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A Review on Recycled Use of Solid Wastes in Building Materials

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***Abstract*—**Large quantities of solid wastes being generated worldwide from sources such as household, domestic, industrial, commercial and construction demolition activities, leads to environmental concerns. Utilization of these wastes in making building construction materials can reduce the magnitude of the associated problems. When these waste products are used in place of other conventional materials, natural resources and energy are preserved and expensive and/or potentially harmful waste disposal is avoided.

Recycling which is regarded as the third most preferred waste disposal option, with its numerous environmental benefits, stand as a viable option to offset the environmental impact associated with the construction industry.

This paper reviews the results of laboratory tests and important research findings, and the potential of using these wastes in building construction materials with focus on sustainable development. Research gaps, which includes; the need to develop standard mix design for solid waste based building materials; the need to develop energy efficient method of processing solid waste use in concrete; the need to study the actual behavior or performance of such building materials in practical application and the limited real life application of such building materials have also been identified.

A research is being proposed to develop an environmentally friendly, lightweight building block from recycled waste paper, without the use of cement, and with properties suitable for use as walling unit. This proposed research intends to incorporate, laboratory experimentation and modeling to address the identified research gaps.

***Keywords*—**Recycling, solid waste, construction, building materials.

I. Introduction

SOLID wastes such as paper, glass, metal, textile and plastic constitute a major part of the municipal solid wastes that originate from household, schools, hospitals and business activities. Construction and demolition wastes such as waste concrete and wood waste are other types of waste common in the environment nowadays [1] .

Large amount of these wastes are generated around the globe from various human activities, in both developed and developing countries due to population growth, rise in living standard and urbanization [2].

According to the world bank statistics on solid waste management, the world cities is currently generating about 1.3billion tones of solid waste per year and this volume is expected to increase to 2.2 billion tones by the year 2025 [3]. Also, waste generation rate is expected to double over the next twenty years in lower income countries.

One of the global environmental impacts of solid waste is the emission of methane which is regarded as a powerful greenhouse gas GHG, whose impact can be felt within a short period of time. Flooding, air pollution and other public health impact are also associated with uncollected solid waste.

TABLE I
Current Estimates on Global Type of Waste Composition by Country Income Level [3]

Income level	Organic (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low income	64	5	8	3	3	17
Lower middle income	59	9	12	3	2	15
Upper middle Income	54	14	11	5	3	15
High income	28	31	11	7	6	18

TABLE II
Future Estimates on Global Type of Waste Composition by Country Income Level (Projection for 2025) [3]

Income level	Organic (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low income	62	6	9	3	3	17
Lower middle income	55	10	13	4	3	15
Upper middle income	50	15	12	4	4	15
High income	28	30	11	7	6	18

TABLE III
Global Solid Waste Composition [3]

Wastes	Percentage (%)
Organic	46
Paper	17
Plastic	10
Glass	5
Metal	4
Other	18

Tables I and II indicate the global current and future estimate of waste composition based on country income level while Table III presents the global solid waste composition [3]. Presently, in most low and low middle income countries, these wastes are either burnt or land filled. This is an approach which could cause various environmental problems like air pollution, emission of greenhouse gases and occupation of useful land. The increasing charges of landfill are further aggravating the problem. Moreover, these methods of disposal are certainly wastage of a primary resource. In addition, the biodegradation of these wastes in landfills, emits methane, a greenhouse gas which has 72 times heating effect relative to

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that of CO2 [4], besides, composting and burning of certain wastes is prohibited by legislation [5].

The need for alternative disposal of these waste is therefore paramount, to achieve environmental sustainability. The building construction industry is a major sector when it comes to environmental sustainability due to its high consumption of material, the possible utilization of solid waste in this sector stands to be a viable of option for it disposal.

II. Characteristics of Waste

Solid waste is any unwanted or discarded material that is not a liquid or a gas. Wastes such as paper, glass, bottles, cans, metals, certain plastics, fabrics, clothes, and wood can be classified under recyclable materials,

The physical and chemical properties of the solid wastes vary considerably with their source and storage condition as well as time. The main sources of solid wastes are household, industrial, domestic, commercial, construction demolition and furniture industry wastes.

The productive use of waste material represents a means of reducing some of the problems associated with solid waste management; it minimizes the use of natural resources and in some cases results in the production of environmentally friendly products. The need for safe and economic disposal of waste material is part of the reasons for the continuous advancement of research into innovative use of waste materials. Clean environment, reduced use of natural resources, and dumping spaces are being achieved through the use of recycled waste materials such as recycled aggregates, recycled glass, recycled paper, recycled plastic, recycled metal, and recycled textile in building materials.

A. Recycled Plastics in Building Materials

Plastics have become an inseparable and integral part of human daily activities, the steady growth in its consumption may be attributed to its low density, strength, user friendly designs, fabrication capabilities, long life, lightweight, and low cost characteristics

Large quantities of varieties of plastics such as high density polyethylene from milk bottles, polyethylene terephthalate (PET) from beverage bottles, or even unsegregated plastic mixture are available in municipal solid waste stream. The world’s annual consumption of plastic materials increased from around 5 million tons in the 1950s to nearly 100 million tons in 2001 [6]. Building materials can be an alternative means of using recycled waste plastics resulting from packaging.

Previous studies by [7]-[12] showed that it is indeed possible to use plastic waste in concretes or mortars. In particular, a research into the use of recycled polyethylene terephthalate (PET), a packing material byproduct, as binder in the production of high-performance composite known as polymer concrete was reported. The plastic was transformed by means of a transesterification reaction, in the presence of glycols and dibasic acid, into unsaturated polyester resin. The resin was then mixed with sand and gravel. The polymer concrete obtained was reported to exhibit high resistant in both compression and flexion, compared to conventional Portland cement concrete [13], [14], it also has the advantage of developing over 80% of its ultimate mechanical strength within 1 day but with low resistance to temperature [11], [14], [15].

Other authors have also used PET waste mixed with high density polyethylene waste (HDPE) as aggregates, as a partial substitute for between 5–20% of the total volume of sand in order to draw comparisons with glass fibres generally used as structural reinforcement [14], [16]. The study revealed that a volumic substitution exceeding 15% decreases the mechanical properties of the new composites with respect to the reference mortar that contains no waste.

Reference [17] conducted a research with the objective of investigating the mechanical properties which includes; the compressive strength, the splitting tensile strength, and the flexural strength of polymer concrete using an unsaturated polyester resin based on recycled PET. The relationships between the mechanical properties was analyzed, it was reported, that, the polymer concrete using resin based on recycled PET can achieve compressive strength of 73.7 MPa, flexural strength of 22.4 MPa, splitting tensile strength of 7.85 MPa, and elastic modulus of 27.9 GPa, at 7 days, which means that some relationships exist between the compressive strength of polymer concrete and other properties such as, elastic modulus, flexural strength, and splitting tensile strength.

In a study conducted by [14], to investigate an innovative use of consumed plastic bottle waste as sand-substitution aggregate within composite materials for building application, in which, the bulk density and mechanical characteristics of the composites produced were evaluated. The use of scanning electron microscopy technique to study the relationship between mechanical properties and composite microstructure revealed that, substituting sand at a level below 50% by volume with granulated PET, whose upper granular limit equals 5 mm, affects neither the compressive strength nor the flexural strength of composites.

The study demonstrated that plastic bottles shredded into small PET particles may be used successfully as sand-substitution aggregates in cementitious concrete composites, with conclusion that, the composites appears to offer an attractive low-cost material with consistent properties which could resolve some of the solid waste problems created by plastics production and in saving energy.

The use of plastic as an ingredient for the production of building material from the combination of plastic and wood was reported in a study by [18], an example of such is known as thermoformable wood plastic fibre composite which are classified into processed melt blending and non-woven mat formulation, they result from the combination of powdered or pelletized thermoplastic such as polypropylene or polyethylene with wood flour or cellulose fibre. The primary application of this thermoformed composites, both melt and blended and air laid type, is for interior door panels and trunk liners in automobiles [18].

The use of plastic waste in granular form [19], fibrous form [20], [15], and powdery form [21], for purposes such as sand

and natural aggregate replacement, reinforcement and in combination with other materials were investigated. These studies reported improved compressive and flexural strength, however, more research is required in this direction to ascertain the optimum level of substitution. Also, low bond characteristics of plastic wastes has been identified as a major hindrance to use them in concrete, given its smooth surface, there is therefore need to identify a surface roughening treatment for better bond properties.

B. Recycled Textile in Building Materials

There have been increasing environmental concern regarding the textile industry waste and those generated as postconsumer textile waste, due to the enormous amount not being used. In European Union (EU) alone, around 5.8 million tonnes of post-consumer textiles are discarded per year, only 1.5 million tones (i.e. 25%) go into recycling by charities and industrial enterprises. The remaining 4.3 million tonnes goes to landfill or to municipal waste incinerators, thereby making textile wastes from the textile industry another significant source of waste [22]. In 2009, 293,000 tonnes of textile waste was produced, in Portugal, and the main textile waste generated in the country comes from wool, cotton and synthetic and artificial fibers.

Textile waste integrates the group of reusable materials that can be included in the building construction and which have different possibilities of application. These textile wastes may have origin in the textile industry or may simply result from clothes that are no longer used. The study of the performance of these types of wastes in the construction is partly based on the behavior of the tissues when they are used as clothing. The primary function of clothing is to protect the human body from cold and heat, in order to keep thermal comfort conditions. This can be acquired ensuring an appropriate heat transfer between the human body and the outside environment. In this regard, studies to analyze the phenomena of heat transfer through the textile fabrics showed that their thermal insulation properties are highly related to the properties and configuration of their components, namely to the capillary structure, surface characteristics of yarns and air volume distribution in the fabrics [22]-[25]. Therefore, the knowledge of thermal, mechanical and physical performance of various types of textile fabrics and their residues is essential to optimize its use as a raw material in the building construction.

The investigation of different textiles fibers as a material to produce lightweight concrete, as reinforcement of cement mortars elements [26], reinforcement in concrete [27], [28], or as fibrous insulation materials [29] reported an improved mechanical behavior of the concrete, a mortar with physical, mechanical and durability properties similar to glass or polypropylene [26], there are minor changes in the water vapour permeability of the loose-fill cellulose specimens [29]. Another research work with a focus on analyzing the potential application of textile sub-waste as an alternative building thermal insulation material for double external walls, concluded that by using the textile sub-waste, a double external wall's thermal insulation performance may be increased by 33%. Though, further investigation is needed regarding the use of textile waste, the work developed so far are based essentially on the use of textile waste in the production of bricks and lightweight materials [30]-[33], more particularly using cotton combined with other materials, such as limestone powder, fly ash, barite, and paper, in which properties like, Sound insulation, thermal conductivity, bending strength and radioactivity were studied showed that; the produced brick possess good thermal stability [33], increased compressive strength [32], high energy-absorbing capacity and up to 30 minutes fire resistance [30]. It was proved that light-weight construction materials produced with cotton waste, fly ash and epoxy resin could be used for getting better thermal and sound insulation results even though the radioactive permeability of samples containing barite was low [32]. For instance, in the production of Waste Crete Bricks with varying content of cotton waste (1–5 wt.%), recycle paper mills waste (89–85 wt.%) and fixed content of Portland cement (10 wt.%) subjected to testing in accordance with IS 3495 (Part 1–3): 1992 standards. The findings indicated a thermally stable bricks up to a temperature of 280 °C with porous and fibrous nature as shown by SEM monographs but with conclusions that the bricks meets IS 3495 (Part 1–3): 1992 requirement [33].

Research work has also been developed to study the use of woven fabric waste (WFW) and a waste of this residue, named woven fabric sub-waste (WFS), as an alternative solution to commercial insulation materials, such as extruded polystyrene (XPS) or expanded polystyrene (EPS) products. Reference [22] conducted experimental work to examine the influence of introducing each one of these textile wastes in the thermal performance of an external double wall. The heat transmission coefficient (U) of the double wall with the air box filled with these types of waste was determined. These results were used to calculate the value of thermal conductivity of WFW and WFS. The result obtained showed that the application of the WFW and WFS in the external double wall increases its thermal behavior in 56% and 30%, respectively. The thermal conductivity value of the WFW is similar to the values obtain for expanded polystyrene (EPS), extruded polystyrene (XPS) and mineral wool (MW). The value of this parameter for the WFS is approximately equal to the values for granules of clay, vermiculite or expanded perlite. It was concluded that applying these wastes as a possible thermal insulation material seems to be an adequate solution. Environmental, sustainable and economic advantages may result from this practice.

C. Recycled Metal in Building Materials

Metal recycling is the process of reusing old metal material, mainly aluminum and steel, to make new products. Recycling old metal products uses 95% less energy than manufacturing it from new materials [34]. Million tons of energy is required in the chemical reaction process required to produce aluminum and steel products, meanwhile, for the recycling of metal products, only 4% of this total energy is utilized which serves as means of conserving natural resources and reducing greenhouse gas emissions.

Ferrous metal is regarded as the most profitable and recyclable material with highly developed market and demand all over the world and therefore, the applications of these materials had been well accepted on site.

Steel can be melted to produce new one ,apart from it direct reuse, unlike few other waste materials, scrap steel allows repeated recycling, which is one of the factors that enables its 100% recyclability, Steel organization reports that roughly 100% steel reinforcement is made from recycled scrap and 25% steel sections are made from recycled scrap [35].

Waste steel slag which is a by-product produced during the conversion of iron ore or scrap iron to steel is another waste material that has potential for use in construction, it mineralogy composition changes with its chemical components, solid compound of CaO–FeO–MnO–MgO, and free CaO are the common minerals in steel slag [2].

In India, the blast furnace slag, categorized as group I waste and has been used in the manufacture of blended cement to improve its soundness, strength, morphology, and abrasion resistance. The group II material which includes ferro-alloy industrial waste has not been used extensively, but it has great potential for recycling. These solid wastes have been used in production of Portland blast furnace slag cement, super sulphate cement, and also as aggregates in high strength concrete and light weight concrete [36]. The group III materials include the tailings of iron, zinc, copper and gold ore beneficiation and have been used as fine aggregate or concrete filler material in the construction industries [37].

A study by [38] revealed, that reactivity of steel slag is due to the free CaO content ,though a previous study reported that the high free CaO content in steel slag produces volume expansion problems [39].

The use of waste steel slag to produce construction materials such as cementitious pastes and bricks had been investigated. Reference [40] used steel slag to produce combined-alkali slag paste materials. Reference [41] also reported that the incorporation of steel slag enhances brick production, in the sense that, it reduces the firing temperature but with a decrease in the compressive strength and firing shrinkage. It was concluded that these bricks can be used as third class bricks in construction industry; therefore, more investigation is needed to improve the aforementioned characteristics

D.Recycled Glass in Building Materials

Waste glass constitutes a problem for solid waste disposal in many municipalities and the practice of landfilling it, does not provide an environmental friendly disposal, due to its non-biodegradability. Consequently, there is a strong need to utilize/recycle waste glasses.

In 1997, the glass industry recycled 425,000 tonnes of glass in the United Kingdom [35]. However, the recycling rate is relatively low in Hong Kong (1%) in comparison with other countries (the rates in USA, Japan and Germany are 20, 78 and 85%, respectively).Glass can be reused in the construction industry for a number of applications such as: window, tiles, glass fibre, filler materials, paving blocks and aggregate in concrete.

Glass windows units from construction demolition can be reused directly depending on how carefully they are handled, stored, transported and contaminated [35].

Recycled glass can be used for properties enhancement in the manufacture of glass fibre, which is used in thermal and acoustic insulations, which can be mixed with strengthen cement, gypsum or resin products [35]. In Japan practices, recycled glass is adopted as isolation material, including glass wool mat; pipe cover and thermal insulation board with facing for plant; ceiling board and acoustical insulation board for industrial and commercial building

A clean dry glass powder is useful as a substitute for Portland cement in concrete. The finely ground glass having a particle size finer than 38 μm contain a high amount of amorphous silica, which exhibits a pozzolanic behavior [42]. Hence, the use of ground glass in concrete can be advantageous with respect to hardened properties and durability.

In the United Kingdom practices, recycled glass is used as a fine material for cement replacement called "ConGlassCrete", which is used for improving the strength of concrete, aside this, the product obtained from the 100% utilization of recycled glass in the United States for the production of tiles, exhibited an attractive reflective appearance on the surface after polishing.

The possibility of producing paving blocks having various levels of fine or coarse waste glass in place of fine aggregate was also investigated by [43]. It was found that, a 20% replacement by weight of fine aggregate with fine glass has a potential to produce good quality paving blocks.

Paving blocks are produced from recycled glass aggregate by crushing in USA. Hong Kong is also developing this recycling technology, to produce concrete block with properties such as; an attractive reflective appearance on the surface after polishing, reduce water absorption and good compressive strength. However, the drawback of instability, sharpness of aggregate and alkali-silica reaction expansion still requires attention. The adoption of pulverized fly ash for depressant in alkali-silica reaction and reduction of impurities are essential in optimizing the quality of paving block containing recycled glass aggregate. Another option is to crush and grade waste glass and use it as a replacement for fine aggregate in a concrete mix though with a caution of ensuring that the glass used be silica-free in order to avoid alkali-silica reaction (ASR) phenomenon in the final composite. If this basic criterion is met, past studies indicate that recycled waste glass is an acceptable material to be used in concrete. There tends to be a slight decrease in compressive strength as the fraction of recycled glass is increased in a mix, and other properties such as air content and mix are dependent on the shape of the individual grains of the crushed glass [44]-[46]. However, the testing of mortar bar demonstrated that finely ground glass helps to reduce the expansion due to alkali-silica reaction by up to 50% [42].

Reference [47] reported a significant improvement in the compressive strength of fired clay brick due to the addition of waste glass, stating that, the amorphous nature of waste glass particles enhances the sintering action, which leads to achieving a better strength in bricks and that the waste glass can be mixed with clay in different proportions to prepare high quality bricks. Similarly, [48] reported that clay bricks with suitable physical and mechanical properties can be obtained at a proper firing temperature by using waste glass with content in the range of 15 to 30% by weight of clay.

In a recent research by [49], the strength and transport properties of clay bricks were found to improve as a result of the improvement of pore structure when 15% (by weight of clay) of both fine and coarse waste glasses was added.

E. Recycled Paper in Building Materials

Paper can be described as a sheet of cellulose fibre mostly obtained from wood, rags or grass fibre and sometimes other plants such as cotton, rice and papyrus for production of special papers. Ever since its invention, it has formed an important part of human day to day activities, with uses in many applications due to its versatile properties, the most common of such uses being writing and printing upon, other are but not limited to packaging material, cleaning products, industrial and construction processes.

The need to recycle paper is paramount upon the fact that, the more it is being utilized for several applications, the more the amount of waste paper generated and major percentage of these, finds their way to the municipal solid waste stream, according to the US environmental protection agency(US EPA), paper and paper board products make up the largest portion of the municipal solid waste stream in the United States, occupying 40% of the landfill composition in 2005 [50], [51] and 27.4% of the total MSW before recycling in 2012 [1]. Similarly, paper and cardboard waste form largest fraction of the municipal waste stream in Europe, accounting for 35% [52]. Waste paper therefore represents a considerable environmental and social problem, whose recycling can reduce the amount of paper that find its way to waste disposal, and can be used for fuel, building insulation, building materials, potting mixture, insulation in cars and shoes aside it uses for paper and card production.

Several research had been carried out to investigate the use of waste paper in the production of building materials such as, fibre reinforced cement composite [53], [54], wall panel [55], [56], building block [57], adobe [57], [58], brick [59], thin cement sheet [60], low density board [61], [62], Composite panel [63].

Its suitability for use as reinforced fibre cement composite, low density board, and composite panel has been established in previous studies, though with recommendation for more research to improve on the problem of high moisture absorption of fibre and composite, low compatibility of fibre with cement and the unsatisfactory physical and mechanical properties of the composite when the waste paper fibre proportion is increased [64], [65].

Waste paper can be used in concrete as a lightweight aggregate capable of enhancing the weight-to-strength ratio, insulation properties, and toughness characteristics of concrete materials [66]. Also, an improvements in restrained shrinkage crack control and impact resistance were particularly significant and comparable to those of virgin fibers when waste paper were used as discrete reinforcement systems in concrete [67].

Regarding its use in the production of (papercrete) building block, the compressive strength in the range of 0.96-1.1MPa [57], 1.7MPa [68], and 1.12 -2.36MPa [69] were reported. A very low tensile strength ranging between 0.195 and 0.052MPa was reported by [70]. However a much lower thermal conductivity than concrete was reported showing that its insulation value is much higher. This is because the R-value of papercrete is in between 2.0 – 3.0 per inch (0.078-0.12 per mm) with thickness in walls 12-16 inches (304.8-406.4mm) in one or two story house [57]. Similarly, [70] reported the thermal conductivity of papercrete to be 0.10 W/(m•K) and that of concrete was between 1.25 and 1.75 W/(m•K) [70].

Reference [57] stated that, a more useful measure of papercrete's properties is its stiffness i.e., the extent to which it compresses under load. Its stiffness is considerably less than that of concrete, but sufficient for the support of roof loads in some low-height buildings. Varying the mix of papercrete, admixtures and curing procedures results in compromises in its properties. For instance, adding more sand or glass to the mix results in a denser, stronger, more flame retardant material, but adds weight and reduces R-value [57]. Heavy mixes with added sand, glass, etc. increase mass and strength to a point, but reduce workability. In other words, a light mix with just Portland cement is easier to cut with a chain saw and drive rebar through than a mix with larger amounts of sand, clay, etc. Adding more than the minimum amount of Portland cement to the mix increases strength and resistance to abrasion, but also reduces flexibility somewhat, adds weight and may reduce R-value. Therefore, finding the best mix for the application is important.

Reference [71] reported the results of an investigation on the utilization of wastepaper as additional materials in concrete mixes to be used for housing projects, in which. Four concrete mixes containing of the waste, which are control mix, 5%, 10%, 15% as an additional materials to concrete were prepared with ratios of 1:2:3 by weight of cement, sand, and aggregate respectively with a 20mm maximum size of aggregate. The test results revealed that as the content of the paper increased the water to cement ratio for the mix was also increased. With the addition of 25% wastepaper in proportion to the amount of cement, the mechanical strength decreases significantly. Overall, a high correlation was observed between density and strength of concrete containing paper.

F. Recycled Aggregate in Building Materials

Recycled aggregate is a product obtain from the recycling of construction and demolition waste concrete, the need to find an alternative disposal method for this kind of waste instead of landfilling ,coupled with the scarcity of virgin aggregate are the factors that encourage it utilization in building materials such as concrete, and brick.

Several researches had been carried out to investigate the properties of concrete containing recycled aggregates of various types and quantities. Chemical stability [43], physical durability [72], workability [73], strength [74], permeability and shrinkage resistance [75] are some of the properties that have been investigated. Most of these studies came up with the general conclusion that, concrete containing recycled coarse aggregate which are properly cleaned, and in quantities not more than 50% replacement of virgin aggregate would have adequate durability, workability, and strength when compared with concrete containing 100% virgin aggregate [74], [76]. Although, concrete containing recycled aggregate is expected to display slightly more shrinkage than that containing virgin aggregate [75]. The compressive and splitting tensile strengths of concrete made with recycled coarse aggregate depend on the mix proportions [74]. Permeability of concrete containing recycled aggregate at w/c ratios same as that of concrete containing only virgin aggregate is also expected to increase [77]. With regards to chemical stability, it is important that waste aggregates being used do not contain reactive silica in order to avoid alkali-silica reaction (ASR) in the final product.

Reference [78] investigated the flexural behavior of plain concrete containing crushed old concrete as replacement for natural coarse aggregate. Plain concrete beams made with 0%, 50%, and 100% recycled coarse aggregate were tested as simple beams with third point loading. When compared with the ACI standard, the obtained moduli of rupture values were within the acceptable levels. Furthermore, statistical analyses of permeability tests indicated that the concrete was not greatly affected by the use of the recycled aggregates in the mix.

The utilization of recycled concrete aggregate in different construction applications other than in production of new concrete have been considered by few studies, one of such application is the use of recycled concrete aggregate in the production of sand lime brick in Kuwait, which was considered by [79], [80]. The study evaluated the specific gravity, compressive strength, and absorption characteristics of the brick. It was reported, that the brick made from recycled concrete aggregate has properties that are within the specifications requirements.

In Hong Kong, [73] considered the use of recycled aggregate from construction and demolition waste to produce concrete bricks and paving blocks, Laboratory trials were conducted to investigate the possibility of using recycled aggregates from different sources in Hong Kong, as the replacement of both coarse and fine natural aggregates in molded bricks and blocks. The test results based on a series of tests carried out to determine the properties of the bricks and blocks prepared with and without recycled aggregates, showed that the replacement of coarse and fine natural aggregates by recycled aggregates at the levels of 25 and 50% had little effect on the compressive strength of the brick and block specimens, but higher levels of replacement reduced the compressive strength. However, the transverse strength of the specimens increased as the percentage of replacement increased. The author concluded that using recycled aggregates as the replacement of natural aggregates at the level of up to 100%, concrete paving blocks with a 28-day compressive strength of not less than 49 MPa can be produced without the incorporation of fly ash, while paving blocks for footway uses with a lower compressive strength of 30 MPa and masonry bricks can be produced with the incorporation of fly ash.

While recycled aggregates have been used in large amounts in non-structural concretes for building structures, its use in structural concrete is limited to low level of replacement of the total weight of coarse aggregate. Few cases of its use in structural concrete have been reported, An example is a viaduct and a marine lock project in the Netherlands in 1988, and an office building in the UK in 1999 [81]. In the first case, a total of 11 000 m^3 of concrete in which 20% of the coarse aggregates were replaced by recycled aggregates was used in all parts of the structures. Another reported case involved the use of 4000 m3 of ready mixed concrete, which was prepared with recycled aggregates obtained from crushed concrete railway sleepers to replace 40% of the coarse [81].

G. Recycled Wood in Building Materials

Wood waste may be sawdust from the sawing of wood or any other wood wastes. It is used in large quantities in many different sectors and is a part of human everyday lives; large volumes of sawdust and other recovered wood have accumulated in many places over the years. Sawdust can be described as loose particles or wood chippings obtained as by-products from sawing of timber into standard useable sizes [82].

Other wood wastes may include, solid or chipped wood in its natural stage without chemical contamination, glued coated lacquered wood without halogenic materials as timber preservative, wood with halogenic materials (i.e. PVC) but no timber preservatives and wood with timber preservatives [83]. About 30million tonnes of recovered wood are generated in Europe annually [84].

Timber waste from C&D works is produced in large quantity all over the world. It is estimated that more than 2.5 million tonnes of timber wastes are generated in the United Kingdom each year [35].

The potentials of wood waste being recycled and utilized or reuse easily and directly in other construction projects after cleaning, de-nailing and sizing have been considered in some studies, Undamaged wood can be reused as plank, beam, door, floorboard, rafter, panel, balcony parapet and pile [85]. A new technology in turning timber waste into furniture, shoring wooden pile for relocated pine trees, bench and timber stair was developed in Japan in 2004. A special lightweight concrete can be produced from aggregate made from recycled small wood chunk [86].

Reference [82] considered the development of a new building material from wood. This new building material named as Wood-Crete was developed using sawdust, waste paper and tradical lime. The results of the study showed that lightweight sustainable blocks can be produced with good insulating and other relevant properties for building construction with density ranging from 356 to 713 kg/m^3 and compressive strength from 0.06 to 0.80 MPa. The properties were closely related to the composition of Wood-Crete with an addition of waste paper being a dominant influence on both strength and thermal conductivity, reflecting its effect on the structure of composite and contribution of self-strength of paper fibres. The combined effect of sawdust and waste paper and tradical lime had a direct effect on the strength properties of Wood-Crete. Of significant importance was the contribution of self-strength of Wood-Crete due to the influence of the size of sawdust particles used. The developed Wood-Crete was able to withstand considerable amount of impact load and considered like hempcrete most suitable for wall paneling or other non- and semi-structural applications with good thermal insulating properties.

In a previous investigation, [87] used wood particles from construction waste in Japan for making wood-chip concrete. They made concrete with a density range of 920–1250 kg/m^3. They found the flexural strength of the product in the range of 4–7 MPa and compressive strength 5–8 MPa. The ratio between flexural strength and compressive strength was 0.5–0.9, greater than that for normal concrete. This indicates the reinforcing effect of wood particles. They further reduced the density to about 780 kg/m^3 by adding synthetic lightweight aggregates. This resulted in comparatively lower bending and compressive strength values at 2.05 and 2.2 MPa, respectively.

III. Discussions

Based on the investigations into the use of solid wastes reviewed, various research studies had been conducted on the utilization of solid wastes in the production of building materials. Their uses for purposes such as fine aggregate, coarse aggregate, cement replacement, binder, and reinforcement in the production of several building (Table IV) has been established. Most of these researches focused on the influence of solid wastes on the physical and mechanical properties of building products concerned. Some also attempted to study the durability performance of such products containing solid wastes.

The studies reported that, the use of plastic wastes in the fibre, granular and powdery form, have no significant side effect on the properties of the concrete produced [14], [19], but in some cases brought about improvement in compressive [21] and flexural strength [15], [20] higher strength to weight ratio, workability, thermal, insulation and reduction in self-weight.

Utilization of textile fibre with adequate consideration of its thermal, mechanical and physical properties in the correct proportion produces concrete with improved mechanical behavior, mortar with improved physical, mechanical and durability properties similar to glass or polypropylene [26]. A significant increase in the thermal insulation of double wall was observed [22] and combination of cotton with materials such as paper, limestone powder, barite and fly ash produced brick with good thermal stability [33], increased compressive strength [32] high energy absorbing capacity and 30min fire resistance [30].

The use of blast furnace slag was found to improve soundness, strength morphology and abrasion resistance of blended cement [36]. Waste steel slag incorporation resulted in the production of brick with low firing temperature suitable for use as third class brick, though with decreased compressive strength and firing shrinkage [41].

Aside the reuse of glass for windows and tiles [86] finely ground glass exhibit pozzolanic behavior which made it suitable for substituting Portland cement, particularly, glass powder with particles size finer than 38μm [42], 20% replacement by weight of fine aggregate with fine glass has potential to produce good quality paving block [43]. It uses in real practice for the production of ceiling and acoustic insulation board, conglasscrete and tiles in Japan, United Kingdom and United States respectively were also reported [86]. Also, 15 to 30% waste glass incorporation in clay produces bricks with suitable physical and mechanical properties at proper firing temperature [47], [48].

The suitability of wastepaper for use as constituent of building materials such as fibre reinforced cement composite [53], wall panel [55], building block [57], brick [59], thin cement sheet [60] and, low density board [61] were reported. Though more investigation is required to improve on the high moisture absorption of fibre and composite, low compatibility of fibre with cement

Concrete containing recycled aggregates in quantities not more than 50% replacement of virgin aggregates would have adequate durability, workability and strength when compared with concrete containing 100% virgin aggregate [74], [76]. Mix proportion influence the compressive and splitting tensile strengths [74].

Apart from the reuse of undamaged waste wood in construction, a special lightweight concrete can be produced from aggregate made from recycled small wood chunk. The possibility of producing lightweight block with properties such as; density ranging between 356-713kg/m^3, compressive strength from 0.06-0.8MPa and good insulating properties from combination of sawdust, paper and lime was reported by [88]. The reinforcing effect of wood particles was indicated through the production of wood – chip- concrete in Japan, with density range 920-1250Kg/m^3, flexural strength 4-7Mpa, and compressive Strength 5-8Mpa [87]. However, certain issues such as; the problem of low fire resistance and low bond characteristics of plastic waste used as fibre in concrete which usually occurs due to the smooth surface of plastic; high volume expansion problem in steel slag concrete resulting from high free CaO content in steel slag; decreased compressive strength and firing shrinkage of bricks containing waste steel slag. Alkali silica reaction (ASR) phenomenon in concrete containing glass with high amount of silica; and high moisture absorption of building materials containing waste paper still requires more investigations.

To address the issues regarding waste paper use in concrete, a research is being proposed to investigate the applicability of using recycled waste paper to produce an environmentally friendly lightweight, non-load bearing building block, with property suitable for use as walling unit.

TABLE IV
SUMMARY OF RECYCLED USE OF SOLID WASTE IN BUILDING MATERIALS

Solid waste	Recycling Technology	Recycled Use in building materials
Plastic	Transesterification Crushed into Aggregate Grind to powder	Concrete/Mortar, resin binder (for polymer concrete). Fine aggregate, Thermoformable (wood plastic fibre) composite
Textile	Cut Into Fibre	Lightweight concrete, Cement mortar elements, Insulation materials, reinforced concrete, Bricks
Metal	Melt Reuse	Recycled steel, blended cement, Aggregate in high strength concrete and lightweight concrete, cementitious paste, bricks
Glass	Reuse Crushed into Aggregate Grind to powder	Recycled window unit, cement replacement, filling material, recycled aggregate, tile, paving block, brick
Paper	Pulp (blended) Fibre (Shredded)	Fibre reinforced cement composite, wall panel, building block, brick, thin cement sheet, low density board, composite panel.
Wood	Reuse Crushed into Aggregate Combined with other materials	Plank, beam, door, floor boards, rafter etc. Lightweight aggregate Woodcrete (sawdust+ waste paper+ Lime) Wood chip concrete
Concrete	Crushed into Aggregate	Recycled aggregate, e.g. Coarse or Fine aggregate, Concrete bricks, Paving blocks

Speaking of environmental friendliness, it incorporate ; less pollution, less use of natural resources, less energy utilization, affordability, less emission of greenhouse gases, all this are the focus of this proposed research to promote sustainability in the construction industry.

IV. CONCLUSIONS

Significant research studies have been conducted on the development of new building materials using different kinds of solid wastes (Table IV), if this kind of investigation continues at this rate; the possibility of achieving zero waste in the nearest future could be a reality.

The literatures studied establish the possibility of utilizing solid waste materials like, plastic, wood, metal, paper, glass and demolished concrete as constituent of building materials. The use of these wastes at adequate level of replacement or proportions as the case may be, will improve the intrinsic properties of the building materials concerned. The application of these construction materials in real construction is limited. More research is needed to study the actual behavior or performance of solid waste based building materials in their practical applications because, properties like durability which has to do with long-term performance can be best studied through this means. In addition, the need to establish an energy efficient method for processing the solid waste to make them suitable for use in concrete standard mix design formulation is also required

To encourage practical application of the building materials containing recycled wastes, there is need for research which will be focused on promoting the acceptability of these kinds of construction materials to the public and international building standards. This can be made possible by incorporating laboratory experimentation, statistical analysis and modeling of such construction material to validate the outcome of experimentation in a real life condition. The statistical analysis of the result will also enable the understanding of the confidence level of the results, thereby proofing it beyond reasonable doubt. Therefore, to address the research gaps identified in this review, an investigation of the applicability of recycled waste for the production of lightweight building material, with focus on sustainability has been proposed. This proposed research, intends to produce an environmentally friendly lightweight building block from recycled waste paper without the use of cement, with properties suitable for use as non-load bearing walling unit.

Laboratory experimentation will be carried out to develop adequate mixture proportioning process with which the standard mix design will be formulated, to aid the acceptability of this material to building regulating body and the general public, the technology available for producing and for ascertaining the quality of concrete/sandcrete block will be employed as much as possible. Energy efficient equipment to process the material both at preparation and experimentation stage will be designed and fabricated. Numerical modeling will be used to validate the outcome of laboratory experimentation, in order to understand the actual behavior of the material in practical application.

The significance of this proposed investigation can be justified based on the fact that, its success is expected to contribute to the use of recycled waste in concrete, which may result in reduction in environmental pollution, conservation of valuable land fill spaces, conservation of natural resources and energy, minimized use of Portland cement as well as reduction in construction cost

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