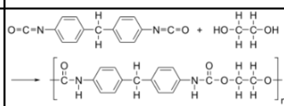
3 Review of Plastic waste in Construction

Since the discovery of polystyrene in 1839, there has been an exponential increase in plastic types, including; polyethene terephthalate (PET), polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS) and polypropylene (PP), amongst others. Global production of plastics has steadily increased over the past 50 years, estimated to be 335 million tonnes per annum in 2016 [49]. . Furthermore, It was estimated that about 6.3 billion tonnes of plastic waste had been generated as of 2015 [52] and total plastics produced is projected to grow to 33 billion tonnes by 2050 [50,51]. This increase in plastic pollution has served as a catalyst for their use in construction [53], as it provides an avenue to divert plastics from unsustainable plastic management practices [54].

Several researchers have investigated the possibility of converting these various forms of plastic waste into sustainable construction materials. Awoyera and Adesina (2020) [55] explored the various approaches to recycling plastic wastes and highlighted the opportunities and limitations of using plastic waste for construction. Kou et al. (2009) [56] investigated the use of recycled PVC granules waste to replace river sharp sand for concrete, highlighting that river sand is becoming a scarce natural resource in countries like China. Similarly, other researchers have investigated the use of shredded PET bottles in manufacturing compressed earth brick [57], incorporating plastic bottles in floor panels [58] and wall panels [59], plastic fibre-strengthened interlocking bricks suitable for load bearing application [60], incorporating polyurethane (PUR) foam waste particles in concrete [61] and using Polyethylene (PE) particles from electric cable sheaths as aggregates in mortar and concrete [62].

Plastic wastes are usually integrated in construction either as fibres or as granules . The method of integration, as well as the mechanical, physical and structural characteristics of the constituent plastic will influence the effect of on the compressive strength. Table 2 presents the mechanical properties of some of the common types of plastics used in construction.

Table 2: Mechanical properties of some plastic polymers

Polymers	Ultimate Tensile Strength (MPa)	Compressive Yield strength (MPa)	Flexural modulus of elasticity (MPa)	Density (Kg/m^3)	Thermal conductivity (W/mK)	Polymeric chain
(PE): Polyethylene	30	20	393	950	0.5	
(PET): polyethylene terephthalate	150	80	2757	1350	0.3	
(PVC): Polyvinyl Chloride	48	55-89	2833	1330	0.2	
(PUR): Polyurethane	28.0 - 96.0	0.185	29- 18000	50	0.14 - 0.5	

The following sections summarise some of the previous studies that have explored the application of plastic for sustainable construction. These have been grouped using the key parameters mentioned previously.

3.1 Compressive strength

3.1.1 Plastic Fibres

Binici et al. (2007) [63], reported the use of plastic fibres and polystyrene fabric in mud brick samples. They used clay as the main matrix, cement, basaltic pumice and gypsum as the stabilisers with the inclusion of the fibre samples. They reported that the fibre-reinforced mud bricks, performed better than the traditional mud bricks and fulfilled the compressive strength requirements of ASTM and Turkish Standards.

In contrast, Mohammadhosseini et al., 2020 [64] included waste metalized plastic (WMP) fibres into concrete specimen in additions of 0.25%, 0.5%, 0.75%, 1% and 1.25% . The inclusion of WMP fibres reduced the compressive strength of the concrete specimen. In another study, Mohammadhosseini and Alyousef, (2021) [65] utilized polypropylene from waste plastic food tray (WPFT) fibres as fibrous materials in concrete composites. Used at dosages of 0–1% in two groups of concrete with 100% ordinary Portland cement (OPC), they report that the compressive strength diminished slightly with the addition of WMP fibres. Awoyera et al. (2021b) [66] examined the properties of concrete made with ceramic tile wastes as fine aggregates and Polyethylene terephthalate (PET) bottles as fibres. They observed an inconsistent trend in the compressive strength of the samples at different curing ages. The best compressive strength were observed in the concrete sample with 100% fine ceramics aggregates and 2.5% plastic fibers while the least was observed in those with 1.5% plastic fibre.

3.1.2 Plastic Granules

Mounanga et al. 2008 [61] incorporated Polyurethane (PUR) foam waste particles into concrete. The PUR foam used consisted of fine (0-5mm) and coarse (0-10mm) particles. The compressive strength tests were carried out on prism shaped samples and revealed that the use of PUR foam in concrete decreased the overall compressive strength. The results revealed that the inclusion of coarse PUR foam particles reduced the compressive strength by a minimum of 54% whereas the compressive strength of the fine PUR foam particles was reduced by at least 86%. The reduction in strength could be explained because of the weak strength of PUR foam and its high permeability to water which increased the water content ratio in the concrete. Similarly, Choi et al. 2009 [9] investigated the use of Waste PET Lightweight aggregates (WPLA) heated at 250 ℃ as a lightweight replacement aggregate. The findings revealed that time increased the compressive strength of all the concrete samples. The highest compressive strength value recorded was for mortar with 0% WPLA content on the 28th day in the region of 44.9 MPa. The samples with 25%,50% and 75% and 100% WPLA content all experienced a decrease in compressive strength (6%, 16% and 30% respectively) whilst the sample containing 100% WPLA content showed a 42% decrease after 28 days.

Kou et al. (2009) [56] investigated the possibility of replacing river sharp sand in the concrete mix with PVC plastic granules of fineness module of 4.42 and 5mm sieve diameter. They observed that as the PVC granule content of the lightweight aggregate concrete increased, the compressive strength subsequently decreased. The concrete block with the lowest PVC granule content of 5% experienced an increase in compressive strength by 9.1%, whereas the concrete block with the highest PVC content had a 47.3% decrease in compressive strength. The reduction in compressive strength is a result of weak bonding between the PVC and cement paste, which is caused by the surface and size of the PVC as well as the internal bleed water of the fully saturated aggregates around the PVC granules. Consistent with the previous research, Frigione, (2010) [67] tested concrete samples to determine the compressive strength contained in unwashed PET waste plastic particles (WPET) with sizes ranging from 0.1-5mm. The samples were tested at 28 and 365 days and had water content ratios of 0.45 and 0.55. The reduction in compressive strength with the inclusion of 5% plastic waste by weight was also seen in this study. The lowest compressive strength value obtained was never more than 2% lower than that of the control sample.

Rahmani et al. (2013) [68] replaced concrete fine aggregates with ground PET particles of max size 7mm. The study showed that, as the PET content increased to 15% the compressive strength decreased. However, up to 5% of the PET content and water content ratio of 0.42, shows an increasing trend in compressive strength, which led to an increase in strength of around 9% compared to that of the control sample. On the other hand, the sample with the 5% PET content and 0.54 water content ratio achieved an increase in strength of around 12%. This trend is seen in the samples with low PET content as when the load is applied, the shape and flexibility of PET increased the chance of interlocking between particles. However, at higher concentrations, the PET inhibits interlocking between the PET particle and the paste due to the weak bonding. The data revealed that 5% PET content by weight yields the best results.

A similar study by Saikia et al. (2014) [69] investigated the use of three differently sized and shaped PET waste, as aggregates in concrete. Two of the three PET wastes were flaky with one being fine and the other, coarse. The third PET waste was pellet shaped and pre-heat treated. The results showed that, like other studies, the compressive strength decreases as the PET content increases. There was a recorded compressive strength loss for both the flaky (coarse and fine) and pre-treated pellet shaped PET waste. The loss in strength is associated with the weak adhesion between the PET and cement paste causing a weak interfacial transition zone. The higher strength achieved by the pre-heat-treated pellet concrete is associated with it having a lower water content ratio compared to the other two.

Saxena et al. (2018) [70] studied the compressive strength of concrete with the addition of fine (0-4.75mm) and coarse (4.75-20mm) shredded PET at different replacement levels (5%,10%,15% and 20%). The compressive strengths of the concrete were observed on the 7^{th}, 28^{th} and 91^{st} day of curing. The results revealed that the concrete samples containing fine plastic aggregates presented higher compressive strength compared to the coarse plastic concrete samples. The compressive strength loss of the samples containing fine PET particles was considered significant after the content exceeded 10% whereas, for the samples containing coarse PET particles the loss was considered significant after the content exceeded 5%. After 20% PET content the compressive strength reduced from 26.7 MPa (control sample) to 5.4 MPa for fine PET particles and 6.9 MPa for the coarse PET particles.

Akinwumi et al. (2019) [57] measured the compressive strength of compressed earth bricks containing various sized shredded PET bottle particles (<6.3mm and >9.6mm) which were heated during the drying process at 125℃ for 24hrs. The samples with smaller PET particles achieved a higher compressive strength than those with larger particles. The trend in the study was that the compressive strength increased with the inclusion of PET plastic particles regardless of their size. However, as the PET particles content increased beyond 1% the compressive strength decreased. This can be attributed to the PET particles in the samples containing more than 1% not melting during the drying process creating larger surface areas where the soil can ‘slide’ during compression.

3.2 Tensile strength

3.2.1 Plastic Fibres

Fraternali et al. (2011) [71], incorporated recycled PET bottle flakes and PP fibres in concrete and observed that the inclusion of PET fibres resulted in increased ductility compared to plain concrete. Mohammad Hosseini *et al.* (2020) [64] investigated tensile strength by adding WMP fibres and increasing fibre content. The tensile strength of concrete significantly improved as compared to that of the control concrete mix. The mixture of WMP fibres and POFA resulted in the improvement of tensile strength. Likewise, Mohammadhosseini and Alyousef, (2021) [65] observed that the addition of waste WPFT fibres significantly enhanced the tensile strength of all concrete mixes. The obtained results showed that the tensile strength of all concrete mixes reinforced with WPFT fibres were higher than those of plain mixes. The WPFT fibres at the dosages of 0.2%, 0.4%, 0.6%, 0.8%, and 1% caused an increase in tensile strength of POFA mixes by 12.2%, 25.7%, 31.1%, 21.6%, and 13.5%. Awoyera et al. (2021b) [66] observed that that the tensile strength increased with the curing age and found the samples with 2.5% plastic fibres improved the strength of the concrete by 10%, 45%, and 20% at 7, 14, and 28 days, respectively.

3.2.2 Plastic Granules

Kou et al. (2009) [56] reported that the inclusion of PVC granules affected the splitting tensile strength of concrete in a similar way to that of its effect on compressive strength. As the PVC granule content increased, the splitting tensile strength decreased accordingly. The concrete sample with 45% PVC granule content had a splitting tensile strength which was 67% lower than that of the control sample.

Frigione, (2010) [67] observed a decrease in tensile splitting strength when plastic was introduced. Due to the same affecting factors as those of the compressive strength, the splitting tensile strength decreased with the presence the PET particles. The lowest splitting tensile strength value had no more than a 2.4% variation in comparison with the control sample. Similarly, Rahmani et al. 2013 [68] showed that with varying water content ratios, the splitting tensile strength decreased as the PET content increased. The reduction in tensile strengths were reported to be 18% and 15.9% for water content ratios of 0.54 and 0.42 respectively and for 15% PET content. The results can be attributed to the surface area and surface texture of the PET particles which prevents strong bonding.

3.3 Flexural strength

3.3.1 Plastic Fibres

MohammadHosseini et al (2021) [65] measured the flexural strength values of all concrete mixes reinforced with WPFT fibres, and observed they were greater than that of the reference concrete mix without any fibres. The outcomes showed a definite rise in the tensile capacity of reinforced specimens owing to the presence of fibres at high dosages. Mohammadhosseini et al., (2020) [64] included waste metalized plastic (WMP) fibres into concrete specimen in additions of 0.25%, 0.5%, 0.75%, 1% and 1.25%. The inclusion of WMP fibres led to enhancement in the flexural strength of concrete specimens.

3.3.2 Plastic Granules

Rahmani et al. (2013) [68] observed that as the PET particle content increased, the flexural strength decreased. This was not the case for the sample with 5% PET content as instead achieved a higher flexural strength value (6.71% increase) compared to that of the control sample. The sample with 15% PET content and 0.42 water content showed a 14.7% decrease in flexural strength whereas the sample with the same PET content and 0.54 water content showed a decrease of 6.25%. This indicates that the water content greatly affects the flexural strength.

Similarly Saikia and De Brito (2014) [69] observed that the flexural strength reduced with the inclusion of all types of PET plastics. The loss in flexural strength increased as the PET content increased. The reasons were like those for the compressive and tensile strengths. The observations of the study were that the sample containing pre-heat treated plastic pellets split in two whereas, the other two samples did not, as the fine and coarse plastic particles bridged the crack and improved post -crack strength due to their size and shape.

3.4 Density

In a study by Kou et al. (2009) [56], PVC granules were added to concrete samples and dried using two methods, in an oven, and by air. It was observed that the densities of concrete containing PVC granules was reduced. Furthermore, it was observed that the oven-dried concrete blocks had lower densities than the air-dried concrete blocks. The lowest recorded densities were for the air-dried and oven dried PVC 45% content at 1540 kg/m^3 and 1460 kg/m^3 respectively. In contrast, the lowest density recorded for the control sample was 1690 kg/m^3.

In a similar study, Choi et al. 2009 [9] used WPLA heated at 250 ℃ as a lightweight replacement aggregate for concrete. They recorded densities between 1940-2260kg/m^3. These results showed that the density decreased by 2-16% depending on the WPLA content compared to that of the control concrete. Similar to both studies above, Ruiz-Herrero et al. (2016) [62] investigated the use of polyethylene (PE) and PVC particles from electric cable sheaths as aggregate in mortar and concrete at replacement values of 2.5, 5, 10 and 20% by weight. They observed that the density of the concrete and mortar decreased as the PVC and PE content increased. The concrete sample containing 20% PE particles showed the greatest reduction in density by about 30% followed by the 20% PVC+PE content concrete sample (around 19% reduction) and 20% PVC content concrete sample (around 14% reduction) compared to that of the control sample. The results were as expected since PVC particles are denser than PE particles. The recorded densities of the PVC and PE concrete samples were between 2018-2382 kg/m^3 and 1658-2370 kg/m^3 respectively.

Furthermore, Sujatha and Selsia Devi (2018) [35] reported a density reduction in their study, ranging from 2.7% to 16.2%. The polypropylene fibres displayed a major decrease in density ranging between 11.2% to 16.2% whereas the recorded density of the control sample was 2040.6 kg/m^3. Likewise, Mohammad Hosseini et al. (2020) [64] observed that the fresh density reduced with rising WMP fibre dosage. This was predictable owing to the lower density of the WMP fibres, which is approximately about 915 kg/m^3 associated with that of conventional concrete. Mohammadhosseini and Alyousef (2021) [65] also found that by increasing fibre content, all reinforced mixtures' wet density decreased gradually. The reduction in the density could be attributed to the fact that WPFT fibres have a density of 0.94 g/cm^3, which is comparatively lower than that of 2.4-0.94 g/cm^3 for conventional concrete mix. For example, by adding 1% fibres into the concrete mix, it reduced density by about 5%. This could also be accounted to formation of pores during the mixing process.

In summary, since plastic has a lower density than concrete mix or aggregates, it tends to reduce the density of the product hence integrating plastic wastes would be beneficial for lightweight construction.

3.5 Thermal conductivity

Binici et al. (2007) [63] reported that the plastic fibre reinforced mud brick house in their study, had a better performance, in terms of maintaining a constant indoor temperature during the summer and winter, when compared to the basaltic pumice brick. Likewise, Mounanga et al. (2008) [61] measured the thermal conductivity of both the air-dried concrete samples and water-cured concrete samples. The results obtained illustrate that the thermal conductivity of the samples reduced as the PUR foam content increased. The highest reduction in thermal conductivity was recorded for the samples which had the highest PUR foam content, highest densities, and no sand present. The lowest decrease in thermal conductivity compared to the control sample was 55% whereas, the highest decrease was seen for the fine PUR foam containing sample at 85%. Overall, the air-dried samples showed lower thermal conductivity values compared to the water-cured samples.

Fraternali et al. (2011) [71], compared the thermal conductivity of recycled PET fibre-reinforced concrete (RPETFRC) to plain concrete. The thermal conductivity was measured using a one-dimensional steady state comparative method. Evidence from the experiment shows a 20% decrease in thermal conductivity of RPETFRC over plain concrete.

Similarly, Ruiz-Herrero et al. (2016) [62] used Polyethylene (PE) and PVC particles from electric cable sheaths as aggregate in mortar and concrete at replacement values of 2.5, 5, 10 and 20% by weight. They observed that the thermal conductivity decreased as the PVC and PE content increased. The thermal conductivity of the PE concrete showed a greater reduction in comparison to the PVC concrete. This study only considered thermal conductivity data of concrete samples with up to 10% PE and PVC content, as no data for the 20% PE concrete sample was obtained due to the poor surface conditions. A similar trend to previous studies was observed, the thermal conductivity decreased with the increase of waste plastic content. The highest conductivity reduction at 10% waste plastic content was around 44% (PE) followed by PVC at around 32% and PVC+PE at around 16%.

4 DISCUSSION

The previous sections highlighted the various ways agricultural and plastic wastes have been used for construction, including being used in different proportions, employing different methods, and for different building components such as soil bricks, cement stabilized soil, lightweight concrete and thermally insulated walls. Results from thermo-mechanical tests were used to examine the material suitability as it relates to compressive strength, tensile strength, flexural strength, density and thermal conductivity. This section discusses the trends observed.

4.1 Performance for compressive strength

Figure 1 shows the relationship between compressive strength and agro-waste fibre and granule content. In both cases, it can be observed that there is a slight rise in compressive strength with fibre content when the percentage of agro-waste is low, but beyond a certain threshold, the compressive strength begins to decrease with increase in agro-waste. This was true for both cement and soil-based blocks. It was observed that the addition of 0.05-0.5% content agro-waste fibre in soil blocks resulted in an increase in compressive strength, however, beyond this point, further addition of fibres resulted in decrease of compressive strength. The range for improving compressive strength in concrete blocks is slightly higher as a bracket of 0.25-1% was observed. A similar trend was observed for the inclusion of agro-waste granules, although the threshold was observed to be much higher.

The agro-waste materials with the highest compressive strength in this review are coconut shell, sugarcane bagasse ash and rice husk ash, which met the requirement for sustainable construction of several standards such as the AS/NZS4455 2008 and Bureau of Indian Standards (BIS) 1992. Similarly, jute fibre recorded the highest compressive strength values, showing up to 50% increase when combined with soil blocks.

Figure 2 shows the relationship between compressive strength and plastic waste content. It can be observed that, plastic waste used either as fibres or granules results in a decrease in compressive strength, although compressive strength stays constant or increases slightly when the content is small. The threshold at which it begins to drop will depend on the type of plastic although [56,68] recommend a replacement value of 5% as optimum for granule content because the strength starts to fail at higher replacement values.

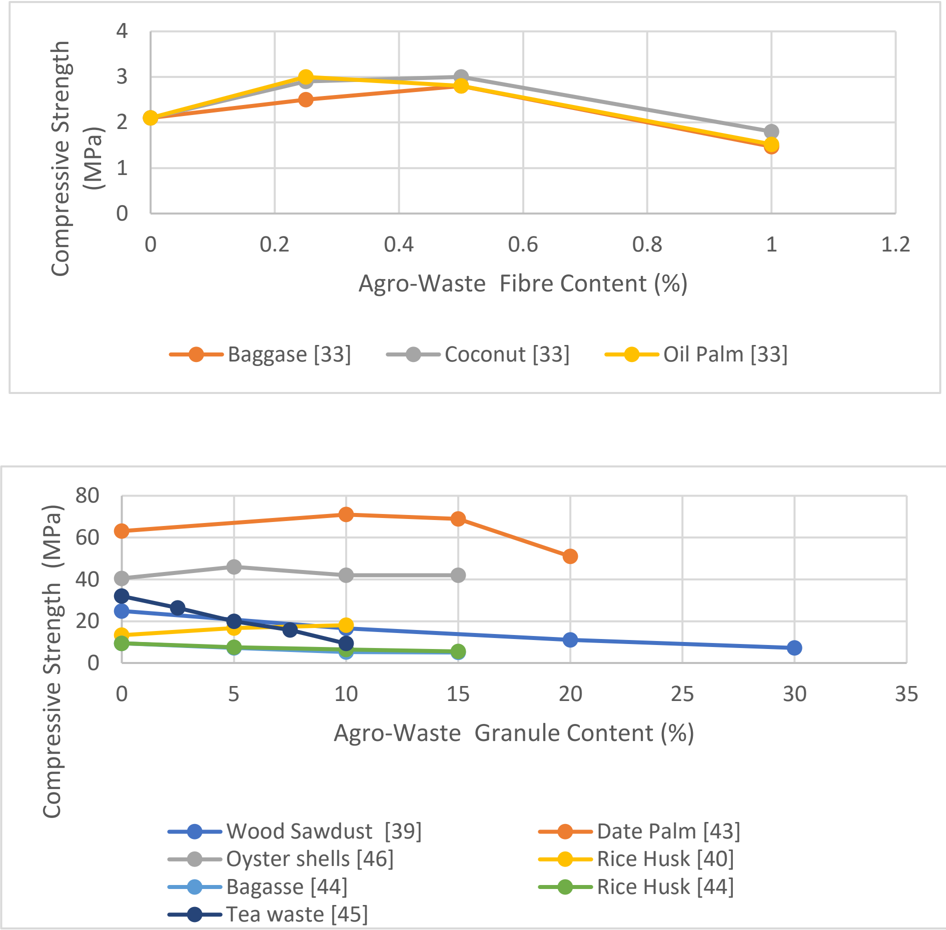


Figure 1: Relationship between compressive strength and (a) Agro-waste fibre content (b) Agro-waste granule content

The review highlighted a wide variation in compressive strengths quoted by various studies, which is not surprising, considering the wide variation of methods and materials employed by scholars in making soil or cement-based blocks. However, the results show a consistent trend, which suggests that the compressive strength is affected more by the mechanism of bonding rather than the properties of the waste materials integrated. .

Agro-waste such as jute fibre, coconut shell, sugarcane bagasse ash and rice husk ash, can be used in developing sustainable construction materials when a design compressive strength is specified. Also, plastic waste materials with relatively low compressive strength can be used in producing sustainable non-structural materials which can be utilised as a partition member in building construction.

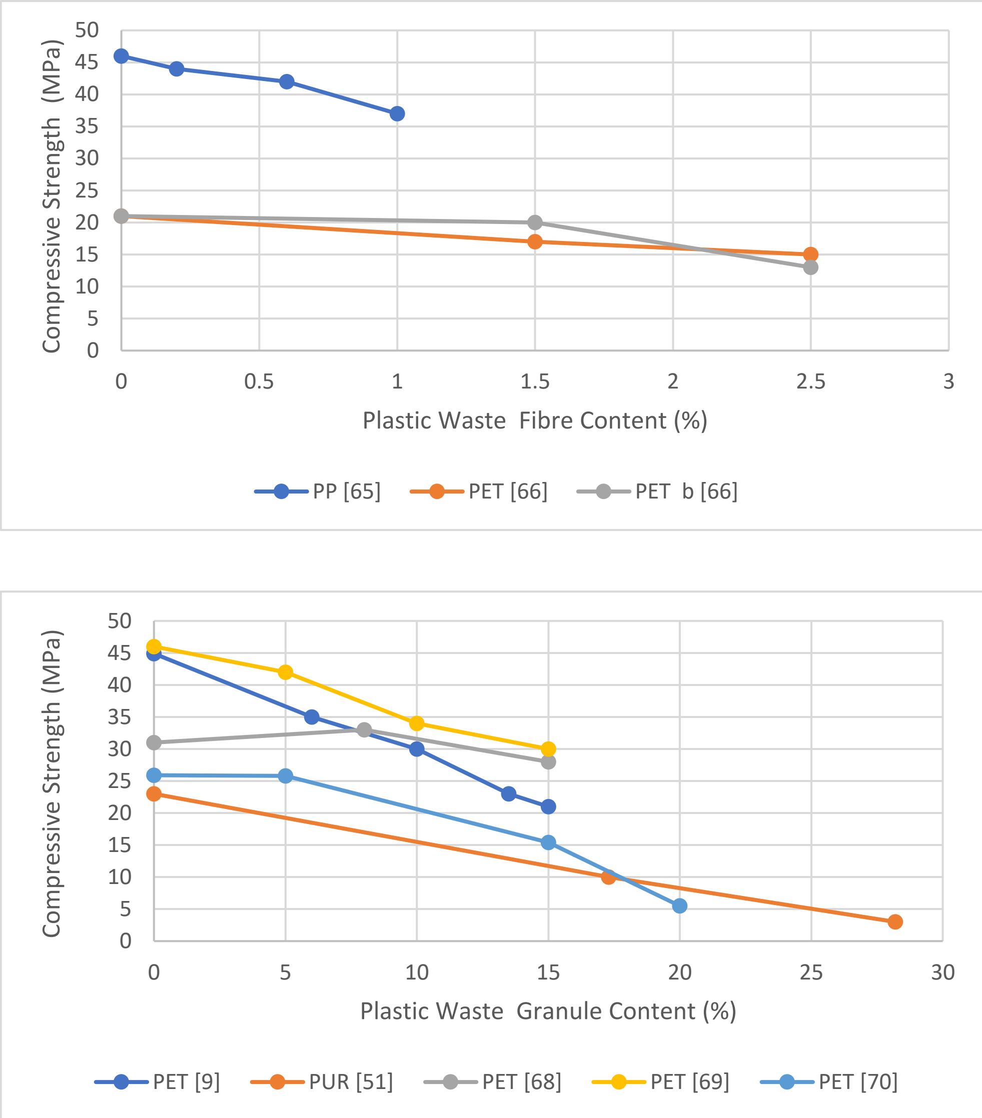


Figure 2: Relationship between compressive strength and (a) Plastic-waste fibre content (b)Plastic-waste granule content

4.2 Performance for Tensile strength

The relationship between tensile strength and fibre content in soil blocks incorporating agro-waste is presented in Figure 3. The trend observed is similar to that for compressive strength i.e. an initial increase in tensile strength and then a decrease as the percentage of agro-waste increases beyond a certain level. This similarity is expected as tensile strength is the opposite of compressive strength. i.e., compressive strength relates to the ability to withstand the force pushing it together while tensile strength relates to the ability to withstand the force pulling it apart. Therefore, this behaviour can also be attributed to the weak bonding resulting from higher fibre content. This goes to show that the bonding seems to play a more important role compared to the constituent materials because the tensile properties of these natural fibres suggest that their integration in soil blocks should improve their tensile properties. Comparing the tensile strength of the of the pure fibres in Table 1 to the components in Figure 3, it can be observed that the tensile strength of the components, which range from 0.25-0.35 MPa, are much lower than the fibres, which range from 25-222 MPa. This suggests that the components may not directly benefit from the mechanical properties of the fibres.

Figure 4 shows a similar trend for Plastic-waste fibres and particulates. Studies with a finer data grid indicate an initial increase before a decrease. However, other studies are not able to observe this trend due to their data grid not being fine enough. This explains the conflicting conclusion as they would only have observed a decreasing trend as shown in Figure 4b . The literature indicates that both plastic waste and agro-waste can be employed to make construction materials more affordable and sustainable when a lower tensile splitting design strength is specified. It should be noted the tensile strength will be more important for building components exposed to external tensile forces such as wind and gravity.

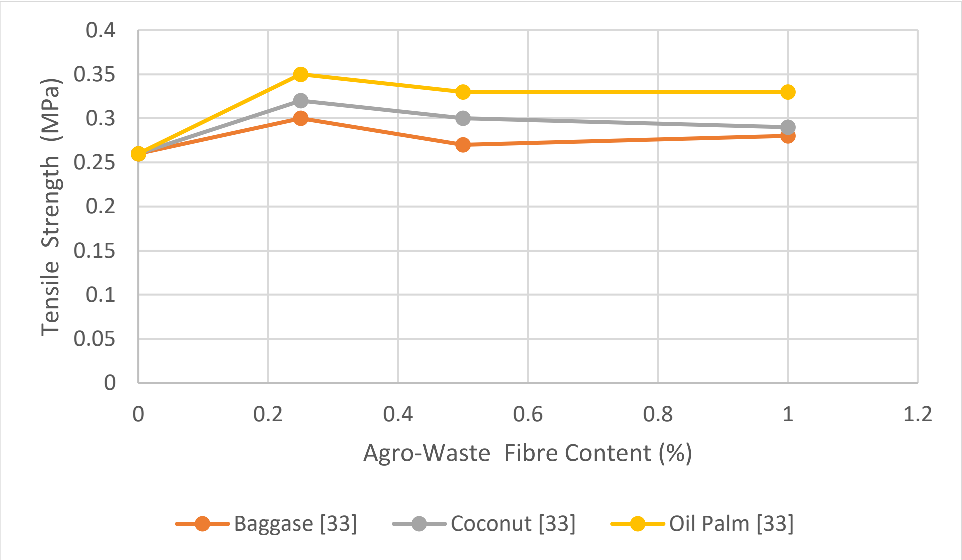


Figure 3: Relationship between Tensile strength and Agro-waste fibre content in soil blocks (adapted from [33])

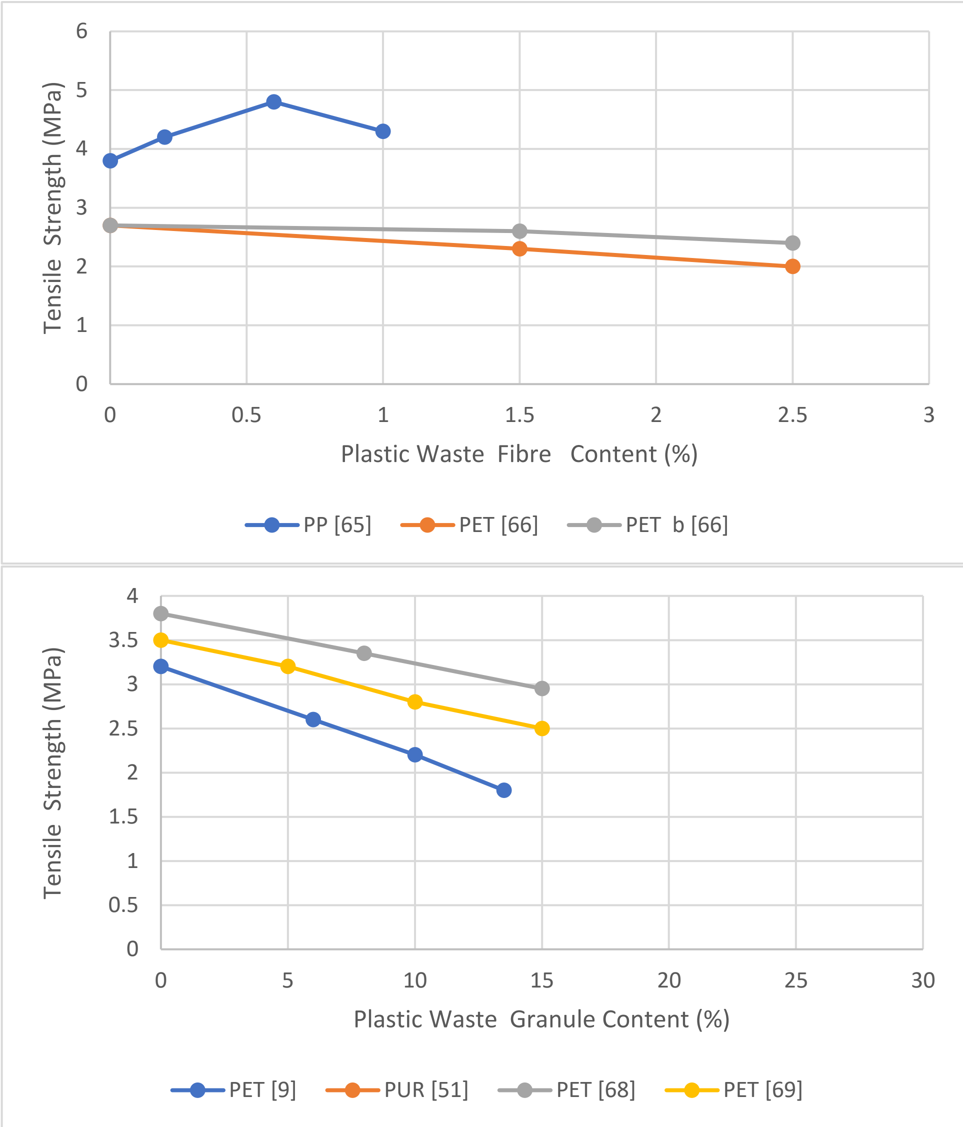


Figure 4: Relationship between tensile strength and (a) Plastic-waste fibre content (b)Plastic-waste granule content

4.3 Performance for Flexural strength

Figure 5 shows the relationship between flexural strength and granule content for agro-waste and plastic-waste. Only few studies in this review reported on the flexural strength however, it is closely related to tensile strength as the flexural strength will be the same as the tensile strength if the material was homogenous. It can be observed from Figure 5 that the flexural strength reduces with waste content just as was observed for tensile strength. it is worth noting that the length of the fibres can impact the flexural strength negatively beyond a certain point [36]. Furthermore, the wide variation in flexural strength can be attributed to the wide variation in the constituent materials used by various scholars.

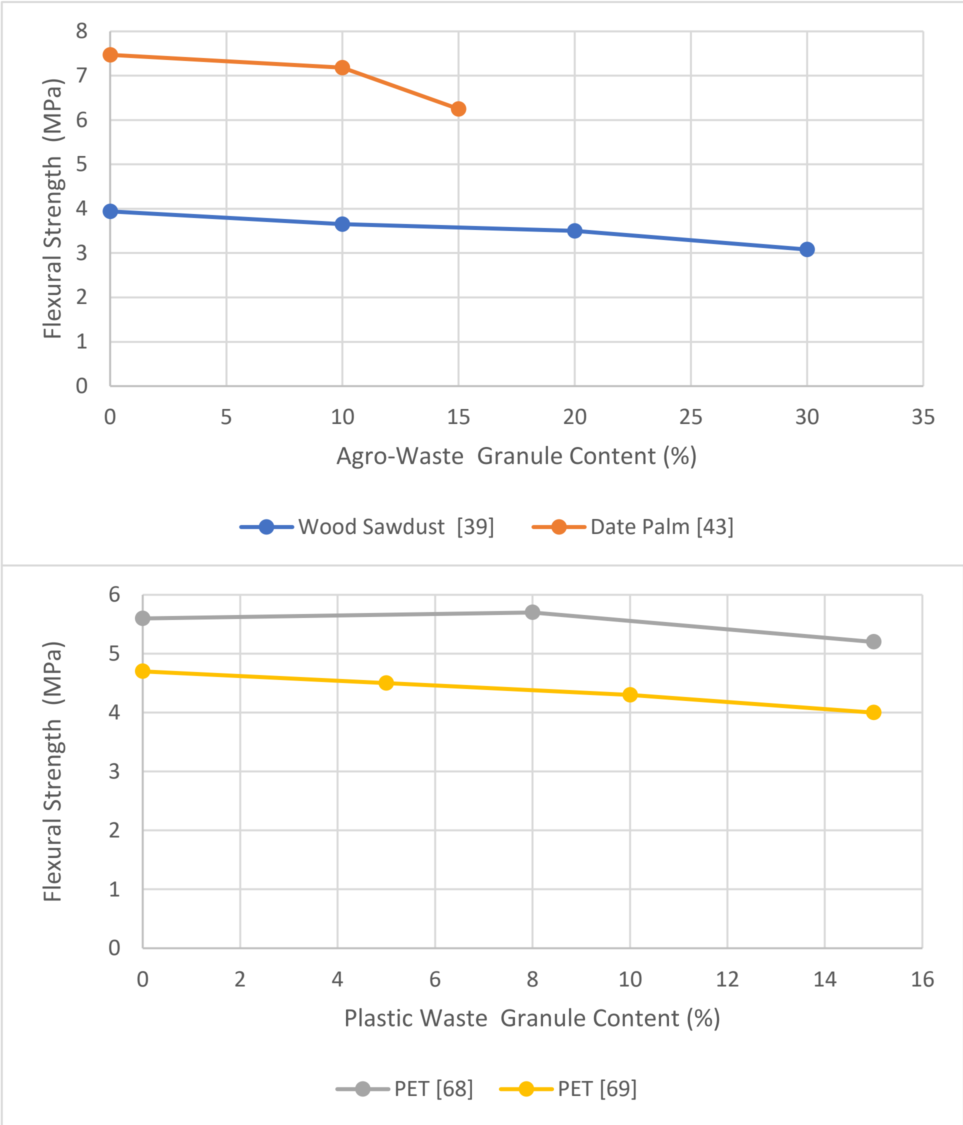


Figure 5: Relationship between flexural strength and granule content for (a) Agro-Waste (b) Plastic-waste

4.4 Performance for Density

It can be inferred from Figure 6 and Figure *7* that as the waste content increases, the bulk density decreases. This is expected as both plastic and agro-waste have a lower density compared to concrete mix or aggregates and as such tends to reduce the density of the end product. The implication of this for the construction industry is that light weight concrete with low density can be produced cheaply with an inclusion of either plastic wastes or agro-waste.

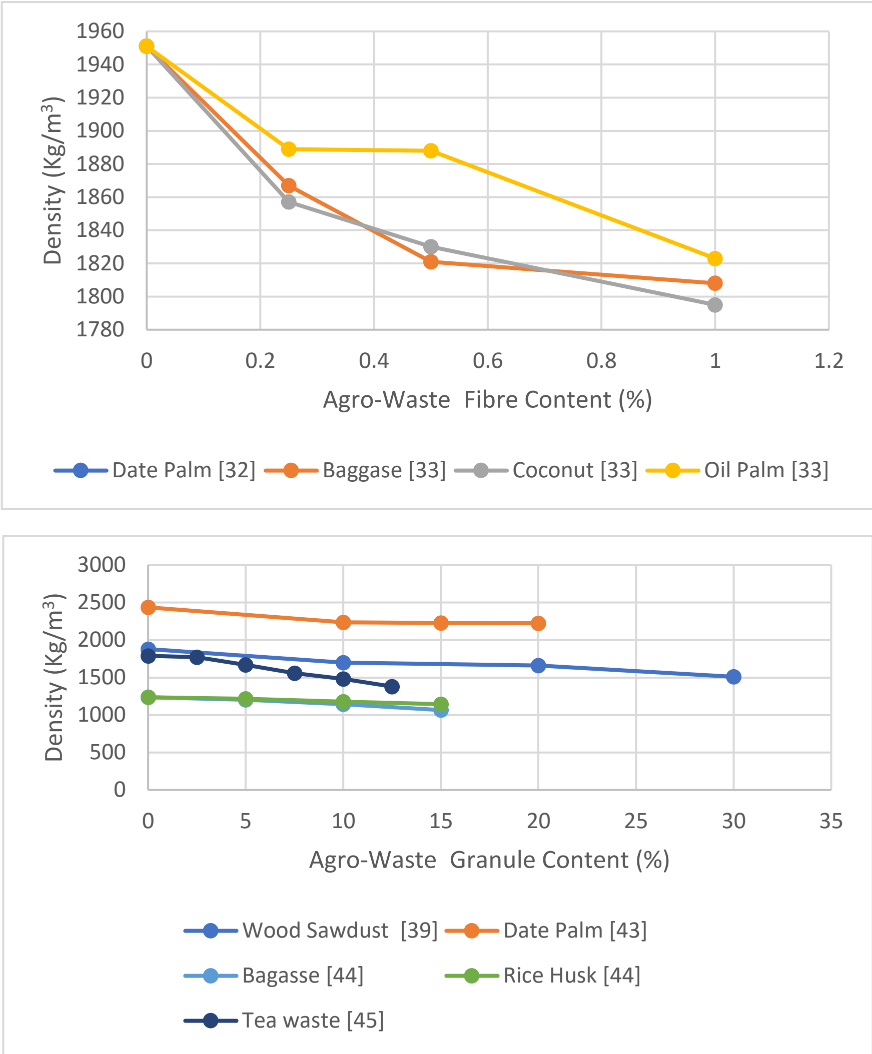


Figure 6: Relationship between density and (a) Agro-waste fibre content (b) Agro-waste granule content

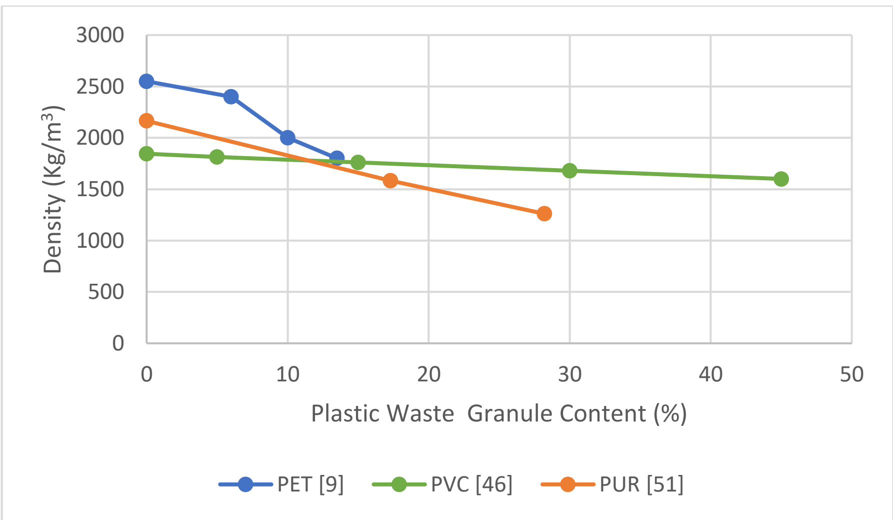
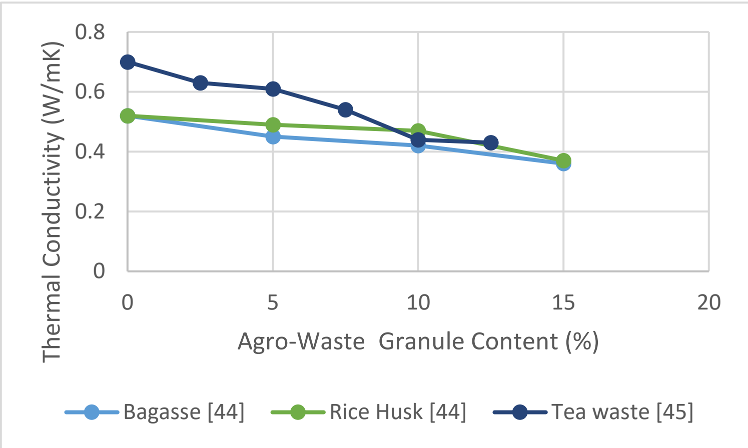


Figure 7: Relationship between density and Plastic-waste granule content

4.5 Performance for Thermal conductivity

Figure 8 shows the relationship between thermal conductivity and granule content for agro-waste and plastic-waste. This shows that scholars are in agreement that thermal conductivity is reduced with an increase in waste content. The trend observed is expected as She et al. (2020) [72] noted that a higher volume of pores in cementitious materials would create more obstacles for the conduction of heat within the cementitious matrix resulting in a reduction in the thermal conductivity. Furthermore, Adesina, (2021) [73] and Hannawi et. al [74] highlighted that there is a good relationship between density and thermal conductivity, which can be observed here. As apparent porosity increases, thermal conductivity decreases whereas when bulk density increases, thermal conductivity also increases. The link between thermal conductivity, porosity and bulk density was also demonstrated by Ozturk et al. (2019) [45] while thermal properties of agro-waste was presented by [75], [76] and [77].



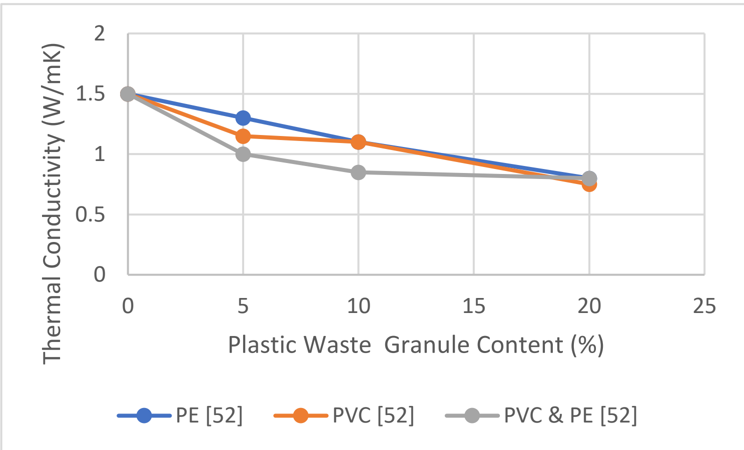


Figure 8: Relationship between thermal conductivity and granule content for (a) Agro-Waste (b)Plastic-waste

5 CONCLUSION

This paper reviewed the development of sustainable construction materials from plastic and agricultural wastes. Five key parameters, compressive strength, tensile strength, flexural strength, density and thermal conductivity were used to examine the suitability of the resulting material. Overall, it was observed that there is a narrow range for improving the compressive, tensile and flexural strengths by increasing the quantity of waste, as beyond this range, the strength begins to decrease with an increase in waste content. This behaviour suggests that integrating waste materials has an effect on the bonding capability of the component, regardless of it being cement or soil based. This indicates that the resulting construction material does not directly benefit from the mechanical properties of the waste materials used. Despite the reduction in mechanical properties, it was observed that components with waste materials can be used for non-structural elements, thereby reducing the quantity and cost of new materials to be used. The results also showed that integrating waste materials results in a reduction in density of the resulting component which has implications for light weight construction. Furthermore, both agro-waste and plastic waste caused a reduction in the thermal conductivity, indicating that waste materials can improve the thermal performance of buildings. While this study has focussed on plastic and agro –waste, for future work, there is significant scope to explore the use of other waste materials, such as glass or industrial wastes, whose production and disposal is also increasing at an alarming rate. Also, a better understanding of the effect various waste materials have on bonding is required.

6 DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

7 REFERENCES

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