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Cementless building materials made from recycled plastic and sand/glass: a review and road map for the future

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ABSTRACT: Plastic and glass can be sorted using machines and recycled into new plastic and glass, as opposed to producing them from raw materials. However, contaminated plastic and glass, as well as certain types of plastic and glass, cannot be recycled using traditional methods and must be disposed of in landfill. Researchers have been looking into this and have tried a variety of solutions to convert this waste into functional products. The development of composite construction materials, based on these two materials was identified as a worthy solution. On the other hand, carbon dioxide is emitted during the cement manufacturing process and the use of that cement in the production of construction materials contributes 7% of total global greenhouse gas emissions. Hence, plastic sand/glass composite is environmentally friendly in two ways. It reduces landfill while also replacing the equivalent concrete product, lowering CO_2 emissions. This paper examines the literature on the development of such materials, including technology, challenges, quality, and properties. The development of a glass/sand composite to use as a material in the commercial scale production of roof and pavement tiles is described based on studies that are available.

KEYWORDS: Composite, Waste Recycling, Plastic, Circular Economy, Sustainability, Cementless Building Material, Net Zero Carbon.

1 INTRODUCTION

The management of solid waste in developing nations is often insufficient, with low rates of waste collection, disposal that mostly involves dumping, and few opportunities for recycling (Wilson & Webster, 2018). Additionally, developed nations used to ship their waste to underdeveloped nations, which contributed to the overabundance of plastic there (Nielsen et al., 2020). As a result of the lack of recycling infrastructure in developing countries, waste plastics frequently have little to no value and are disposed of in an unregulated manner in landfills, as seen in Figure 1 (Zurbrugg, 2003). As a result, researchers, and innovators in those countries such as Ghana and Philippines have first started studying methods of producing construction materials by using plastic as a binder or filler.

The variability of post-consumer plastic trash is the fundamental barrier to more efficient recycling. Based on Australia's national plastic recycling survey 2018/2019, highest plastic consumption and recovery by polymer type is Polyethylene terephthalate (PET) make up 21% of the plastic waste stream, followed by 19.7 % high-density polythene (HDPE), 17.3 % Low-density polythene (LDPE) and linear low-density polythene (LLDPE), 11.6% polystyrene (PS), 8.6% Polypropylene (PP), 2% polyvinyl chloride (PVC), and 19.8 % other plastics (O'Farrell, 2020). The physical and chemical differences between plastics are typically the basis for the established separation methods for mixed plastic trash, which also include spectral, electrostatic, optical, gravimetric, and other methods (Sadat-Shojai & Bakhshandeh, 2011). However, there are drawbacks to every technique used, and total plastic separation is very challenging to accomplish. Additionally, some products (such toothbrushes, plastic bottles and their cups, etc.) combine two or more types of polymers in a way that makes it difficult or impossible to separate them (Walker et al., 2020).

Figure 1 Landfill of unregulated solid waste disposal site at Ampara, Sri Lanka (Tilaxan, 2020)

Most hard plastic types, including HDPE, PET, and PP, are recycled to the identical raw material in the factories by sorting, washing, and flaking in developed nations. Where governments invest in material recovery facilities and infrastructure as well as strictly enforced waste disposal methods. This reduces the use of virgin material in production. However, during the sorting process a significant proportion of plastic is thrown away to the landfill as they are not cost effective to sort further. As a result of several reasons, such as machines are not capable enough, too small to be recovered, multi layered plastic and waste is mixed with soft plastics. Hence, these material recovery factories must pay money and send those material to landfills. Several attempts have been made by previous researchers to recover energy from mixed plastic waste, using thermal treatment techniques such as incineration, pyrolysis, and gasification (Sharuddin et al., 2016; Vollmer et al., 2020). However, the presence of undesirables such as chlorinated compounds, high moisture content, heavy metals, and inert materials, in addition to plastics, posed a challenge to the efficacy of these techniques (Intharathirat & Abdul Salam, 2016).

There have been numerous attempts to produce materials with mix plastic, and investigations date back to 1987 (BREWER, 1987). There are patented extruders that have been created to provide an answer to this problem, but none of them succeed in the long term. There are many types of polymers which are immiscible and incompatible to process together. When an attempt is made to mould a mixture of two or more polymer types, the different materials form separate phases, and the overall material sample typically has very poor mechanical properties and poor integrity (Robeson, 2007). Even small amounts of ‘impurity’ in polymer can have a negative effect on properties. Given that there are numerous different polymer types, implies that either the waste stream must be very efficiently sorted into its different components, or a new way must be found to compatibilism the various phases.

Alternatively, they can use this material in the manufacturing process of composite products. There are methods described in the literature that attempt to improve the qualities of mixed plastic by sparingly incorporating additional components like glass fibre and fly ash (Dhawan et al., 2019; Paul & Thomas, 1997). Utilizing recycled plastic in the production of wood plastic composite is an another alternative strategy (Awoyera & Adesina, 2020; Krause et al., 2018). Using wood fibres as a component of plastic is usually performed to replace more expensive plastics (Schwarzkopf & Burnard, 2016). The benefit of using recycled materials is not only the lower cost, but it is also more environmentally friendly to recycle materials, rather than dispose them. Wood plastic composite products already have a diverse range and a large number of different types, with North America and China being the two largest producers, with Europe coming in third (Partanen & Carus, 2016). Researchers discovered that wood particle incorporation could tolerate HDPE contamination with PP, allowing the composite's tensile strength to remain nearly unchanged as the HDPE/PP ratio changed (Selke & Wichman, 2004). The tensile strength of an LDPE/PP composite, on the other hand, increased monotonically as the PP content increased. It should be noted that, in addition to incompatibility, other factors such as changes in morphology, ageing, and impurities can all have a negative impact on the recyclability of plastics (Turku et al., 2017).

According to National Waste Report 2020, indicative price for disposing of unrecyclable mixed glass costs more than $30 per ton (Joe Pickin, 2020). Current applications for mixed glass waste lack integration of design aspects to their raw materials, and products resulting in slow uptake of market and inconsistent demand from end-users to use recovered glass sand, even in current low-level applications such as pipe bedding or asphalt mixes. Figure 2 depicts a typical recycling process diagram and how plastic and glass waste can be reused in the production of construction materials and re-circulated in the sequence contributing to the circular economy. Sand that has been used in steel processing and is currently being disposed of as foundry dust can also be used in the process.

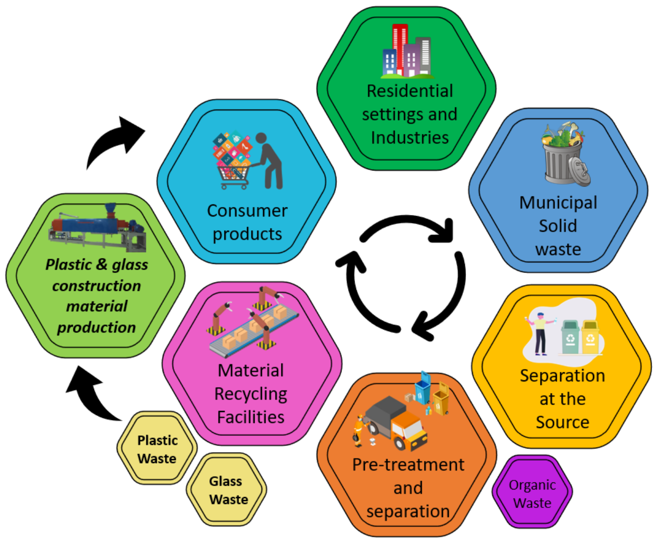

Figure 2 - Recycling solution to unrecyclable plastic and glass waste

Almost all building materials, including roof tiles and pavement tiles, are produced using cement as their primary binder. Cement production industry emits 900 kg of CO_2 in the making of 1000 kg of cement (Mahasenan et al., 2003). Portland cement was discovered to be the primary source of CO_2 emissions produced by typical commercially produced concrete mixes, accounting for 74%-81% of total CO_2 emissions. The next major source of CO_2 emissions in concrete was discovered to be coarse aggregates, which accounted for 13%-20% of total CO_2 emissions (Flower & Sanjayan, 2007). However, due to the environmental effect and the carbon footprint of this process, alternative products are required in the market. Clay based products and machine cut rocks are alternatives, but they promote durability and cost problems. If the strength and other specifications of the finished product can be met, any other binder and filler may be used in place of cement and aggregate to create the same product. Researchers are therefore constantly exploring for sustainable and more environmentally friendly alternatives to traditional building materials.

This paper focuses on the commercial scale manufacturing of roof or pavement tiles using non-recyclable plastic as a binder, with sand or glass as a filler. There are some commercial-level companies manufacturing machinery for the production of sand, cement tiles, and pavement blocks (Rostpolicraft; SinterMachines). However, little research has been conducted in this area. Few researchers have investigated the development of plastic sand building materials, and there is no literature that investigates the change in properties, when filler sand is replaced with recycled glass. Products that are manufactured using sand and plastic in a commercial machine (SinterMachines) is shown in Figure 3.

2 MATERIAL DEVELOPMENT

The type of plastic and sand used in each study is one of the primaries focuses of material development. The main goal is to compare the attributes of the manufactured good to the characteristics of the raw material. The density, strength, and percentage of the raw material (filler-to-binder ratio) are likely to have a significant impact on the end product's qualities. In addition to raw material characteristics, pre-processing, such as cleaning and shredding, is expected to be critical. If it is needed, these pre-processing costs will be incurred and should be factored into the total cost of production. Table 1. summarises details of plastic type, sand properties, pre-processing, cleaning, and filler to binder ratio from the five research studies examined.

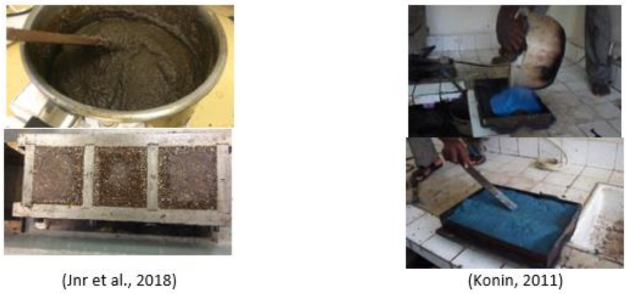

Figure 4 - polymer sand manufacturing methods found in the literature

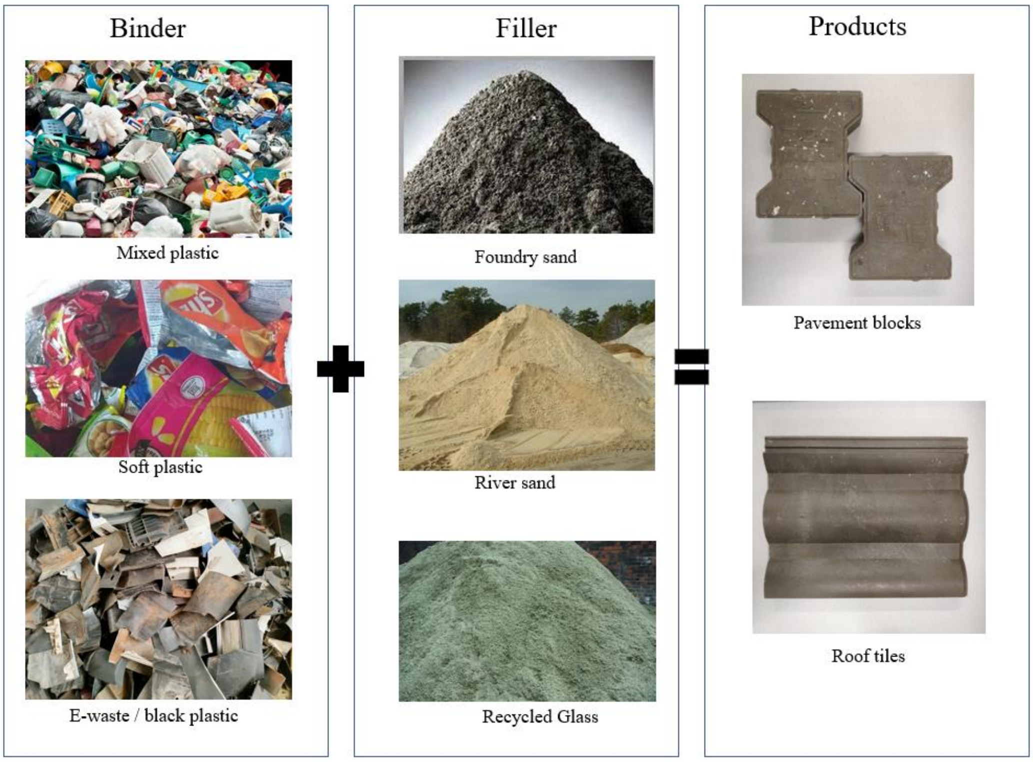

Figure 3 Plastic/Sand Roof and pavement tiles

Table 1. Material properties across research studies

	(Jnr et al., 2018)	(Susila et al., 2019)	(Konin, 2011)	(Khatwa et al., 2005)	(Tulashie et al., 2020)
Plastic type	LDPE	LDPE	PP	80% - LDPE, HDPE and PS 10-15% - PET and PVC 5-10% - Paper, wood, cardboard, food scraps, cloth fragments and small metal chips	Mix plastic waste
Sand Properties	Ungraded d < 500 mm 0.5 mm < d < 1.0 mm 1.0 mm < d < 2.4 mm 2.4 mm < d < 4.7 mm	3.0 mm	silica sand rolled granular grade 0/2	1.18 mm 2.36 mm	Uncontrolled pit sand or sea sand.
Pre-processing	Sand is classified according to its size.	A cutting machine was used to cut the plastic.There is no size specified.	A cutting machine was used to cut the plastic.	Sand is classified according to its size.	Plastic shredded in to 3mm particles.
Cleaning	Clean plastic is used as raw material	Both Plastic and Sand was washed and drying naturally in the sun for 24 hours.	Not specified	Raw materials are not cleaned before using	Plastic Cleaned for impurities and dried
filler-to-binder ratio (%)	50%, 66.7%, 75%, 80%, 83.3%, 85.7%	75%, 83.3%, 87.5%	50%, 60%, 70%, 80%	20%, 40%, 60%	10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%

Soft plastics such as LDPE or PP were used in some studies (Jnr et al., 2018; Konin, 2011; Susila et al., 2019). Studies by two research groups, (Khatwa et al., 2005; Tulashie et al., 2020), employed a mix of wide range of plastic waste, including HDPE, LDPE, PET, PS, and PVC. However, in most of the above studies, plastic was washed and dried (cleaned from any impurities and dirt) before use. Only one study (Khatwa et al., 2005), utilises mixed plastic waste with all impurities in the process of manufacturing sand plastic composite. It also noticed that waste plastic used in all of these studies was pre-processed at least by cutting / shredding into small particles before mixing with sand. Most studies attempted to investigate the effect of filler grain size (in this case sand) and thus classified using sieve analysis prior to use in experiments. The study by (Tulashie et al., 2020) used both pit sand and sea sand with no particle size classification and is a good reference for real world commercial level production.

In the selected studies, the proportions of sand filler by weight ranged from 10%-85.7%. Given the above material properties and mix designs, it is clear that the above studies are adequate for reaching a good overall conclusion on the type of plastic and sand, as well as mix proportions, that are best to be used together in the development of sand and plastic construction materials. In terms of glass and plastic, the similarities between recycled glass and sand can be considered for further studies.

3 MANUFACTURING PROCESS

Some of these studies used a primitive approach (heating plastic in a cooking pan) to prepare materials, while others used standard commercial extruders or custom-built extruders. The primary reason for the primitive approache in some studies is that the viscosity of melted LDPE and PP is low enough that the plastic can be mixed by hand, and the melting point is also lower. In three studies, (Jnr et al., 2018; Konin, 2011; Susila et al., 2019), first plastic is melted in a pot up to 200℃, and then sieved sand is added and mixed by hand. Because the plastics used in these studies are relatively soft, the sand plastic mix had a high flowability index and can be easily poured into moulds, as illustrated in Figure 4.

A bench scale heater mixer machine is used in the study by (Khatwa et al., 2005) so it is possible to manage and change the mixing temperature. The effects of two mixing temperatures, 185°C and 240°C, were investigated in that study. One study used an extrusion machine to mix material at 175°C until no flake was observed (Tulashie et al., 2020). Given that the mix plastic from material recovery facilities contains impurities, moisture, and foreign materials such as wood and paper, it is clear that extrusion is the best manufacturing method that can be used. Controlling the plastic temperature at a constant level during the mixing is also important. Table 2. summarises the heating method, mixing, moulds, compression, and cooling across all five studies considered.

Table 1 manufacturing method across selected studies

	(Jnr et al., 2018)	(Susila et al., 2019)	(Konin, 2011)	(Khatwa et al., 2005)	(Tulashie et al., 2020)
Heating method	Gas or induction cooker and a pot	Gas or induction cooker and a pot	Gas or induction cooker and a pot	Electric heater mixer	Electric heat in a extruder barrel.
Mixing	Hand and a stick	Hand and a stick	Hand and a stick	Heat mixer details are not available	Extruder details are not available
Moulds	50 × 50 × 50 mm cube	Cut into sizes according to ASTM D695	Steel mould shaped roofing tile	bricks measuring 24×12×6 cm	50 × 50 × 50 mm cube
Compression	Moulds were preheated to 100C before pouring the mixer and finished using hand tools	N/A	No compaction	Using a hydraulic press and apply pressure up to 10 Mpa	pressed down using a flat rectangular board
Cooling	24 h immersion in distilled water	N/A	3 min	N/A	N/A

Steel moulds of the required shape can be filled with a heat-melt plastic, sand mix and can be compressed, using a hydraulic press to achieve the desired strength and shape. Only in one study a hydraulic press was used to compress the hot melt paste of sand and plastic to produce bricks, measuring 24×12×6 cm for length, width, and depth. In that study, the material in the mould is compressed up to 10 MPa before being left to harden in the mould. In all other studies, moulding was carried out either with no pressure at all or with pressure that could be applied using the body. Before demoulding, the mould must be cooled and then transferred to a cold-water bath. Based on these findings, a process diagram, as shown in Figure 5, is developed as the most practical approach for producing cementless building materials, made from recycled plastic and sand/glass on a commercial scale.

4 MECHANICAL PROPERTIES

The density of the composite is an important parameter because it indicates the product's strength. This can be influenced by a number of factors, including the density of the polymer or mix of polymers, the grain size and distribution of the sand particles, the sand and plastic mix ratios, impurities in the mix plastic waste, and initial compaction or voids in the heat-melt mix prior to solidification. Four of the five research studies examined the density of the material. According to research, the higher the filler and binder ratio, the higher the density of the tile (Jnr et al., 2018; Khatwa et al., 2005; Konin, 2011; Susila et al., 2019). Density values for a mixture of 50% sand filler and 50% polymer binding range from 1420 kg/m^3 to 1450 kg/m^3 (Jnr et al., 2018; Khatwa et al., 2005; Konin,

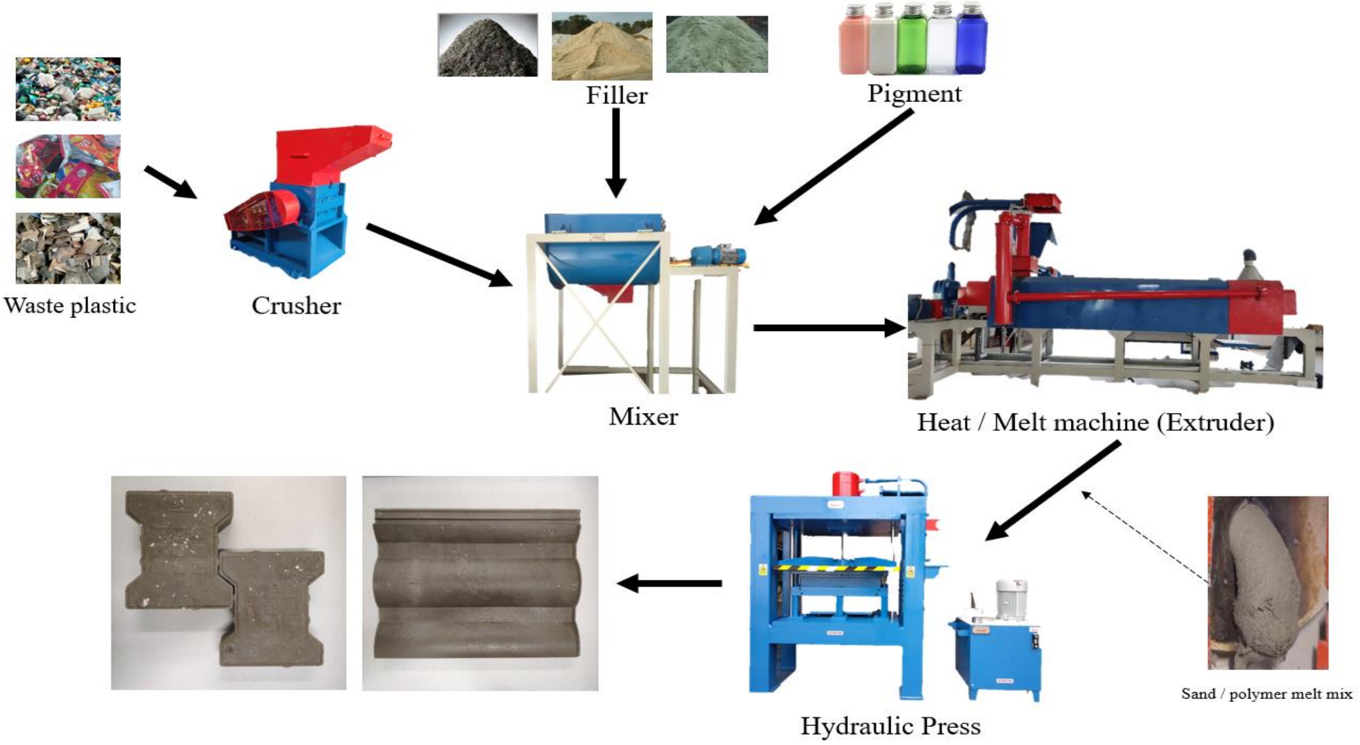

Figure 5 Process diagram of a manufacturing of sand plastic composite roof or pavement tile - machine images are from (Sinter Machines)

2011). By increasing the percentage of sand filler to 80% (0.5 mm grain size) and mixing with 20% LDPE binding, a density of 1750 kg/m^3 was attained (Jnr et al., 2018). By using rolled granular grade 0/2 silica as filler and Polypropylene as binding medium, (Konin, 2011), were able to reach a density of 2050 kg/m^3. Most importantly, this increased density was achieved without the use of any hydraulic compression. Hydraulic compression was utilised by (Khatwa et al., 2005) to get the right compaction and shape of the finished product. There is no specific reason given for the use of hydraulic compression up to 10MPa in the moulding stage. However, even using hydraulic compression, they could only reach 1600 kg/m^3 with a filler and binder ratio of 60% to 40%. This result is only a small improvement (50 kg/m^3) to the density recorded for the same filler-binder ratio by (Jnr et al., 2018) using sand <0.5mm particle size, LDPE and no compaction. Additionally, it was observed by comparing these studies, that the density of the composite did not significantly change when the polymer type was switched from LDPE or PP to mixed plastic. It is concluded that while mixing plastic with impurities can reduce overall density, hydraulic compression did not significantly increase density. Additionally, it was also discovered that the composite's density was not greatly impacted by the mixing temperature (Khatwa et al., 2005).

The compressive strength of the material is another important property of the composite. Plastic type, sand grain size, sand grain distribution, compaction, and mix temperature were all expected to have an effect on final product strength. The filler-binder ratio was assumed to be the main variable influencing the compressive strength of the mix. Figure 6 compares the compressive strength of the composite in MPa to the weight percentage (wt%) of sand proportion in each sample produced across all studies. According to (Jnr et al., 2018), compressive strength increased with increasing sand filler percentage up to 75% but decreased with filler percentage higher than 75%. This was expected because the higher the sand filler content, the lower the total binder content available in the composite. Increasing strength with increasing filler was also observed in the range of 20%, 40%, and 60% in the study by (Khatwa et al., 2005). In the study by (Susila et al., 2019), similar behaviour of decreasing strength with increasing filler was observed in the ranges of 70%, 83.3%, and 87.5%. The variation of compressive strength vs filler-binder ratio was studied for a wide range of 20% to 90% in the study by (Tulashie et al., 2020). It was discovered that the compressive strength of composite increased up to 80% with increasing sand filler but did not increase further with additional filling (remained almost constant). As shown in Figure 6, compressive strength results above 80% are inconsistent between research results and should be investigated further. Depending on the cheaper material (filler or the binder), the additional filler content above 80% can be accounted based on the product cost (i.e.: recycled glass or recycled mix -plastic waste). It was also noticed that the higher mixing temperature (240°C) resulted higher compressive strength in the composite (Khatwa et al., 2005). Therefore, it is important to study the effect of mixing temperature on the compressive strength of the composite

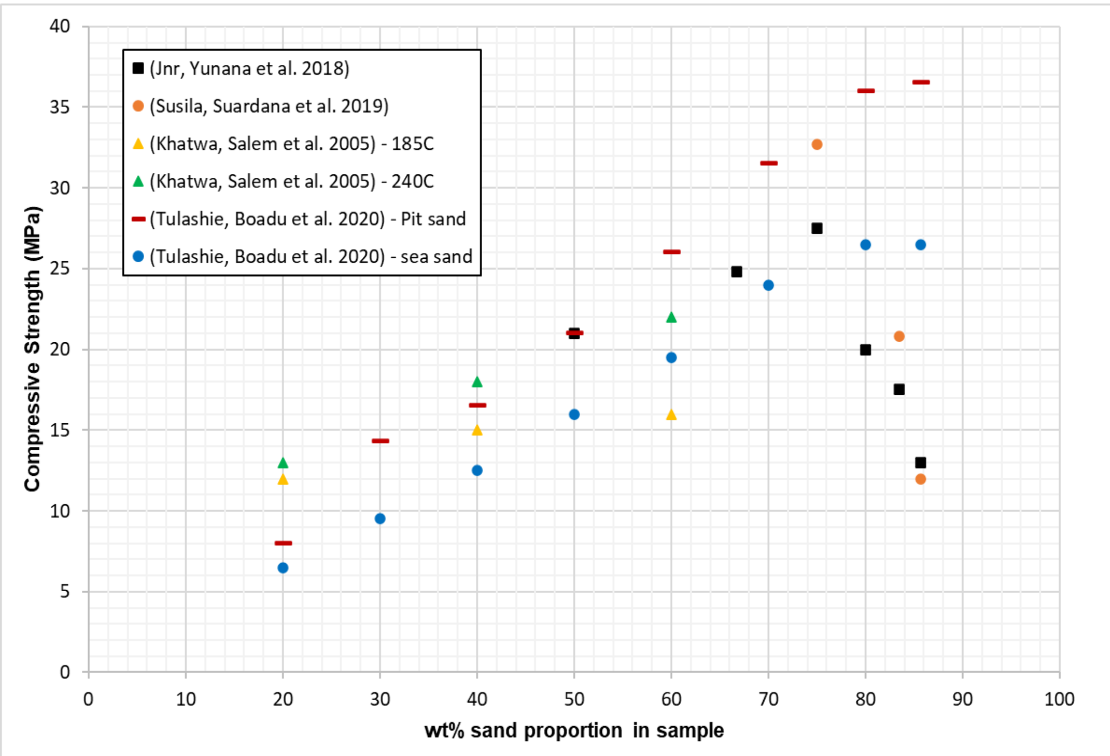

Figure 6. Compressive strength vs weight percentage of sand proportion in sample

material.

Furthermore, when the results of (Khatwa et al., 2005) and (Tulashie et al., 2020) were compared, it was discovered that the hydraulic compression (10MPa) used by (Khatwa et al., 2005) added additional strength up to a filler percentage of 40%. But when the filler percentage was higher than 40%, this additional hydraulic compression did not add any additional strength. The literature also revealed that finer the filler, the greater the strength of the composite (Jnr et al., 2018).

The use of graded sand and ungraded sand had no significant effect on the composite's strength. It also appears that the plastic type and impurities of the mixed plastic waste had no discernible effect on the compressive strength of the composite. Based on the results, it can be assumed that mix plastic has a higher binding effect than LDPE or PP alone, which could explain why compressive strength decreased after 75% sand with the LDPE binder medium but remained constant up to 90% with mix plastic binder.

In addition to the density and compressive strength tests, researchers have used electron or optical microscope images to study the bond between the filler and binder (Jnr et al., 2018; Khatwa et al., 2005; Susila et al., 2019; Tulashie et al., 2020). Other tests used by researchers discussed in this article include water absorption, surface humidity percentage, flexural strength, abrasion loss, hardness, chemical resistance, and penetration testing. It was discovered that none of these researchers conducted any long-term durability or fire testing of this composite.

5 CONCLUSION AND WAY FORWARD WITH GLASS PLASTIC COMPOSITE

This article goes into detail about research which attempts to develop a composite material, using sand as the filler and recycled polymer as the binder, to produce roof or pavement tiles as a replacement for cement-based equivalents. At the product stage, the density and strength of the composite were the two most important material characteristics considered. At the raw material selection stage, the effect of sand grain sizes, gradation, plastic type, plastic mix, impurities, pre-processing, and cleaning was investigated. At the material processing stage, the filler to binder ratio, mixing temperatures, mixing methodology, and compaction were all examined.

It was identified plastic type and a mix of plastic, as well as impurities did not affect the density or strength of the composite significantly. However, more studies are needed to evaluate this with the change of percentage of impurities in the mix (i.e. wood, paper, chemicals, and oil etc). Small grain size (<0.5 mm) of the filler particle can result in higher density, as well as higher compressive strength. However, uncontrolled filler with good grain distribution showed good results, as composite with filler <0.5 mm. Highest density that has been achieved using sand as the filler and plastic as the binder is 2000 kg/m^3 which is equivalent to the counterpart cement-based product. Interestingly, compaction of the material in the mould before solidifying did not show any significant improvement in the strength or density parameter. As a result, if the material can be moulded into the shape of a roofing or pavement tile without the use of high hydraulic pressure, it is worthwhile to investigate alternative low-pressure moulding methods that can significantly reduce composite production time and cost. Heat at the mixing stage was also observed to influence the strength parameter, which should be investigated further alongside compression and moulding.

The compressive strength of the composite products manufactured in the preceding studies is comparable to C20/25 concrete and greater than that of typical Portland cement sand equivalent pavement blocks. Most importantly, the higher the filler binder ratio, the higher the composite's compressive strength (up to 80% of filler). Above this point, the filler-to-binder ratio must be adjusted, based on the cost of the two components. Given that the material properties of recycled glass are very similar to those of sand, it is expected that the ratios found in the preceding studies will be adequate for recycled glass / plastic composite as well.

The main issue with this composite material is its susceptibility to environmental attack by ultraviolet radiation, as well as its fire resistance and fumes. Further research into this issue, as well as tests for organic compound leaching should be carried out.

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