Supplementary Cementitious Materials as Sustainable Partial Replacement for Cement in the Building Industry

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Abstract**—**Cement is the most extensively used construction material due to its strength and versatility of use. However, the production of Portland cement has become unsustainable because of high energy usage, reduction of natural non-renewable resources and emissions of greenhouse gases. Production of cement contributes to anthropogenic greenhouse gases emissions annually. The growing concerns for the environment resulting from this constant and excessive use of cement has therefore raised the need for more green materials and technology. The use of supplementary cementitious materials (SCMs) is considered as one of the many alternatives suited to address this issue and serve as a sustainable partial replacement for cement in construction. This paper will examine the reuse of these waste materials to partially replace Portland cement. It provides a critical review of literature analysing various supplementary cementitious materials which are applicable in the building industry as either partial replacement for cement or aggregates. These materials have been grouped based on source into industrial wastes, domestic/general wastes, and agricultural wastes. The reuse of these waste materials could potentially reduce the negative effects of cement production and reduce landfills which constitute an environmental nuisance. This paper seeks to inform building industry professionals and researchers in the field on the applicability of these waste materials in construction.

Keywords**—**Cement, greenhouse gases, landfills, sustainable, waste materials.

I. INTRODUCTION

CEMENT is constantly used for construction all over the world. The construction industry utilizes about 75% of natural resources for construction activities and is contributing to its depletion [1], [2]. Cement manufacture is responsible for depleting fossil fuels, reducing natural minerals and growing environmental concerns related to the changing climate [3]. The production of cement consists of two activities, obtaining the fuels and raw materials and calcination of raw materials to form clinker and then cement.

Portland cement is said to be one of the most widely utilized construction materials in the world comprising of finely inter-ground mixture of clinker and about 3-7% gypsum and anhydride [4]. Cement production contributes up to 18% of total industrial CO_2 emissions [5].

Fig. 1 shows the total CO_2 emissions across Portland cement production process. Grinding, Quarrying and transportation make up 15% while the pyro-processing makes up 85% [3].

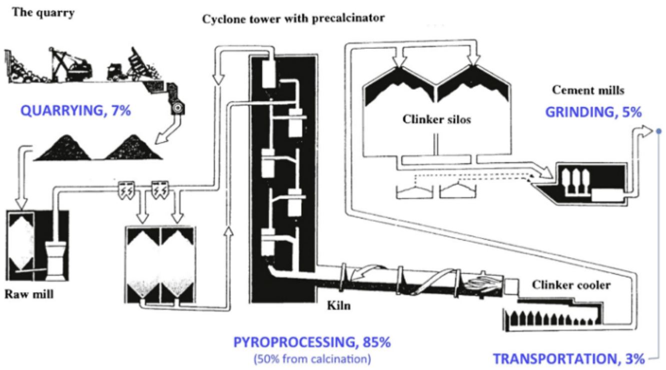

Fig. 1 Share of total CO_2 emissions across the cement production process [3]

Reference [6] explains that during cement manufacture 50% of CO_2 emissions is from the burning of limestone and the other 50% from the combustion of fuels, with one ton of cement producing about same ton of CO_2 [7]. According to [8], global cement production was 3.27 billion metric tons in 2010 and is estimated to increase to 4.83 billion metric tons by 2030. Furthermore, production of Portland cement contributes to about 5-7% of anthropogenic greenhouse gases generated, equal to 2.54 billion tonnes out of the global generation of 36.2 billion tonnes annually [9]-[11]. Thus, the negative effects of cement manufacture have led to increasing research for locally available materials, recycled materials and waste materials which would be suitable alternatives for cement. This, therefore, calls for developing clinker using alternative mineral, low carbon cements, less carbon intensive fuels and production process. Several methods have been suggested for reducing the CO_2 emissions from cement manufacture. One method is carbon capture and storage where emissions from the cement kilns can be captured and stored. Another method is the use of geopolymers. Geopolymers have been considered an ideal alternative as they are produced at low temperatures and obtained from heat-treated industrial wastes [12]. It also reduces fuel and energy costs up to 70-90% less than that of cement manufacture [13]. Another method, according to [14], consists of introducing alternative cements that are clinker free. These methods, however, are still new and currently under research. Buildings can also be designed to require less cement. In the same manner, the use of alternative fuel sources has also been proposed [15] as they are an effective substitute

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for reducing high energy utilization from fossil fuels and reducing emissions. These are mainly non-fossil fuels usually obtained from commercial or industrial wastes, biomass residues or sewage sludge e.g., plastics, waste tyres, waste oils [16].

A more ideal alternative involves the use of supplementary cementitious materials such as fly ash and slag, as these have been proven to produce good results when used to partially replace cement. Reference [9] suggests that it would take about 1.58 billion tonnes of supplementary cementitious materials (SCMs) use annually to eliminate 1 billion tonnes of CO_2 from the processing of cement. This paper will thus provide an overview of commonly used SCMs and their effects when used in construction as well as benefits to the environment.

II. SCMs

One of the solutions to tackling the negative impacts of cement manufacture is by using SCMs. SCMs have become very common, recently, as either partial replacements for Portland cement or as additives in cement production due to the increased environmental concerns with the unsustainable utilization of cement [17]-[19]. SCMs are considered inorganic materials that contribute to the properties of a cementitious mixture (e.g., paste, mortar, concrete or grout) through hydraulic or pozzolanic activity or both [20]. Another reason for the accepted use of SCMs is because they have been reported to greatly improve the durability properties of cement mortars and concretes [21].

Reference [22] reports that about 500 million tonnes of SCMs are produced annually. These SCMs are usually industrial or agricultural by-products that constitute waste in the environment. Their utilization can improve the micro-structure of cement paste or concrete (as regards to strength, permeability, rheology, alkali-silica reaction and durability), reduce environmental footprint, excavating of minerals, landfilling and negative impacts of built environment globally [7], [17], [23]. Agricultural waste ashes are said to contain high amounts of silica in amorphous form and could therefore serve as SCMs [24]. Likewise, industrial by-products have no economic or commercial value which is why they are been considered for reuse [25].

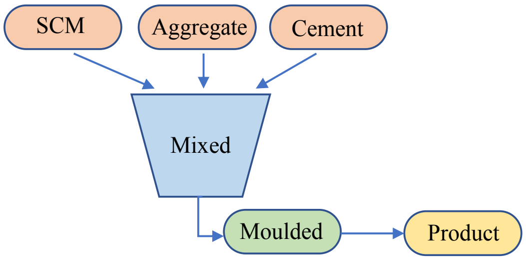

Fig. 2 Schematic process for SCMs adoption, adapted from [26]

Fig. 2 shows a sample schematic process for SCM adoption. Additionally, the benefits of using these SCMs include diverting waste materials in major landfills, decreasing the cost related to cement utilization, producing more durable products with longer life cycle, and producing products that are carbon conscious and environmentally friendly [17].

A. Pozzolanic Reaction

According to [4], during cement hydration, the important reactions are those of tricalcium silicate, C_3S and dicalcium silicate, C_2S. These are formed when lime (CaO) combines with silica (SiO_2). These silicates are responsible for strength enhancement of cement during the curing process [24].

$$C_3S: 2C_3S + 6H \text{ (water)} \Rightarrow C_3S_2H_3 \text{ (tobemorite gel)} + 3CH \text{ (hydrated lime)}$$

$$C_2S: 2C_2S + 4H \Rightarrow C_3S_2H_3 + CH$$

Reference [4] points out that this tobemorite gel is the main binder in hydrated cement. According to [21] and [27], the amorphous silica in SCMs reacts with the calcium hydroxide (CH) produced during cement hydration which is said to cause poor durability in hardened pastes and converts it to calcium silicate hydrate, CSH (tobemorite gel).

TABLE I
ASTM C618-12 STANDARDS REQUIREMENTS FOR UTILIZATION OF CALCINED SCMS [28], [7], [29]

Chemical composition (%)	Requirement	Class N (%)	Class F (%)	Class C (%)
$SiO_2+Al_2O_3+Fe_2O_3$	Minimum	70.0	50.0	50.0
Calcium oxide (CaO)		Report only	18.0 max	>18.0
MgO	Maximum	5		
Sulphur trioxide (SO_3)	Maximum	4.0	5.0	5.0
Loss on Ignition (LOI)	Maximum	10	6.0-12.0	6.0
SiO_2-CaO	Minimum	34		
Moisture content	Maximum	3.0	3.0	3.0
Available Alkalis (Na_2O, K_2O)	Maximum	1.5		
Strength activity Index (with cement, at 7- or 28-days min. % of control)	Minimum	75.0	75.0	75.0
Fineness (% retained on 45µm sieve)	Maximum	34	34	34
Water requirement (% of control)	Maximum	115	105	105

*Class N refers to naturally occurring pozzolans. Class C and Class F refer to different types of fly ash obtainable from industries.

The formation of more CSH binder could lead to long term strength improvement. Furthermore, [29] explains that the pozzolanic reactivity of any SCM depends on its mineral contents, chemical composition, extent of amorphous phase, specific surface area, the amount of lime in the cement pastes and the mixing conditions during usage. Several standard specifications are available for the proper production and utilization of these SCMs, such as ASTM C618-19, ASTM C311-18, ASTM C1697, highlighting their physical as well as their chemical compositions [30]. Table I shows the stipulated requirements by the ASTM C618-19 [28] standards for the utilization of calcined SCMs.

III. PHYSICAL AND CHEMICAL PROPERTIES OF SCMS

The ability of any SCM to react, according to [18], depends on properties such as the parent material, addition rate, chemical composition, size of particles, temperature, and others.

A. Physical Properties

i. Particle size and Specific surface area: The particle size of any SCM directly affects the way it would react when mixed. As silica from the SCM reacts with calcium hydroxide, the rate of pozzolanic reaction is proportional to the amount of surface area available for reaction [18].
ii. Relative density/Specific gravity: Relative density is the ratio of the mass of an aggregate to the mass of a volume of water equal to the volume of the aggregate particles.
iii. Bulk density: According to [31] the bulk density depends on how densely packed the material is. It will affect how the material is handled, transported, or packaged.
iv. Strength Activity Index: The strength activity index with Portland cement is a measure of reactivity with a given cement and is subject to variation depending on the source of both the SCM and the cement [28].
v. Texture: The SCM texture whether smooth or coarse could affect the initial and final setting times of cement paste or concrete [27].

B. Chemical Properties

i. Alkali content: The alkali content (Na_2O and K_2O) should not be high, as it can have harmful effects on mortar or concrete strength and can lead to disintegration of concrete or mortar [27], [24].
ii. Chloride and moisture content: Chloride ions may migrate through the concrete over time and can accelerate corrosion of the steel in reinforced concrete [32].
iii. Loss on Ignition (LOI): The LOI test measures the amount of unburned carbon remaining in the product. According to the ASTM C618-19 standards [28] and EN 450-1 standards, high values of LOI in the SCM could mean poor quality ash and could reduce workability and increase water demand thereby reducing compressive strength. Maximum of 10% LOI is advised [28].
iv. Silica phase: SCMs are said to have better pozzolanic reactivity when combined in amorphous state rather than crystalline state [33].

These chemical properties should be limited as they may have negative effects on the end product [32].

IV. DURABILITY PROPERTIES OF CEMENT MORTARS OR CONCRETE INFLUENCED BY SCMS

According to [34], substituting any SCM in cement or concrete production is meant to improve one or more of its durability properties.

A. For Freshly Mixed Cement Mortars and Concrete

i. Workability and Consistency: This indicates the ability of concrete mix to flow. Reference [35] explains workability as the effort required to manipulate freshly mixed concrete with little loss of consistency.
ii. Setting Time: The setting time of concrete signifies the conversion of concrete mix from liquid to solid [36]. Reference [37] explains that the initial setting time affects the casting and compacting process while the final setting time affects the strength development of concrete.
iii. Heat of Hydration: Hydration of cement is considered an exothermic process, according to [38], this can cause cracking in the hardened paste or concrete.
iv. Curing and Water requirement: Curing and water requirement are parameters that influence strength of mixtures [33].

B. For Hardened Cement Mortars and Concrete

i. Strength: According to [1], strength is considered a major index for safety of a structure.
ii. Porosity and Permeability: The volume of fluid absorbed by a material can signify its porosity value [34]. According to Darcy's law, permeability measures the rate of fluid flow through a porous medium.
iii. Resistance to Sulphate, Chloride ion, and Alkali-Silica Reaction (ASR): Reference [39] explains ASR as the chemical reaction between the reactive constituents of the cement aggregates and the alkali ($K+$ and $Na+$) and hydroxyl ($OH–$) ions present within the concrete. According to [4], Alkali-Silica Reaction can cause the hardened concrete to crack and weakens its interior making it vulnerable to sulphate and chloride ion attacks and freeze-thaw damage in cold regions.
iv. Thermal properties: Some thermal properties that can be affected include thermal conductivity, specific heat capacity and thermal diffusivity. Reference [34] explains that the thermal properties of materials are important to consider in most climes as they contribute to the heating and cooling loads of buildings.

V. COMMON TYPES OF SCMS

Several researchers have investigated the use of different SCMs to be combined with cement mortars or concrete for construction purposes. These SCMs are usually obtained from naturally occurring minerals, volcanic residues [18] or from agricultural or industrial wastes.

According to [17], SCMs can be categorized as either self-cementing or pozzolanic in behaviour. Self-cementing SCMs react like Portland cement in the presence of water as they contain traces of calcium or lime similar to the quantity in Portland cement. Conversely, the pozzolanic SCMs [40], [17] do not react without added lime, usually from cement, and water ($Ca(OH)_2$). These pozzolanic SCMs are further grouped as natural or artificial; where the natural pozzolans do not need to be ground or calcined before use but the artificial pozzolans require grinding, calcination or both before it can be utilized. The ASTM C125-19 standards [20], however, describe a natural pozzolan as a raw or calcined naturally occurring material that behave as a pozzolan. These include volcanic tuffs and ashes, diatomaceous earth, opaline cherts and shales, clays, and shale [20], [28]. Artificial pozzolans,

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however, are mainly by-products or waste from man-made or industrial processes such as fly ash, rice husk ash, sugarcane bagasse ash, blast furnace slag, recycled glass waste, etc. Some of the commonly used SCMs are described below.

A. Industrial By-Products

1) Coal Fly Ash (FA)

FA can be obtained from combustion of coal or lignite in thermal power stations as they fly out with the flue gas stream; they are then collected using mechanical separators or bag filters [40], [41]. FA is an industrial waste that is rich in aluminosilicates [25] and is one of the most abundant man-made materials [38]. It has presently been produced in vast amounts in China, USA, and India and accounts for 5-20% of coal that is fed in and captured by electrostatic or mechanical precipitation from flue gas. Annual global coal production, according to [38] was about 750 million tonnes in 2012, with only about 25-50% being reused, and is bound to increase in coming years due to more coal-fired electricity generation. The improper disposal of FA has become a major environmental concern according to [38]. It can cause pollution or irritation to human body and could also contaminate ground water with heavy metals if improperly disposed. Reference [42] argues that about 20% of anthropogenic greenhouse gases is from coal fired power stations, therefore, using FA as a SCM will help reduce this value.

ASTM C618 standards and BS EN 450-1 standards specify classes of FA and regulations for use in the United States and Europe respectively [17]. These specifications further classify FA into class C and class F. Class C FA is typically from calcination of sub-bituminous coal or lignite whereas class F is from the calcination of anthracite or bituminous coal [28]. Class C, unlike class F FA (< 15%), has higher calcium content (> 15%), resulting in it being among the self-cementing SCMs [38], [17]. Fig. 3 shows the chemical composition of coal FA. The FA produced will vary depending on the type of coal used, furnace type, oxidizing condition of said furnace and mineralogical differences of the coal used.

Durability Properties of Coal FA

Reference [41] agrees that FA could yield good outcomes in terms of improving mechanical properties and lowering density when added to cement paste. Class F FA is said to increase compressive strength up to 60% [17] when used as an additive or fine aggregate at 55% replacement rather than for cement replacement; it also improves workability of fresh concrete and durability of hardened paste unlike class C FA [43]. Reference [25] also reports that FA reduces the heat generated during concrete hydration and can be employed to stabilize soft soils and as structural fill material. Similarly, [40] reports that FA concrete exhibits lower chloride permeability when compared to control based on their study. In terms of enhancing fire resistance of concrete, [19] argues that FA and blast furnace slag perform better than silica fume. Class F FA, according to [38], improves the permeability and strength of hardened concrete with optimum replacement value of 15-35% for structural concretes and up to 70% for mass concrete works. Optimum temperature to soften components of FA is said to be between 850-900 °C according to [38]. Consequently, transporting coal FA more than 200 km is considered unwise as this will reduce its economic benefits.

2) Granulated Blast Furnace Slag (GBFS)

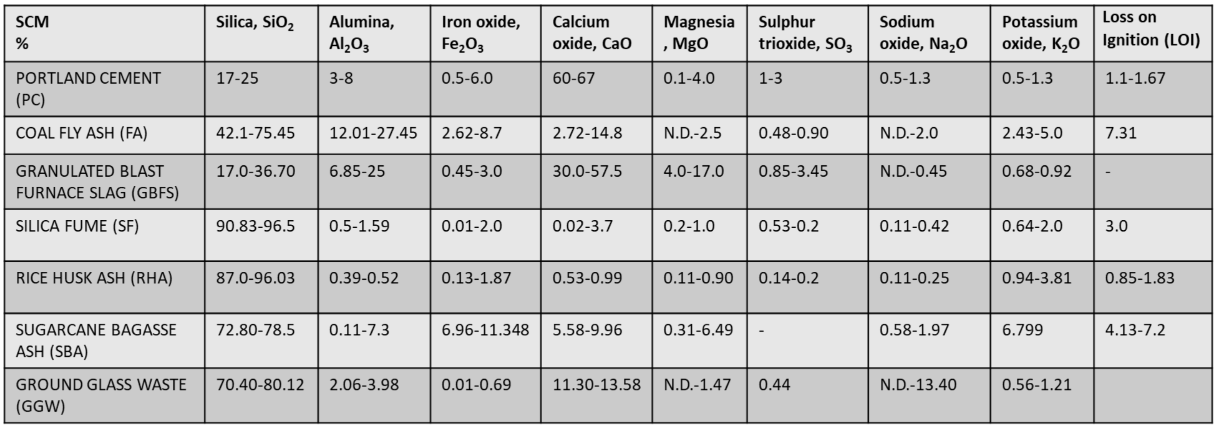
According to [22], GBFS was first developed in 1853 in Germany. Made of about 95% amorphous calcium-aluminosilicates; and because of its self-cementing ability, it is used directly for cement replacement during concrete production [17]. GBFS is obtained from steel and iron producing industries as a by-product resulting from floating silicate and aluminate atop molten steel or iron during the production process. The blast furnaces are fed with iron ore, coke and limestone and calcination occurs at 1500 °C. The slag produced is either cooled slowly with air or rapidly with high pressure water jet and it solidifies forming a stony material [44]. The slow cooled slag, according to [45], is used as aggregate replacement in concrete production whereas the slag that is rapidly cooled can be used as partial cement replacement. The rapid cooling of slag, according to [44], prevents the particles from becoming crystalline and will produce GBFS having 95% amorphous siliceous contents.

The steel industry is said to be one of the largest contributors to global CO_2 emissions [5]. 1 ton of steel is reported to produce about 340-421 kg of blast furnace slag [23]. With about 23-250 million tonnes being produced annually worldwide, its most common usage has been for partial replacement for airport runways concrete to reduce the thickness of hardened concrete required [17]. Fig. 3 shows the chemical composition of GBFS with huge amounts of calcium oxide.

Durability Properties of GBFS

According to [17], studies have revealed that optimum cement replacement for GBFS is within 40-60%. GBFS is observed to improve strength, reduce water absorption and porosity when used for concrete production [45]. Furthermore, [46] states that GBFS improves the workability of fresh cement mortars and concrete. It also reduces the chances of thermal cracking after concrete has hardened due to the low heat of hydration produced when it is used. Reference [45] studied the effect of GBFS on concrete as regards porosity, water absorption, strength and density using GBFS of 20-80%weight of cement to replace fine aggregate and water to cement (w/c) ratios of 0.45 and 0.55 for concrete production. After 7 days of curing, they observed increased strength more than the control of 1.48%, 2.1% and 7.96% with w/c of 0.5, and 1.5%, 4.18% and 5.42% with w/c ratio of 0.45 using 20%, 40% and 60% replacement values respectively. The strength increased further after 28 days of curing. This is similar to results from [37], who report that GBFS has positive effects on the later stage strength development of concrete. However, the use of 80% replacement value for GBFS recorded a decrease in compressive strength at both 0.45 and 0.55 water/

cement ratios. Therefore, higher values of strength can be attained using w/c ratio of 0.45 instead of 0.50. Similarly, GBFS reduced water absorption of concrete more than control by 0.49% using 20% cement replacement and 1.36% and 1.92% using 60% and 80% cement replacement respectively, showing that water absorption in concrete reduces with more GBFS additions. Furthermore, the porosity is reported to reduce by 2-3% with more GBFS replacements. The density, however, increased slightly with more replacements from 2290.69kg/m^3 at 0% replacement value to 2348.56kg/m^3 at 80% replacement value.



SCM %	Silica, SiO_2	Alumina, Al_2O_3	Iron oxide, Fe_2O_3	Calcium oxide, CaO	Magnesia, MgO	Sulphur trioxide, SO_3	Sodium oxide, Na_2O	Potassium oxide, K_2O	Loss on Ignition (LOI)
PORTLAND CEMENT (PC)	17-25	3-8	0.5-6.0	60-67	0.1-4.0	1-3	0.5-1.3	0.5-1.3	1.1-1.67
COAL FLY ASH (FA)	42.1-75.45	12.01-27.45	2.62-8.7	2.72-14.8	N.D.-2.5	0.48-0.90	N.D.-2.0	2.43-5.0	7.31
GRANULATED BLAST FURNACE SLAG (GBFS)	17.0-36.70	6.85-25	0.45-3.0	30.0-57.5	4.0-17.0	0.85-3.45	N.D.-0.45	0.68-0.92	-
SILICA FUME (SF)	90.83-96.5	0.5-1.59	0.01-2.0	0.02-3.7	0.2-1.0	0.53-0.2	0.11-0.42	0.64-2.0	3.0
RICE HUSK ASH (RHA)	87.0-96.03	0.39-0.52	0.13-1.87	0.53-0.99	0.11-0.90	0.14-0.2	0.11-0.25	0.94-3.81	0.85-1.83
SUGARCANE BAGASSE ASH (SBA)	72.80-78.5	0.11-7.3	6.96-11.348	5.58-9.96	0.31-6.49	-	0.58-1.97	6.799	4.13-7.2
GROUND GLASS WASTE (GGW)	70.40-80.12	2.06-3.98	0.01-0.69	11.30-13.58	N.D.-1.47	0.44	N.D.-13.40	0.56-1.21	

Fig. 3 Chemical composition of some common SCMs [1], [7], [19], [23], [25], [27], [29], [33], [37], [40], [52], [55], [57], [60], [64], [68], [70]

3) Silica Fume or Microsilica (SF)

Over 6 million tonnes of silicon were produced in 2018, with countries like China, Russia and the United States recording the highest production [47]. Silica fume is a popular SCM derived from silicon and ferro-silicon industries as by-product having about 1.5 million tonnes being produced annually [48], [17].

Silicon is produced at temperatures above 2000 ºC from silica (SiO_2) derived from quartz, and carbon (C) derived from coal, coke, or wood chips. According to [49], this calcination process produces SiO_2 vapours that oxidize and condense to form silica fume having 75-95% amorphous silica content depending on the silicon alloy being calcined.

SF has 25% and 50% of its particle size less than 100 nm and 150 nm respectively with specific surface (Brunauer-Emmett-Teller, BET) ranging from 15-30 m^2/g. Having 95% of its particle size below 1 µm, silica fume is about 85-90% of SiO_2 in amorphous state and reacts vigorously when added to cement or concrete mixtures [17], [48]. This high reactivity is due to its fine particle size and amorphous nature. Fig. 3 shows the chemical composition of silica fume.

Countries that have high production, according to [48], include China, Norway, South Africa, Canada, Spain, Russia, and France. Additionally, [49] reports that its durability and flexibility lend it a wide variety of use in the construction industry including high strength concrete, highway bridges, shotcrete production, marine structures, refractory and ceramics, grouting of oil wells, fibre concrete, refractory materials and mortar repairs.

Durability Properties of Silica Fume

Reference [50] carried out a study on the mechanical properties of high strength concrete using silica fume to replace cement at 6%, 10% and 15% weight of cement and 0.35 water/cement ratio. Due to the very fine nature of silica fume, they added a superplasticizer in the mix to enhance binding in the concrete. Each blended concrete recorded higher strength than control, having 11%, 14% and 17% increase using 6%, 10% and 15% silica fume replacement values respectively. With increased additions of silica fume, autogenous shrinkage of the concrete increased while the drying shrinkage reduced. Strength, however, ceases to increase beyond 90 days curing age. Similarly, [37] considered partial replacement of cement for concrete production using silica fume, slag and FA to determine and compare the setting time and compressive strength properties when each is utilized with different water to cement ratios. They report that the use of 7% replacement value of silica fume recorded about 16% increase in strength after about 90 days of curing, which is similar to the results obtained by [50]. Silica fume also had positive influence on the early and later strength development of the concrete unlike with FA and slag which only had positive effects on later stage strength development. They also recorded about 6% increase in strength with 15% cement replacement whereas slag recorded a decrease in the strength of concrete up to 4% and 20% using 25% and 35% replacements, respectively.

Reference [49], therefore, concludes that silica fume accelerates hydration process when used without retarding the strength of concrete or cement mortar. Although silica fume is noted to improve strength with up to 30% replacement value, optimum replacement value should not exceed 10% as the mixture will become stiff with more SF addition and will require superplasticizer or increased water to cement ratio [37], [49].

B. Agricultural Wastes

1) Rice Husk Ash (RHA)

RHA is derived from the burning of rice husk, which typically makes up about 20-23% of total harvested rice mass [51]-[54]. RHA is a promising SCM for partial replacement of cement and reducing environmental impact of the construction industry as the rice husk does not burn or biodegrade easily thereby contributing a nuisance to the environment [55]. This husk has also been considered for power generation in areas with large production of rice because rice husk is reported to have similar calorific value to coal (14MJ kg^{-1} of energy) and can therefore be used to produce electricity [56], [57]. According to [27], FA and silica fume are more globally accepted for use than RHA which is only popular in rice producing areas due to availability.

Rice production in developing countries is about 500 million tonnes and its husks generate about 20% ash when burnt which is high in silica, highly porous, lightweight and has large surface area when ground making it highly reactive [24], [33]. Rice husk is typically made of 50% cellulose, 25-30% lignin and 15-20% silica but increases in silica content upon calcination [55], [17]. RHA is mostly utilized in many Asian countries, although worldwide production of rice has increased from 650 million tonnes in 2010 to 769 million tonnes in 2017 [17], [58]. RHA has most commonly been utilized as fertilizers, soil amendments [56], for production of composite materials, for production of particleboard [26], for manufacturing insulating powder, for production of refractory bricks [59] or as fuel in rice drying. It is recently being used as supplementary cementitious in cement mortar or concrete production due to its high silica content (Fig. 3) and pozzolanic behaviour [60], [61].

According to [1], the use of RHA can help save energy costs as it utilizes 500-700ºC during combustion whereas Portland cement production utilizes about twice of that 1500ºC during limestone combustion.

Durability Properties of RHA

Reference [52] conducted their research using Indian paddy to achieve RHA with 87% silica content when burnt for 1 hour at 650ºC. Using 30% RHA for cement replacement improved the strength properties of the blended concrete in their study and reduced 35% permeability, 28% chloride ion diffusion and 75% chloride permeation.

Reference [55] investigated the effects of RHA blended with white Portland cement to produce mortar resulted in off-white rice husk ash (OWRHA) which had SiO_2, Fe_2O_3 and Al_2O_3 contents equal to 95.45%, higher than the 70% minimum stipulated by ASTM C618 standards [28] for natural pozzolan usage. At 15% cement replacement, using 0.44 w/c ratio, this OWRHA recorded 17% increase in compressive strength, 9% increase in tensile strength, 4% decrease in porosity, 15% reduction in water absorption and reduced thermal conductivity and density of the cement blocks produced as opposed to the control after 90 days of curing. In addition, combining this OWRHA to produce cement mortar resulted in 5.5% and 10.7% increase in compressive strength with 7.5% and 15% cement replacement respectively. According to [57], 10-20% weight of cement replacement is the optimum replacement for RHA when blended with concrete as it has high particle porosity and would require a superplasticizer to ensure proper mix, compactness and concrete finish if higher replacement was used.

2) Sugarcane Bagasse Ash (SBA)

This is another SCM popular for its high siliceous contents [19]. Bagasse is dry crushed stalk resulting from production of cane juice [17]. Bagasse is commonly used as fuel in co-generation to produce steam and electricity [62], [63]. The resultant ash when calcined is the SBA which makes up about 25-40 kg/ton of bagasse burnt. Consisting of silica and aluminosilicates, it is mostly be produced as waste in sugar and ethanol industry when bagasse is burnt for electricity and heat co-generation.

According to [63] sugarcane is mostly found in tropical and sub-tropical countries and is used to make sugar and ethanol [64]. With about 1.8 billion tonnes recorded in 2017 globally, sugarcane is largely produced in countries like India, Brazil, and China [58].

SBA is typically used as fertilizer or disposed in landfills but recently has been considered for cement or aggregate replacement in the construction industry due to it pozzolanic characteristics. It is used to produce polymeric concrete, ceramics, silica aerogels or as a catalyst. Additionally, when combined in concrete production, it is reported to improve concrete durability, reduce chloride attacks and decrease heat of hydration [63].

With high amounts of quartz and amorphous alumina, [63] agrees that SBA is best utilized as filler or sand replacement in concrete production. Grinding the ash is also proven to produce homogenous ash with improved pozzolanic reactivity. Fig. 3 details the chemical properties of SBA. Like most SCMs, SBA produced is affected by variety of sugarcane used, calcination temperature and duration, presence of impurities, location, cooling, and collection methods.

Durability Properties of SBA

For aggregate replacement in cement mortars, optimum replacement value is between 30-50%. Reference [63] reports that with higher SBA additions, water requirement increases along with the setting times for concrete. Reference [62] investigated the use of co-generation boiler SBA to replace natural sand in concrete production between 5-20% weight of cement. They produced silica rich SBA having 65% of its mass passing 50 µm sieve. After 28 days of curing, they recorded an increase in compressive strength of concrete having 5-15% replacement value when compared to control. However, they observed a reduction in workability with increasing SBA additions. This was resolved using superplasticizer but eventually caused a decrease in the strength of the concrete and increased the water demand. Reference [64] conducted similar studies using SBA to produce concrete. They, on the other hand, did not obtain the SBA from a co-generation boiler but burnt the sugarcane bagasse in a furnace at 700 ºC. This produced greyish-black ash having S+A+F value equal to 80.55%. They replaced cement using SBA replacement values of 10%, 20% and 30% weight of cement. From their results after 28 days of curing, they observed a decrease in compressive strength for the concrete by 17%, 25% and 36% for the respective SBA additions. The 10% and 20% cement replacement using SBA, however, achieved 83.2% and 75% Strength Activity Index respectively in line with the ASTM C618 standards [28]. Workability of fresh concrete is recorded to reduce also, along with density which reduces with further SBA additions.

C. Domestic/General Wastes

1) Ground Glass Waste (GGW)

This is obtained from grinding recycled glass waste. According to [25], ground recycled glass is derived from crushing mixed colour glass bottles and other glass products. It has particle sizes below 45 µm and silica contents like concrete [17]. Glass is considered the fifth most disposed solid waste after plastic, according to [65], with almost 100 million tonnes being disposed of yearly. The use of these wastes is therefore imperative to ensure the sustenance of our natural resources [66].

GGW is being considered as a SCM because of its amorphous nature and high amount of silica (Fig. 3) [67], [68]. The most used type being ground soda-lime glass as it is found in major landfills around the world. Recently fluorescent lamps, funnel glass from television screens and liquid crystal displays have also been considered as they are found in landfills in large quantities also.

About 72% of recovered glass is not recycled and remains in landfills as it is non-biodegradable, which is one of the reasons ground glass is being considered as a SCM [67]. It is reported to have slightly negative effects on the strength of concrete but can perform as a SCM when ground finely [17]. It is usually introduced as fine or coarse aggregate in concrete. However, [69] and [67] opine that the use of GGW as cement replacement yields better results compared to when it is used as aggregate replacement. GGW is mostly used for mass concrete works for roads, foot paths and pipe bedding [25].

Durability Properties of GGW

Reference [67] examined the use of different sized ground soda lime glass from fluorescent lamps to study the pozzolanic reactivity of the GGW, and the compressive strength and potential expansion when used in concrete production. They observed that the strength activity index using 30% replacement value increased when the glass was ground to particle size of 38 µm after 28 days of curing. The 75 µm glass had slightly less compressive strength to control. However, the 150 µm GGW did not reach the minimum required compressive strength. This is due to the different sizes of the GGW particles. After 90 days of curing, the 38 µm GGW was observed to have attained 12% higher strength than control concrete. It can therefore be inferred that GGW when ground finely will perform as a suitable SCM for cement replacement. In a similar manner, [69] carried out research using four variations of ground glass powders to examine the pozzolanic reactivity and strength development when used to replace cement in cement mortar. Like [67], they conclude that the glass powder ground the finest performed better than the rest. However, they report that this increase in GGW fineness leads to an increased water requirement typical of many SCMs. Reference [69] recorded strength activity index values of 74%, 92%, and 110% using the various glass powders at 20% replacement value after 28 days, which is comparable and much higher than the minimum of 75% stipulated by ASTM C618 standards [28]. It is also reported to have reduced the alkali induced expansion by 0.3%. Furthermore, [70] carried out research using waste glass from bottles ground to 400 m^2/kg and 600 m^2/kg to produce mortars having 30% GGW replacement value. They produced GGW having high alkali content of about 13.25%. This GGW, however, proved to be an effective SCM using the Fratini test especially when ground to specific surface area of 600 m^2/kg, similar to results by [67] and [69]. After 180 days of curing, mortars blended with both variations of GGW developed higher compressive strength than the control.

2) Shredded Plastic Waste (SPW)

Plastics are organic polymeric materials that can be molded under pressure and heated into a variety of forms [71], [72]. According to [73], about 400 million tonnes of plastic are being produced annually. Reference [72] estimates that the global demand for plastics will rise to 304 million tons by 2020. The strength, low density, durability, low cost, easy storage, and versatility of use lends plastic a myriad of applications in food packaging, medical, and automobile industries among others [74], [75].

Plastic utilization results in vast amounts of wastes which are recycled in some countries, but poorly disposed in others. About 80% of plastics are landfilled, 8% incinerated and only about 7% is recycled [74]. According to [76], landfilling prevents plant growth, disposing of plastic wastes into oceans causes water pollution as they float easily, also incineration produces harmful gases contributing to air pollution. These wastes are non-biodegradable and require about 100 years before they are broken down. Therefore, the reuse of these plastics is advised as it takes less resources and energy to reuse rather than to recycle them.

Plastic wastes have been considered for use as SCM in polymer concrete or cement blends as either partial replacement for aggregates or filler material [43], [46], [76]. Some of these plastic wastes include Polypropylene (PP), Polyethylene (PE), Poly-ethylene Terephthalate (PET), Polyvinyl chloride (PVC) and Polystyrene (PS). Reference [71] considers these five types of as large volume plastics. According to [74], PE and PET are the most disposed plastics found in waste streams.

Durability Properties of SPW

Reference [74] points out that the use of plastic wastes can reduce the bulk density of concrete. Reference [43] utilized 25% weight of PET waste and converted this to unsaturated

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polyester resin (PET resin). Using ternary blend of 10% PET resin and 13% FA to partially replace cement produced geopolymer precast concrete recorded about 80% increase in strength after just one day of curing. Similarly, [46] carried out research using PET bottles but finely ground into granules of < 4mm size with specific gravity of 1.27 g/cm^3. This was done to produce light weight mortar. they considered PET waste as both partial sand replacement and partial cement replacement. They also experimented with ground blast furnace slag and PET waste to produce polymeric mortar. The mortar was produced using 16.95% and 25.64% partial replacement of cement. In contrast with [43], these blended mortars recorded 48% and 58% strength of the control mortar after 28 days of curing. This strength value increased by 21%, however, with addition of ground blast furnace slag to the mixture. They also recorded water absorption of 13.4% and 11.9% after 28 days with higher porosity than control signifying that the mortars are lighter in weight. This shows that the use of plastic wastes is feasible for lightweight cement mortar or concrete production but will produce better results when combined with another highly reactive SCM.

Another similar research was carried out by [77]. They investigated the physical and mechanical properties of mortar blended with polycarbonate (PC) and PET wastes. They replaced natural sand, like [46], using 3%, 10%, 20% and 50% PET and PC wastes. They observed that the porosity and water absorption increased with more addition of PC and PET while the density reduced with more plastic addition. In addition, compressive strengths decrease of 9.8%. 30.5%, 47.1% and 69% for PET and 6.8%, 27.2%, 46.1% and 63.9% for PC were recorded for the four different replacement values respectively. This strength reduction is because of the weak bond between the hydrated cement and the plastic, as plastics are created to be hydrophobic [66]. Of the two plastic types, however, PC waste blended concrete recorded better results than PET waste.

In conclusion, SPW can be used to replace fine aggregates to produce lightweight mortars and concrete. Reference [72] recommends that plastic wastes should be used in non-structural applications or lightweight concrete products such as concrete masonry units, pavement blocks, kerbs, etc. However, the strength of the product is expected to reduce. This can be remedied by including highly reactive SCMs like FA, blast furnace slag or silica fume. In addition, optimal replacement value to produce low to medium strength plastic-blended concrete or mortar is 5-10% but can increase to 25% to produce ternary blend geopolymer concrete.

In general, most SCMs require further grinding to increase their surface areas and ensure better reaction with the cement or concrete mix [18]. Additionally, using SCMs in amorphous phase is usually better than using the partial crystalline or crystalline phase [32]. Reference [78] suggests that calcined SCMs can be kept in an airtight container to prevent amorphous silica from becoming crystalline.

VI. SUSTAINABILITY IMPLICATIONS OF SCMS UTILIZATION

About 2.01 billion tonnes of solid wastes are generated annually from manufacturing processes, industries, and construction and is predicted to increase to about 3.4 billion tonnes by 2050, as seen in Fig. 4 [65]. According to [74], solid waste management has become a major environmental concern due to the limited space and resources for disposal. Therefore, the reuse and recycle of wastes should be encouraged. Reference [79] estimates that by 2050, the world's population will rise to 9 billion which will lead to increased demand for energy, food, housing, and clothing. This has prompted increased research into the effectiveness and availability of SCMs that can partially replace cement as these wastes remain in the environment, remain unused and more wastes are produced with population growth. In addition, [80] explains that it takes about 1450 °C to heat up the solid particles for cement production. The use of these SCMs can substantially reduce this energy consumption as most SCM calcination requires about half that amount of energy say 500-800 kWh/ton. These SCMs when adopted can influence the properties of cement mortars and concrete [65], reduce amount of cement utilized [81], reduce landfilled wastes and reduce CO_2 generated from clinker manufacture.

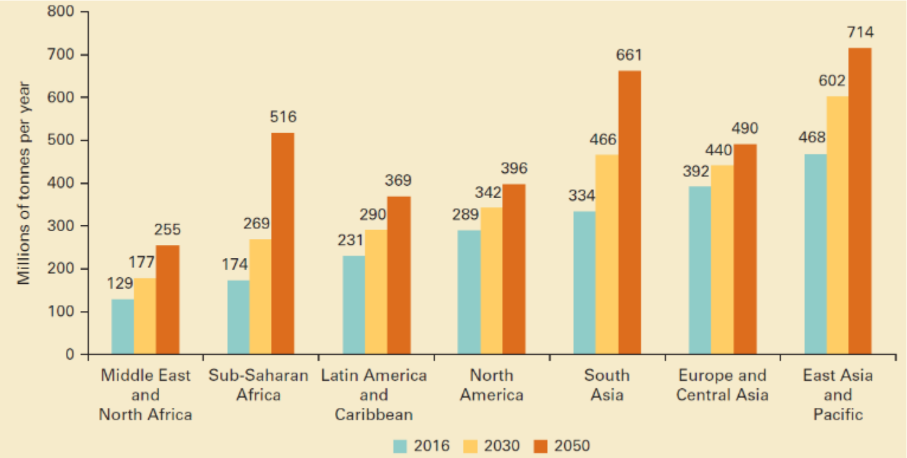

Fig. 4 Projected waste generation, by region (millions of tonnes/year) [65]

Increased consumption of natural resources will lead to higher production of wastes and invariably environmental pollution [82]. Therefore, using these wastes can create partial solution to this indirectly through landfill reduction, energy saving during cement production, reduced environmental pollution, and reducing CO_2 from cement manufacture.

The choice of which SCM to use, according to [29], depends on its abundance, environmental impact, mechanical properties, and the economic standpoint. The use of these SCMs is, therefore, recommended as it will encourage efficient waste management and reduce the need for mining virgin materials [25]. One disadvantage of using SCMs, however, is that transporting them from far distances could contribute negatively to the economy and environment [83].

VII. CONCLUSION

This paper has provided an overview on the use of SCMs as well as highlighting the most common ones in use today. Utilization of these wastes will provide a solution to landfilling of wastes which constitute a nuisance, will reduce energy consumption during cement production, and reduce carbon emissions from cement manufacture. It will also encourage the use of sustainable construction materials to reduce the negative impact of the building industry on the environment and foster sustainable communities. This research will be useful to industry experts as well as researchers in the field.

Future work will focus more on the use of agricultural waste materials as SCMs. Agricultural waste materials are considered as being the most sustainable of all the SCMs as the CO_2 emitted during their calcination is offset by the CO_2 absorbed during the plant's life cycle.

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